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Review

A Review on Industrial Perspectives and Challenges on Material, Manufacturing, Design and Development of Compressed Hydrogen Storage Tanks for the Transportation Sector

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Abstract: Hydrogen fuel cell technology is securing a place in the future of advanced mobility and the energy revolution, as engineers explore multiple paths in the quest for decarbonization. The feasibility of hydrogen-based fuel cell vehicles particularly relies on the development of safe, lightweight and cost-competitive solutions for hydrogen storage. After the demonstration of hundreds of prototype vehicles, today, commercial hydrogen tanks are in the first stages of market introduction, adopting configurations that use composite materials. However, production rates remain low and costs high. This paper intends to provide an insight into the evolving scenario of solutions for hydrogen storage in the transportation sector. Current applications in different sectors of transport are covered, focusing on their individual requirements. Furthermore, this work addresses the efforts to produce economically attractive composite tanks, discussing the challenges surrounding material choices and manufacturing practices, as well as cutting-edge trends pursued by research and development teams. Key issues in the design and analysis of hydrogen tanks are also discussed. Finally, testing and certification requirements are debated once they play a vital role in industry acceptance.

Keywords: hydrogen; storage; transportation; filament winding

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1. Introduction

Today, the transportation sector faces a new paradigm to address the threat of climate change and environmental pollution. Sustainable and innovative fuel and powertrains keep emerging and maturing, in a scenario driven to mitigate the environmental impacts generated by greenhouse gas emissions provoked by the combustion of fossil fuels [1]. The evolution of our energy supply system seems to encompass different and non-exclusive solutions for mobility centered on clean energy sources and zero-emission vehicles.

Fuel cell (FC) electric vehicles powered with hydrogen have attracted worldwide attention and are considered viable green alternatives in the decarbonization of transportation. Hydrogen has since been well established as an advanced option of energy carrier, providing clean and cyclic utilization with an unlimited supply [2]. To date, there are several chemical and physical hydrogen storage methods, such as high-pressure gaseous hydrogen storage, liquid hydrogen storage, metal solid hydrogen storage and complex hydride hydrogen storage [3].

The hydrogen storage system, once a technical barrier limiting the widespread use of hydrogen energy, has since become a key enabling technology, ensuring good safety performance, cost competitiveness and weight efficiency. Hydrogen tanks nowadays are fully commercialized and sophisticated products, and part of a very competitive market [4–6]. This paper summarizes the challenges experienced in hydrogen storage for fuel cell vehicles both in an academic and in an industrial engineering context. A broad perspective of the state-of-the-art of this emergent technology is traced, thus, capturing its main applications and industrial prospects in several sectors related to transportation. It also addresses particularities related to material choices, manufacturing and cost for composite tanks produced with filament winding. Design and certification processes are also covered.

2. Compressed Hydrogen Tank Applications across Transportation

The application of hydrogen fuel cells in transportation offers a great possibility to decarbonize an activity sector, which alone is responsible for the largest share of greenhouse gas emissions [7]. This is particularly attractive to sectors with limited low-carbon fuel options, such as aviation and maritime sectors [8]. The present review addresses only application-oriented developments from recent decades, emphasizing current research and development (R&D) trends.

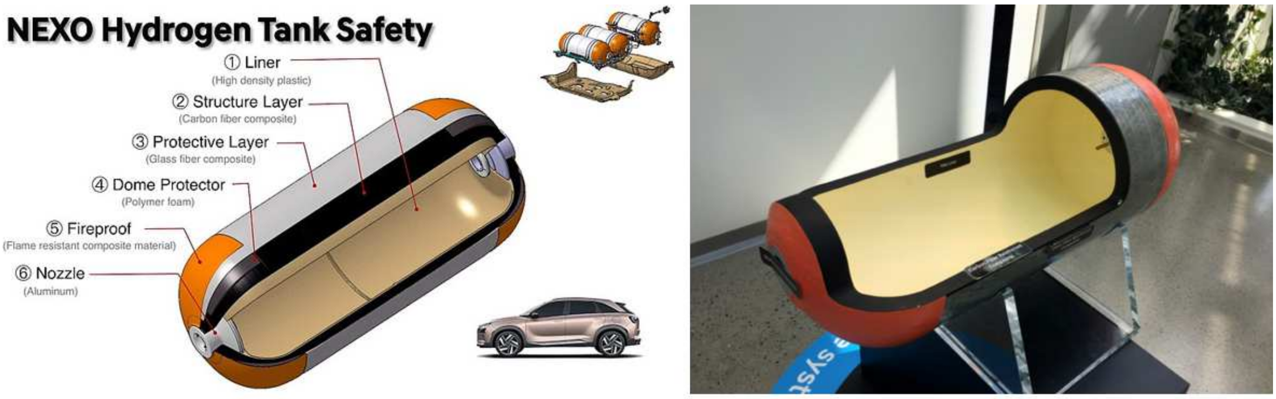
2.1. Light-Duty Vehicles

Transport by road, which includes automobiles, buses and trucks, accounts for three-quarters of the greenhouse gas emissions attributed to the transportation sector [9]. Today, hydrogen fuel-cell light-duty vehicles are in the early stages of commercialization, with the launching of several models developed by different automakers across the world in order to replace internal combustion engine models. Nonetheless, the selling cost of these vehicles is not yet competitive, and infrastructure issues such as the lack of a diffuse hydrogen refueling station network act as constraints for widespread FC vehicle commercialization [10].

Toyota, Hyundai and Honda are the leading manufacturers of passenger FC vehicles [11], and Table 1 compares various technical specifications of their best-seller models. All of them employ tanks composed of composite materials (type IV classification, as approached in Section 3.1 and illustrated in Figure 1), which have shown the proven ability to answer to technological issues raised by on-board compressed hydrogen storage, and are currently the industry's choice when taking into consideration the degree of maturity of the technology, its weight efficiency and its costs [12–15]. This configuration is composed of a thin polymer liner fully overwrapped with fiber wound layers. The state-of-the-art on-board hydrogen storage technology operates at high pressures, with compressed hydrogen gas typically stored at 35 or 70 MPa [16].

Table 1. Comparison of specifications for the three best-seller models of FC vehicles [17].

Description	Hyundai 2019 Nexo	Toyota 2018 Mirai FCV	Honda 2017 Clarity FCV
Photos			
Driving distance after one charge (m)	370	312	366
Hydrogen tank mass (kg)	6.33	5.00	5.46
Motor (kW/lb.ft)	113 kW/291 lb.ft	120 kW/247 lb.ft	100 kW/256 lb.ft
Maximum output (hp)	163	154	1744
Maximum torque (km·m)	40.3	34.2	30.6



(a) (b)

Figure 1. (**a**) Schematic cross-section of a hydrogen tank for Hyundai Nexo [18]; (**b**) photograph of a sectioned Hyundai Nexo hydrogen tank [19].

2.2. Heavy-Duty Vehicles

The heavy-duty market also shows considerable potential for hydrogen fuel cell adoption, even though it presents different operating conditions and driving cycles. These vehicles present higher power output needs as well as requirements of improved durability and fuel efficiency [20]. While light-duty passenger vehicles used for typical short low-speed journeys could be managed with electric batteries and range-extender devices, long-haul heavy vehicles such as trucks and buses call for a higher utilization and are likely to require hydrogen [21].

With the scheduled banning of diesel trucks by many major city centers [22], several vehicle suppliers, such as MAN, Scania, VDL and Hyundai, have developed hydrogen FC trucks [23]. The design space assessment of hydrogen onboard storage for fuel cell electric trucks demonstrated the feasibility of employing type IV tanks to meet the range demands of various market sectors, while exploring different operating pressures and vehicle packages [24].

Fuel cell buses have likewise attracted great attention and become a public demonstration tool and R&D source of data for full-scale validation [25,26], especially due to the implementation of several government actions and funding projects. This includes the European CUTE (Clean Urban Transport for Europe) bus program [27], US National Fuel Cell Bus Program [28], Korean hydrogen economy roadmap [29], among others. On-board tanks are typically stored in the bus's roof and a higher space availability allows for storage at 35 MPa, reducing tank and compression costs [21]. Table 2 depicts the technical specifications of FC buses developed by different key manufacturers.

Table 2. Overview of major characteristics of FC buses currently used in European cities [30].

Bus Type	Van Hool Bus	Evobus	Solaris	Wright Bus
	Standard	**Standard**	**Articulated**	**With Supercapacitors**
Bus length (m)	12/13	12/13	18.75	12
Fuel cell system (kW)	150	120	100	75
Battery system (kW)	100	250	120	-
Supercapacitor system (kW)	-	-	-	240
Hydrogen storage system	7 tanks, 35 MPa	9 tanks, 35 MPa	9 tanks, 35 MPa	4 tanks, 35 MPa
Full tank capacity (kg)	35	35	45	33

The Belgium company Van Hool has established itself as the market leader with the A330 model, with buses in operation in both Europe and the US [31]. Toyota, in cooperation with Hino Motors, developed the Sora, introducing more than 100 buses in the Japanese public transport fleet ahead of the 2021 Tokyo Olympic and Paralympic games [32]. In

South Korea, Hyundai has been commercializing the Elec City Fuel cell since 2019, with more than 100 units put into operation and in-service trials having been conducted by different European bus operators [33]. Wrightbus has developed the world's first double-decker FC bus in England [34]. VDL Bus & Coach delivered FCs in 2011 as part of its demonstration activities, and, since 2020, deployed vehicles in the Netherlands, adding a trailer to battery buses, housing the fuel technology for range extension [35].

2.3. Tube Trailers

High-pressure tube trailers are a vital part of hydrogen transportation logistics. With the rollout of hydrogen fuel cell electric vehicles, a wide availability of refueling stations becomes a key issue for an efficient operation. Today, the available infrastructure of pipelines is very limited, mainly focused on large industrial users, such as petroleum refineries and fertilizer plants [36]. The utilization of tube trailers allows for a more economical delivery mode for lower-demand customers and refueling stations at reasonable distances from production sites (less than 100 miles). This strategy has played a major role in enabling an early and widespread deployment of hydrogen refueling stations once it required a lower initial capital investment, granting an optimization of costs associated with gaseous compression and storage [37,38].

Typical tube trailers utilize long pressure vessels bundled together into packs of between 6 and 15, and their outlets are manifolded together [39]. These pressure vessels can be composed of steel or composites. Steel-made tube trailers (using type I tanks) are a more common configuration, although on-road weight restrictions limiting their capacity may be applied. Their maximum hydrogen payload is approximately 250 kg per trailer. On the other hand, tube trailers using composite pressure vessels provide a higher strength and lower weight solution, albeit at a higher cost. Both type III and type IV configurations have been employed, and they can deliver more than a 1000 kg payload [36].

On a global basis, there are several key industrial players involved in the delivery of gaseous hydrogen by tube trailers. Air Products and Chemical Inc. is probably the leading company, having joined programs to develop and validate composite tube trailers in association with the US Department of Transport (DOT), as well as with the Hydrogen Transport in European Cities (HyTEC) project [40–42]. It operates an ever-growing tube trailer fleet, delivering large volumes of hydrogen at high pressure. ILJIN HYSOLUS, the executive supplier of hydrogen tanks for the Hyundai Nexo, has received global accreditation for its type IV hydrogen tube trailers [43,44]. The Kawasaki Group has developed Japan's first hydrogen tube trailer with type III composite cylinders, backed by its national research and development agency NEDO. Its hydrogen tube trailer operates at a pressure of 45 MPa [45,46].

2.4. Fuel Station

The development of a reliable fueling infrastructure is a cornerstone for the use of hydrogen energy in transportation. Compression, storage and dispensing are key stages of the gaseous hydrogen refueling process, with direct implications to the final fuel cost paid by customers. In hydrogen refueling stations, the storage system not only locally stores the compressed gas, addressing the mismatch between fuel supply and demand during daily operations, but also plays a role in accelerating the filling process and avoiding frequent starts/stops of the compressor [47,48].

There are different possible approaches to a hydrogen station design, and the storage system, in particular, may assume two types, namely, buffer and cascade storage [49]. Both usually employ several banks of pressure vessels, although single-tank configurations can also be found. In buffer storage, all fuel reservoir cylinders are connected together and maintained at the same pressure at all times. In cascade storage, the gas is usually divided between three reservoirs under low-, medium- and high-pressure levels, and during the filling of the vehicles, the on-board tank is alternately connected to different reservoirs in an ascending order of pressures. Cascade storage systems have showed a lower energy consumption in high-pressure refueling scenarios, whilst buffer storage may present shorter refueling times [48,50].

Storage tanks are core elements of hydrogen refueling stations. Considering dispensing for light-duty vehicles operating at 70 MPa, high-pressure storage in a cascade system may be typically performed at 90–100 MPa, thus, ensuring the charging pressure difference needed for a short refueling time. Type II (usually steel-reinforced with carbon fibers) or type IV tanks are frequent configurations of choice for storage at such elevated working pressures once type I tanks become an uneconomical and heavy option and type III may be prone to fatigue due to the large number of fueling cycles [47,51]. Low- (approximately 20 MPa) and medium-pressure storage (approximately 40 MPa) may employ type I steel tanks.

2.5. Railway

Conventional locomotives employing diesel-based propulsion systems have been the basis of the rail transportation of industrialized countries, whether for the transport of commodities or passengers. Fuel-cell-powered locomotives, however, have been considered promising environmentally friendly options for achieving a fast and consistent decarbonization. FC trains and trams are expected to perform particularly well for long-range and high-power demand scenarios, and can present lower infrastructure costs in comparison with catenary electric and hybrid diesel–electric configurations [52,53].

The first functional hydrogen-fueled locomotive was a 3.6 ton/17 kW underground mining vehicle demonstrated in Val-d'Or, Quebec, in 2002. Using 3 kg of metal hydride storage, it was developed as part of a joint project by the governments of the US and Canada, together with a private company later called Vehicle Projects LLC [54]. As initial key development milestones, in 2006/2008, the East Japan Railway Company trialed a hybrid passenger car on an actual service line (one railcar, 130 kW FC system/19 kWh battery, gaseous hydrogen stored at 35 MPa [55]); in 2006, the Railway Technical Research Institute, also in Japan, implemented running tests of its FC railcars, manufactured by US/Italian-based Nuvera Fuel Cells (two railcars, 120 kW FC system, 36 kWh battery/18kg of gaseous H_2 stored at 35 MPa) [56]. A North American partnership funded by the BNSF Railway Company and the US Department of Defense rolled out a prototype fuel cell battery hybrid switch locomotive for urban rail applications (130 ton, 240 kW FC system/maximum power of 1.2 MW, 70 kg of H_2 at 35 MPa) [56].

Most recently, Alston pioneered sustainable mobility solutions by presenting the world's first passenger train powered by a hydrogen fuel cell, the Coradia iLint (Figure 2). In 2018, the two-car model entered into commercial service in Germany and, since then, the iLint has run successful test runs in Austria, the Netherlands and Sweden [57]. JR-East announced in 2019 that it was developing a two-car train using the hydrogen FC technology from Toyota, with trials expected by 2021 and commercialization by 2024 [58]. Siemens is developing Mireo, a fuel cell variant planned in cooperation with Ballard. Ballard plans to supply two 200 kW fuel cell modules to be installed in a two-car passenger train for a trial operation in Bavaria [59]. Stadler is producing the first US hydrogen-powered train that is expected to enter service in 2024 in San Bernardino County, California [60]. TIG/m is currently supplying the world's first municipal trams to use hydrogen fuel cell technology for propulsion to the governments of Dubai and Aruba. Three hybrid battery/fuel cell vehicles have been delivered since 2012 [61]. Hyundai Rotem has announced its entry into the hydrogen train market with the current development of Korea's first hydrogen-powered light rail vehicle for the urban rail network in the city of Ulsam [62].

Current projects of hydrogen-powered passenger trains employ different solutions for the on-board storage systems. Compressed gaseous hydrogen systems are the most common, with working pressure values ranging from 30 to 70 MPa. Market availability and the successful application of heavy-duty vehicles with lower costs makes the 35 MPa system the most frequent configuration employed in railways, achieving ranges of approximately 1000 km [63]. For instance, Alstom's Coradia iLint uses twenty-four roof-mounted 35 MPa type IV cylinders fabricated by Xperion [64]. Stadler's project will have 35 MPa type IV tanks provided by Hexagon [64]. Thirty-six Luxer type III hydrogen tanks have been used in the HydroFLEX project, the UK's first full-sized hydrogen powered demonstrator train [65]. The JR-East and Toyota partnership intends to utilize 70 MPa type IV tanks [58].

Figure 2. (**a**) Coradia iLint, the world's first hydrogen fuel cell passenger train [66]. Reproduced with permission from Alstom/R.Frampe; (**b**) Layout of FC train elements onboard [67].

2.6. Maritime

Advanced hydrogen mobility has also started its penetration into the maritime sector with the development of several demonstration programs. A wide variety of maritime fuel cell projects has been tested across Europe in the last 20 years. These projects have approached the applicability of fuel cell technology to maritime transportation from different research perspectives, including feasibility investigations, design concept development and prototype demonstrations (Table 3).

Table 3. Noticeable demonstration ship projects of marine fuel cell systems using H_2 as fuel since 2000 (adapted from [68]).

Start Date	Project	Concept	Main Partners	FC Capacity
2006	ZemShip—Alsterwasser	Fuel cell system developed and tested onboard of a small passenger ship in the area of Alster in Hamburg	Proton Motors, GL, Alster Touristik GmbH, Linde Group, etc.	96 kW
2007	Cobalt 233 Zet	Sports boat employing hybrid propulsion system using batteries for peak power	Zebotec, Brunnert-Grimm	50 kW
2010	MF Vägen	Small passenger ship in the harbor of Bergen	CMR Prototech, ARENA-Project	12 kW
2012	Nemo H_2	Small passenger ship in the canals of Amsterdam	Rederij Lovers, etc.	60 kW
2012	Hornblower Hybrid	Hybrid ferry with diesel generator, batteries, PV and fuel cell	Hornblower	32 kW
2012	Hydrogenesis	Small passenger ship which operates in Bristol, UK	Bristol Boat Trips, etc.	12 kW
2015	SF—BREEZE	High-speed liquid hydrogen fuel cell passenger ferry and hydrogen refueling station in the San Francisco Bay area	Sandia National Lab, Red and White Fleet	120 kW per module. Total power 2.5 MW
2021	RiverCell—ELEKTRA	Fully electric hybrid energy system for a towboat that operates on inland waterways	TU Berlin, BEHALA, DNVGL, etc.	3 × 100 kW

Among the challenges posed by the maritime sector are the harsh working environment and limitations related to onboard energy storage space that ultimately affect the payload [69]. The applicable power range demands for maritime vehicles may be situated from a few kW to several MW, so the employment of hydrogen, a low volumetric energy density fuel, may not be ideal for long-distance travels, being viable for inland and short-sea shipping instead [70].

Hydrogen FC for underwater applications has also gathered attention for commercial and military purposes [11,71]. Fuel cell systems for undersea vehicles must store not only hydrogen as fuel, but also oxygen so that they can be catalytically combined to produce water, heat and useful electricity [72]. HELION, an AREWA renewable subsidiary, tested its fuel cell technology for the propulsion of the Idef^x, an autonomous undersea vehicle operated by the French marine science research institute Ifremer. It carried 100 L of H_2 at 30 MPa and 50 L of O_2 at 25 MPa [73]. The US Navy has an ongoing project in partnership with General Motor to adapt its hydrogen fuel cell technology to an autonomous robotic submarine [74]. A British start-up, Oceanways, is currently developing a hydrogen-fueled autonomous cargo submarine to collect microplastics from the oceans, an effort towards clean-shipping research [75]. Type 212 is a new generation of German submarine intended to be used as a reconnaissance boat and ship hunter that uses hydrogen fuel cells for its air-independent propulsion system. It features a nearly silently submerged cruise that could last for three weeks, and it is virtually undetectable. Hydrogen fuel is stored in between the outer and inner pressure hulls [76].

2.7. Aviation

The global civil aviation industry has establish a long-term climate commitment to reaching net zero carbon emissions by 2050, and sustainable aviation fuels such as hydrogen play a major role in its energetic transition strategy, once batteries remain far too heavy for aviation purposes [77]. The forecasted applications of hydrogen in aviation can be categorized into two main directions: the first involves the combustion of hydrogen as a replacement of kerosene for large airplanes, while the second employs hydrogen and fuel cell systems for the propulsion of small airplanes. Fuel cells also have the potential to replace diesel as fuel for auxiliary power units of aircraft and to replace batteries that power other devices and systems. Powering ground support equipment in the airport is also considered a viable way of integrating fuel cell technology in the aviation industry [78].

Major milestones of hydrogen and fuel cell use in manned aircrafts date back to the last two decades. In 2008, Boeing Research and Technology conducted flight tests for the first manned fuel cell airplane, a Diamond DA20 (a modified two-seater motor glider, hybrid: H_2 fuel cell/Li-ion battery [79]). Airbus followed with a successful application of a fuel cell system to power auxiliary hydraulic and electric systems of an Airbus 320, activating ailerons, rudders and other flight control systems [80]. In 2009, the German Aerospace Center (DLR) developed the motor glider Antares, the world's first manned aircraft to take-off by only employing power from high-performance fuel cells (25 kW, 5kg of H_2 @ 35 bar) [81]. The RAPID 200-Fuel Cell, an airplane developed within the European Union's ENFICA-FC project coordinated by the Politecnico di Torino, completed several flight tests using a completely electrical hybrid power system (20 kW FC, 35 MPa H_2 storage and a 20 kW Li–Po battery), breaking the world speed record for electrically powered airplanes [82]. HY4, a four-seater powered with an hydrogen fuel cell, also developed by DLR, completed its maiden flight in 2016 (9 kg of H_2, 4 × 11 kW FC and 2 × 10 kWh batteries) [83].

Today, several R&D groups are committed to further developing fuel cell propulsion systems for aviation. The HyFlyer project intends to decarbonize medium/small passenger aircrafts by optimizing a high-power fuel cell. Led by ZeroAvia, a California-based startup, in partnership with the UK Government's Aerospace Technology Institute (ATI) program, completed the first flight of a commercial-grade aircraft powered by hydrogen-fueled fuel cells, a modified propeller Piper M-class six-seat plane coupled with an FC and batteries.

The project will conclude with a groundbreaking 19-seat hydrogen–electric aircraft with a 350 mile flight in early 2023 [84,85]. In 2021, General Motors and Liebherr-Aerospace started the joint development of a hydrogen fuel cell power system for aircraft applications. Focusing on commercial airplanes, this project does not focus on propulsion, but intends to replace the auxiliary power unit that runs the electrical systems of aircraft for a fuel-cell-powered one [86]. The Airbus ZEROe program has unveiled three concepts for the world's first zero-emission commercial aircraft, employing hydrogen as the primary power source. They are designed to utilize hydrogen fuel cells to complementarily power modified gas turbines, providing a highly efficient hybrid electric propulsion system that could be placed into service by 2035 [87].

The use of FCs as a major energy propulsion source has also become very popular for unmanned aerial vehicles (UAVs) and autonomous and remote-controlled aircrafts, capable of executing increasingly difficult and varied missions [88–90]. Fuel cell adoption reduces the weight of conventional UAV propulsion systems, and lowers the noise and vibration while addressing environmental concerns. For instance, the weight of a hydrogen FC UAV can be 3.5 times lower than that of the lithium-based battery counterpart with the same energy capacity [91]. Table 4 summarizes the applications of hydrogen FC UAVs developed. While early research has mainly focused on fixed-wing configurations, multi-rotor and helicopter drones are being investigated today [92].

Table 4. Examples of FC-powered UAVs.

Date	Organization, "Program"	Aircraft Type	Reactant Storage Type	Remark
2003	AeroVionment, "Hornet"	Fixed wing	H_2 sodium borohydride	First UAV flight with fuel cell
2005	Fachhochschule FH Wiesbaden, "Hy-Fly"	Fixed wing	H_2 gaseous	-
2005	US Naval Research Lab (NRL), "Spider Lion"	Fixed wing	H_2 gaseous	No payload
2006	Georgia Institute of Technology	Fixed wing	H_2 gaseous	-
2007	California State University, Oklahoma State University and Horizon Fuel Cell Technologies, "Pterosoar"	Fixed wing	H_2 gaseous	Broke several official FAI world aviation endurance and range records
2007	DLR and Horizon Fuel Cell Technologies, "HyFish"	Fixed wing	H_2 gaseous	FC jet, performed aerial acrobatics such as vertical climbs and loops
2009	US Naval Research Lab (NRL), "eXperimental Fuel Cell (XFC)"	Fixed wing	H_2 gaseous	Tube-launched unmanned platform, designed for operational military use
2009	US Naval Research Lab (NRL), "Ion Tigger"	Fixed wing	H_2 gaseous	Achieved 26 h flight while carrying a 5 lb payload
2009	United Technologies Research Center (UTRC)	Helicopter	H_2 gaseous	First flight of a hydrogen/air fuel cell rotorcraft
2010	Korea Aerospace Research Institute (KARI), "EAV1"	Fixed wing	H_2 gaseous	Hybrid electric propulsion system (battery and hydrogen fuel cell)
2012	Korea Aerospace Research Institute (KARI), "EAV2"	Fixed wing	H_2 gaseous	Hybrid electric propulsion system (battery, hydrogen fuel cell and solar cell)
2013	US Naval Research Lab (NRL), "Modified Ion Tigger"	Fixed wing	H_2 liquid	Achieved 48 h flight
2015	Horizon Energy Systems, "HYCOPTER"	Multi-rotor	H_2 gaseous	First hydrogen fuel-cell-powered multi-rotor UAV
2015	EnergyOr Technologies, "H2 QUAD"	Multi-rotor	H_2 gaseous	Longest fuel-cell-powered multi-rotor UAV flight (3 h 43 min)
2019	Intelligent Energy + BATCAM, "Rachel"	Multi-rotor	H_2 gaseous	First hour-long flight for hydrogen multi-rotor UAV with 5 kg payload

3. Manufacturing, Materials and Cost

Hydrogen tanks for a variety of applications have employed composite materials as the most mature solution, with these tanks usually fabricated using winding methods.

Manufacturing with winding in turn is highly dependent on the selection of the material; therefore, researchers have since explored several material choices not only for resin matrix systems, but for liner ones as well. Fabrication approaches vary between the traditional and well-stablished wet winding and the more recent and innovative tape winding. In terms of winding equipment technologies, there are several industrial options distinguished by the applicable degrees of freedom for fiber guidance and mandrel motions. All these choices are interconnected, deeply affecting the final fabrication cost of the tank, and have to be created by the designer when planning viable manufacturing.

3.1. Industrial Hydrogen Tank-Type Classification

Pressure vessels used in the marketplace for general applications assume different architectures and are currently organized into five main types, numerically classified from I to IV [93,94]. With the growing popularity of advanced hydrogen solutions employed in mobility, R&D efforts are now pursuing cost-efficient lightweight materials, designs and production technologies to take hydrogen tanks even further.

Figure 3 and Table 5 introduce a classification for the sub-types of hydrogen tanks aimed to comprehend recent advances and future design trends, with additional distinctions established between the reinforcement type, matrix type and winding method.

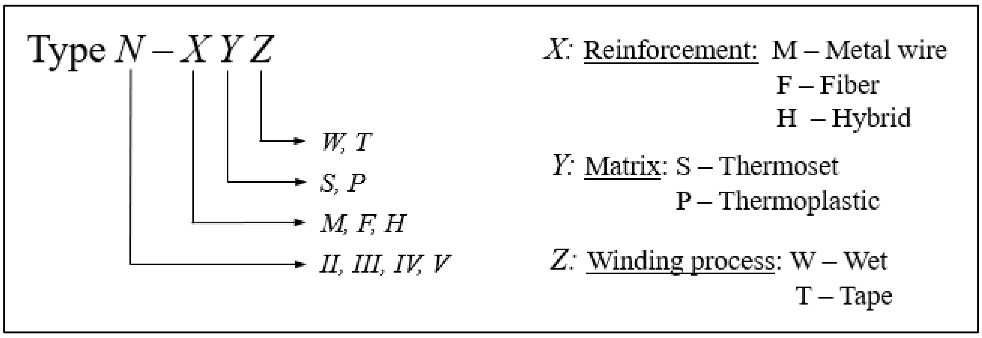


Figure 3. Classification for the sub-types of hydrogen tanks used in industrial applications.

Table 5. Industrial winding configurations for hydrogen tanks; recent advances and future design trends.

[95]	Sub-Type Classification	Liner	Wrap Extent	Winding Method	Resin Type	Fiber Type	Low Cost	Recyclability	Light Weight
	Type II—FSW [1]	Metal	Cylinder	Wet	TS	CF	+++	++++	+
	Type II—MSW	Metal	Cylinder	Wet	TS	SW	+++++	+++++	+
	Type III—FSW [1]	Metal	Full	Wet	TS	CF	+++	+++	++
	Type III—MSW	Metal	Full	Wet	TS	SW	++++	++++	+
	Type IV—FSW [1]	Plastic	Full	Wet	TS	CF	+	++	+++++
	Type IV—FST	Plastic	Full	Tape	TS	CF	+	++	+++++
	Type IV—FPT	Plastic	Full	Tape	TP	CF	+	+++	+++++
	Type IV—FPW	Plastic	Full	Wet	TP	CF	+	+++	+++++
	Type IV—MSW	Plastic	Full	Wet	TS	SW	++++	++++	+++
	Type V [2]	Liner-less	Full	Tape	TS/TP	CF	++	++	+++++

TS: thermoset; TP: thermoplastic; CF: carbon fiber; SW: steel wire. [1] Most frequent configuration. [2] Early stage of development. "+", "++", "+++", "++++" and "+++++" denotes a comparative score, from very low to very high.

Type V tanks are bound to be the ultimate step in the hydrogen tank evolution and are currently the focus of intense research [96,97]. This all-composite liner-less configuration promises the lightest solution, with a more efficient use of volume, while also reducing manufacturing costs, operational risks and maintenance costs due to its inherently simpler construction [98]. Avoiding permeation, however, constitutes a major challenge once hydrogen is a gas with very small-sized molecules, usually stored at elevated pressures. The target solutions comprehend the development of microcrack-resistant structural resins and/or barrier coatings [99,100]. For instance, Composite Technology Development, Inc., has included nano-reinforcement in the matrix of its type V pressure vessels to reduce their permeability and achieve better mechanical properties [101].

3.2. Winding Methodology: Wet vs. Tape

Filament winding is a well-stablished manufacturing process for composite parts, and is considered one of the most energy-efficient methods providing a relatively low-cost processing [102,103]. Due to being fast, it is suitable for large-scale productions with applications in multiple branches of the industry, delivering products with a high fiber content (usually greater than 60%) and excellent mechanical properties. Common dimensions for wound components present in diameters of up to 1.0 m and lengths of up to 5.0 m, but larger components can be found [104]. Filament winding is particularly suitable for the fabrication of axisymmetric shapes, such as in the case of storage tanks.

The resin impregnation step in filament winding can be performed in different steps of the fabrication process with the employment of distinct techniques. There are essentially two different types of filament winding, namely, wet winding and tape winding. In wet winding, probably the most well-stablished method, the dry fiber bundle is coated with melted resin prior to its contact with the mandrel by means of a resin bath. Tape winding instead uses previously impregnated materials, such as prepregs and tapes. Each of these methodologies presents its advantages and disadvantages [103,105–107].

The main assets of wet winding are the overall manufacturing costs, mainly the ones associated with raw materials and with the storage and handling of both the fiber and resin, after which no refrigeration is usually needed. As drawbacks, it is more difficult to tightly control the resin content, thereby a greater variability is expected, and there is an intrinsic physical speed limitation to the deposition process. Unwanted features, such as resin pockets, voids, fiber wrinkling, density variations or even fibers, not following the prescribed paths may be more often introduced, compromising the mechanical response. Localized dripping can be prevented during curing. The cleaning of the machinery and its installation space demands a significant use of solvents. Additionally, the operator is exposed to hazardous chemicals and to "dry fly" fibers, thus, consisting of a concerning environmental issue.

The tape winding process is based on the use of an industrialized raw material already subjected to rigorous quality control. Therefore, the wound outcome presents a more precise resin content and higher uniformity, generating final parts with better mechanical performance. Deposition rates can be substantially higher (even an order of magnitude higher), resulting in an elevated production efficiency. Since there are no liquid resin drops, the machinery remains clean, providing better labor conditions for the health of the operator as well of the environment. On the other hand, all these advantages come with a cost. The investment in machines is quite expensive, as well as the prepreg products themself. The latter often require refrigerated storage and have a relatively short shell life.

Opting between the filament winding types to fabricate a particular product is closely connected to the material selection. Prepreg tape winding technology has experienced a great evolution in recent years, so more and more material systems are now commercially available at a lower cost. Initial applications of filament winding were restricted to the use of thermoset resins, with impregnation conducted using a resin bath, a compound of uncured polymers in a low-viscosity state. After the finalization of the fiber placement operation, a curing procedure is then needed, and that could take place at room or at elevated temperature and during long periods of time, according to the resin type. An oven would be needed, consisting of a further processing stage and acting as a limitation for the maximum component size [104].

In filament winding with thermoplastic tapes (Figure 4), the complete in situ consolidation happens during the winding, and no oven is necessary. Therefore, thermoplastic-wounded parts can be processed in a single production step. The on-line consolidation of thermoplastic prepreg takes place in an instantaneous fashion, lasting a fraction of a second, almost in a welding-like process. This allows an extended freedom of possible geometries that can be manufactured without tape bridging, including flat and concave shapes. Another possible improvement concerns local reinforcement orientation possibilities. Thermoplastic consolidation avoids fiber slippage, so stability for different winding paths besides geodesic trajectories can be achieved.

	ADVANTAGES	**DISADVANTAGES**
PROCESSING	• Fast processing cycles • No need of oven/autoclave (no size limitation) • Weldability / Easy of repair • Freedom of geometries (e.g.: flat, concave) • No fiber slippage (non-geodesics)	• More difficult material handling • More expensive winding equipment • Complex manufacturing process (local heat and pressure)
MATERIAL	• Recycling possibility • Better quality (higher fiber content) • Extended shelf life without refrigeration	• Higher cost • Stricter selection of material systems

Figure 4. Advantages and disadvantages of tape filament winding with thermoplastics in comparison with wet filament winding with thermosets.

It is important to clearly establish that although filament winding for material system compounds of thermoset matrices is typically associated with the wet technique (as in type IV—FSW tanks), it is also possible to perform tape filament winding using thermoset prepregs (type IV—FST). This becomes particularly interesting when using highly automated systems and trying to benefit from the inherent upsides from general prepreg forms. Cui et al. [108] used T300/epoxy prepreg tape to fabricate composite bearings with filament winding. The study intended to experimentally investigate the influence of the winding tension on finishing and on mechanical and physical properties of bearings. Chang et al. [109] proposed a design method for the winding manufacture of tee pipes using carbon fiber/epoxy prepreg tape. Kang et al. [110] applied the tape filament winding technology for the construction of cylinders using glass/epoxy prepreg tape, focusing on methods for determining residual stresses.

3.3. Conventional vs. Robotic Winding

The technological evolution provided by numeric control and automation has substantially transformed filament winding. This fabrication process used for composite materials, developed in the early 1940s for the aerospace program [111], has undergone significant progress in the past two decades, aiming for the creation of complex geometries as well as the manufacturing optimization of axisymmetric structures. There are distinguished equipment technologies, ranging in the degrees of freedom of fiber guidance and mandrel motions [103]. The introduction of industrial robots has since allowed a greater control of process parameters, as well as improvements in repeatability and manufacturing times [112].

Conventional filament winding is a lower technological process fairly disseminated across the industry, restricted to wind axisymmetric shapes such as tubes, pipes or pressure vessels. Two-axis winding machines, the simplest manufacturing arrangement, control the mandrel rotation and the carriage horizontal travel, being, therefore, capable of producing only fiber-reinforced pipes and tubes. Also, traditional four-axis machines are general purpose winders, capable of manufacturing pressure vessels as well. The controlled motion degrees of freedom usually consist of a mandrel rotation, carriage horizontal travel, carriage perpendicular travel (cross-feed) and a rotating fiber payout head mounted to the cross-feed axis [113]. Such solutions, however, remain dependable of constant intervention by the operator in different operations of the winding process, which significantly impacts productivity.

The advent of robotic filament winding has been traced back to the incorporation of anthropomorphic robots in the production line, hence, introducing additional degrees of freedom for manufacturing. While typical robotic equipment provides a computer control of six axes (three linear movements and three rotations), arrangements with more degrees of freedom are possible [114,115]. Robotic filament winding is mostly used for advanced applications, and it is well suited to tape winding, achieving higher-quality parts. In this technique, the automation of ancillary operations previously performed manually is also possible, such as mandrel placement, tie-on and cut-off of filaments, the loading of wet fiber-covered mandrels into the curing oven, mandrel extraction, etc. [116].

Different equipment set-ups for the fabrication of composite tanks are available, according to where the flexible robot head is installed [117,118] (Figure 5).

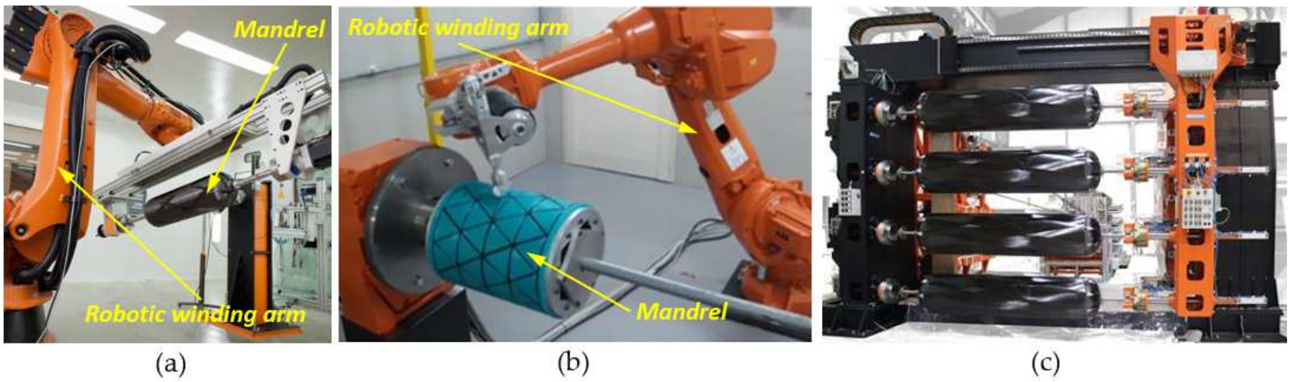


Figure 5. Arrangements of robot head installation: (**a**) fixed fiber guide/payout eye and flexible mandrel [119]; (**b**) flexible fiber guide/payout eye and fixed mandrel [118]; (**c**) Mikrosam's automated production line for CNG and hydrogen tanks [120]. Reproduced with permission from Mikrosam.

- *Fixed fiber guide/payout eye and flexible mandrel*: the robot head rotates the mandrel, and the payout eye unit is fixed at a static position;
- *Flexible fiber guide/payout eye and fixed mandrel*: the mandrel is held in lathe-type rotation equipment, and the robot head moves the payout eye unit.

A third possible set-up consists of adopting a multi-robot fabrication system, with one robot head rotating the mandrel while the other manipulates the payout eye unit. However, this complex arrangement has not been adopted for tank construction, and it is mainly used for the spatial winding of three-dimensional rigid frame structures [121]. All set-up combinations can use standard or custom-made robots, with ABB, KUKA and Fanuc as the main suppliers, and the equipment investment correlates directly with the amount of employed robots and its degree of customization.

The high flexibility provided by robotic winding may have the potential to provide a massive market penetration, allowing for fiber-reinforced product diversification and applications in new sectors. Nevertheless, some drawbacks may be expected [118,122]. The pattern accuracy of robotic winding may be lower than of conventional machines, since the overall stiffness of andromorphic robots is smaller, and problems with the kinematic synchronization between the robot and other equipment units may appear. The size of the mandrel and, therefore, the product is constrained by the limits of industrial robot work cell space. Process productivity when fabricating simplified geometries is lower in comparison with the well-stablished conventional winding.

Prospects of development for the fabrication of composite tanks using robotic winding keep emerging. A consolidated trend is the adoption of automated and integrated industrial cell units and production lines for composite tank construction, therefore, offering a complete turnkey solution in manufacturing. For instance, Mikrosam finished the commissioning of its latest automated production line in Russia, designed to build tanks with a capacity between 40 and 350 L for storing compressed natural gas and hydrogen gas [123]. Another technological breakthrough may be represented by winding hybridization with other processes such as 3D printing and automated fiber placement, which can add fibers where they are needed with speed, precision and practically zero waste [119].

3.4. Material Selection

3.4.1. Resin: Thermoset vs. Thermoplastic

Thermoset matrices have historically dominated the market for fiber-reinforced composites. This includes products originating from a variety of composite manufacturing technologies, such as resin transfer molding (RTM), resin infusion, pultrusion and filament winding. However, the utilization of fiber-reinforced thermoplastics over thermoset-based composites is gaining momentum in different industrial applications, mainly due to their short consolidation cycle, which reduces production time. Other advantages over thermoset manufacturing comprise a longer shelf life, ease of repairing and potential for recycling—the latter is a capability particularly attractive to projects driven by environmental sustainability.

Manufacturing issues, however, limit the widespread employment of thermoplastic resins as they tend to be more complex to process than thermosets. Thermoplastics present with a particular high molecular weight, with melt viscosities at least two orders of magnitude higher than the ones observes in thermosets, making their impregnation significantly more difficult [124]. Nevertheless, great effort has been devoted to developing new techniques and more easily processable thermoplastics. An interesting strategy to improve thermoplastic manufacturability was developed by replacing the in-process fiber impregnation step [111]. As a result, the impregnation of fibers with thermoplastic resins is carried out first in a separated process by means of developing a special pre-impregnated towpreg or tape, generally supplied in the form of wide sheets or narrow tapes with a unidirectional arrangement. Prepreg products exhibit a low void content and high fiber volume fractions, and thermoplastic options are available on the market in different configurations (carbon/PEEK, carbon/PA6 and carbon/PPS) [125].

New material system research is still ongoing. Elium®, a new liquid methyl methacrylate (MMA) resin by Arkema, is as example of a thermoplastic with potential for applications in hydrogen tanks [126]. By applying these semi-finished forms, the consolidation step, when heat and pressure would be applied to form a monolithic structure, may take place only locally, as the so called in situ consolidation [127].

The employment of thermoplastics has become a green trend due to its potential in the partial or even full recycling of raw materials. Current end-of-life options for carbon-fiber-reinforced thermoplastics consist of [128]:

- *Mechanical recycling*: Both thermoplastic and thermoset composites can be crushed into small particles or even fine powders. Afterwards, thermoplastics can be reprocessed several times with the application of heat and pressure. Thermosets can only be employed as fillers or reinforcement for cement, concrete and similar materials.
- *Thermal recycling*: Applicable for both thermosets and thermoplastics with no substantial discrepancies. It usually consists of the removal of the matrix of composite systems with thermal treatments aiming at fiber recovery.

- *Chemical recycling*: It removes the matrix by solvolysis or dissolution in a proper solvent, also suitable for both thermosets and thermoplastics. Nevertheless, thermosets usually present higher chemical stability, so fiber recovery is harder. Furthermore, thermoplastics can be dissolved and recovered, while thermoset matrices are generally degraded.

Significant research effort has since been devoted towards the development of hydrogen tanks using thermoplastic matrices. The HYPE/OSIRHYS project has gathered the French Atomic Energy and Alternative Energies Commission (CEA), TORAY and Citröen to improve the design, calculation, manufacturing and testing of structural vessels composed of full thermoplastic composites aimed for on-board hydrogen storage at 70 MPa. The studied material was the Carbostamp™ polyamide matrix embedded with T700 carbon fibers [12,129]. The DuraStor consortium, later transformed into the HOST project, was a UK attempt to propose a monolithic and recyclable type IV thermoplastic hydrogen tank for operation at 70 MPa. A configuration using a rotomolded POM liner and a carbon fiber/POM composite system was proposed and investigated [130,131]. Since 2019, European representants from the entire supply chain for hydrogen storage have united to develop a cost-effective thermoplastic composite tank for hydrogen, composing the THOR consortium [132] (Thermoplastic Hydrogen tanks Optimised and Recyclable).

3.4.2. Fibers

An important aspect of the hydrogen tank project is selecting a reinforcing overwrap for the liner that provides the tank with high hoop strength, a key quality for high-pressure applications that directly affect burst and puncture resistance [130]. Carbon fibers are today the consolidated option for state-of-the-art hydrogen tank solutions due to their elevated specific tensile strength. They also combine outstanding fatigue performance and resistance to creep and to most chemicals. However, carbon fibers alone represent the main cost driver of hydrogen storage systems and a significant overall increase in their demand is expected, so alternative reinforcing fibers have been the focus of R&D studies aiming at tank cost optimization [133–135].

Glass fibers are commonly used as the reinforcing overwrap in compressed natural gas (CNG) tanks, which operate at significantly lower pressures, and are also present in hydrogen tanks as an outside layer, providing both galvanic corrosion and damage resistance [136]. Glass is a relatively inexpensive material, but it can be prone to strength degradations under exposure to moisture/chemicals and under sustained loading.

Basalt fibers have been introduced as an environmentally friendly cost competitive fiber with slightly higher mechanical properties and thermo-chemical stability than E-glass fibers [137]. In comparison, basalt's stiffness can be estimated as half of carbon fibers', whilst its cost amount to approximately one-tenth. The weight of a basalt pressure vessel has been estimated to be 15% lower than similar E-glass vessels of the same strength [138], although such a configuration is still much heavier than the carbon vessel. Many companies, especially from Russia, are interested in introducing basalt fibers into tank manufacturing, starting with CNG storage.

A novel approach for introducing a realistic alternative to the expensive tanks composed of carbon fiber could be the introduction of ultra-high-strength steel wire as the reinforcement. WireTough Cylinders LLC developed type II MSW pressure vessels for hydrogen storage at pressures ranging from 45 to 87.5 MPa [139]. Although heavy, this configuration is expected to have potential for use in stationary applications, such as fueling stations, while still being 20% lighter than the average type II tank.

3.4.3. Liners

In a composite pressure vessel, the liner is the component whose function is to act as a mechanical barrier between the fluid and the structural overwrap, preventing permeability from the several micro-cracks that are present in the substrate of composite layers [140]. Materials employed in hydrogen tank construction should not only be safe, reliable and cost-effective, but should not interact or react with the gas.

Liners can be created using metal or plastics. Type II and III pressure vessels employ metallic liners usually composed of steel or aluminum alloys depending on the weight requirements. The manufacture of liners composed of metal is usually achieved with deep-drawing of plates, drawing of heated billets or hot-spinning of tubes, followed by heat treatments performed to ensure the desired final mechanical properties [16]. Metallic materials, steel in particular, may be at risk of embrittlement and stress corrosion cracking in the presence of hydrogen, leading to the occurrence of premature cracks and the consequent degradation of mechanical properties.

Plastic liners from type IV pressure vessels usually employ a thin layer of high-density polyethylene or aliphatic polyamide [141]. Their manufacturing is obtained using rotomolding, blow molding or by welding injected domes to an extruded polymer tube [16]. However, polymeric liners present a higher permeability than their metallic counterpart, and, therefore, they need hydrogen permeation tests under high-pressure environments [142]. Polymeric liners may also be vulnerable to collapse and blistering during tank charging and discharging [14], and polymer water uptake could affect the performance of fuel cells [20].

The overall design process of a composite hydrogen tank is closely connected to the liner shape definition, notably the dome region. Tanks for transportation are severely space-constrained and, therefore, must be sized to present a limited total length and diameter, while still providing the largest possible fuel capacity [143]. Furthermore, the shape of the liner is greatly affected by constraints imposed by the filament winding process, influencing fiber slippage and the minimum number of required layers to provide full coverage. Optimizing the liner shape is then the first step to maximize the tank volume and minimize its total mass.

3.5. Cost Analysis

The representative cost estimation of composite pressure vessels necessitates a thorough examination of all costs associated with the manufacturing process. Identifying all of the variables that influence the total final cost is a time-consuming task. Only considering direct labor and raw material expenses is insufficient. For a true picture of the end item cost, factors such as the manufacturing throughput, scrap, cleanup time and environmental compliance expenses must all be taken into account [106]. Tank cost reduction strategies may focus on increasing production rates and/or reducing the material costs.

The production/output rate has a significant impact on the final product. The output rate of a production system is defined as the ability to produce a large number of parts per time unit, and it is an important feature in hydrogen tank manufacturing. Because machines require capital inputs and operators, the output rate has a substantial impact on the final part cost [144]. The higher the output rate, the lower the tank final cost.

In filament winding, the output rate is dependent upon the winding speed. The maximum winding speed in conventional wet winding is approximately 1600 mm/s, whereas it can reach up to 2000 mm/s in the thermoplastic tape winding process. Weiler [144] presented a comparison between the fiber placement speed vs. cost per manufactured part weight as shown in Figure 6. The assumptions in plotting the graphs in Figure 6 were: 250 workdays/year, three-shift operation (24 h coverage), winding operator cost of 50,000 EUR/y and a 500,000 EUR tape placement machinery with 5 years of depreciation. Energy costs was also evaluated, considering 6 kW overall power (2 kW optical and 4 kW cooling) for a 25 mm wide tape and 250 mm/s process speed and 0.19 EUR/kWh. The energy demand actually decreased with the increase in placement speed, by virtue of minor heat soaks. Given this cost structure, the optimization of the process speed becomes a key issue for tape placement, as it significantly influences the final product cost.

As for the raw material cost concern, carbon fiber represents the single highest cost component of hydrogen tanks [145]. For example, the cost breakdown presented in Figure 7 shows that carbon fiber represents 62% of the total system cost at 500K systems per year. Considering this, one can easily conclude that an alternative cheaper fiber is required to lower the hydrogen tank cost [146]. Another dominant factor is the balance of plant

(BOP), which includes the equipment and components required for the tank operation. It is expected to reduce with an increase in the system production rate.

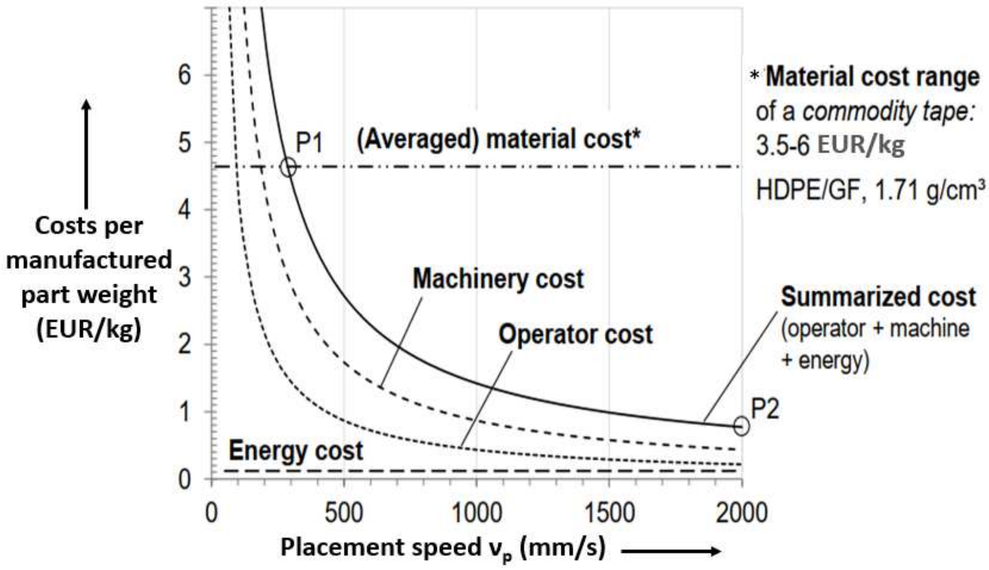


Figure 6. Breakdown of costs per produced part weight for various placement speeds [144].

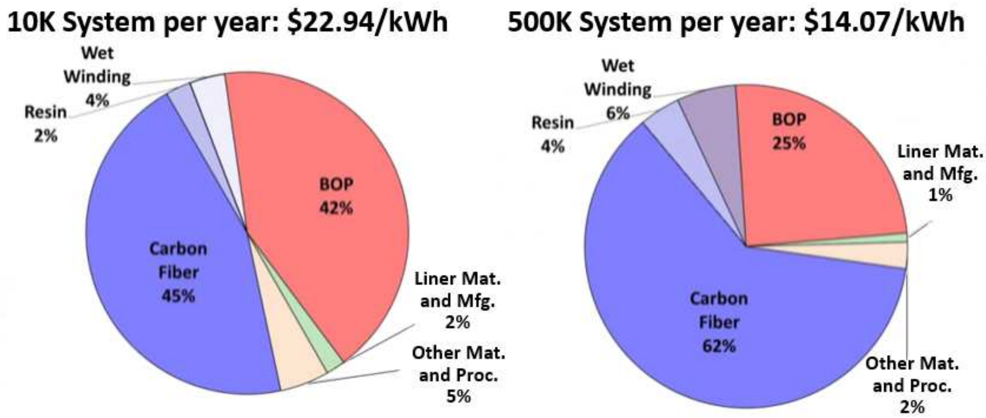


Figure 7. Cost breakdown of 70 MPa tank type IV system [145].

In the end, to reach a successful commercial deployment, compressed hydrogen tanks need to establish a trade-off between weight and cost requirements. Potential cost saving strategies are epitomized by reducing the raw material and/or manufacturing-associated costs. The use of composites remains mandatory for weight saving in on-board applications; therefore, optimizing the fiber architecture or even finding a cheaper alternative to carbon fiber employment may constitute valid alternatives towards cost reduction. From the manufacturing point of view, production rate dependence may be the main route to be pursued, considering both mature and nascent technologies.

4. Design and Analysis of Hydrogen Tanks

4.1. General

The fuel tank is the most expensive and critical component of a hydrogen storage system. Engineering design practices for the hydrogen tank must consider the whole operational lifecycle of the product, aiming at a long-term safe performance. Tank storage, transportation, handling, multiple fillings, inspections and maintenance are important scenarios to be considered. Ultimately, the purpose of the design is to achieve a tank solution with a reduced mass, reduced cost and increased performance. The tank performance goal can present multiple definitions, such as maximum volume under space restrictions, maximum burst pressure, maximum performance factor, among others.

Several hurdles in the commercialization of hydrogen tanks for the fuel cell vehicle industry include minimizing the cycle time in filament winding, safe design, lightweight, low-cost, etc. Having recognizing these challenges, the US Department of Energy (DOE) Office of Fuel Cell Technologies [147] initiated a project for the design and development of hydrogen tanks. The project took steps to improve the performance of hydrogen tanks by investigating alternatives for the matrix resin, carbon fiber and the shape of the tank design [148]. However, in the resin alternative, they did not consider the thermoplastic resin which is environmentally friendly and also helps in reducing the manufacturing cycle.

Researchers have studied the behavior of the liner in type III tanks [149]. Park studied variations of the helical winding on the semi-geodesic path [150]. Similarly, Roh et al. investigated the design of the end cap by providing the doilies on the dome section [151]. The use of doilies seemed to reduce the employment of carbon fibers, but the manufacturer rejected its use due to some manufacturing technical issues. Later, researchers also tried to reduce the tank weight by replacing the epoxy resin with low-viscosity vinyl ester, which is also a thermoset resin [152].

4.2. Design and Analysis Methodology

A complete design cycle of a composite hydrogen tank is illustrated in Figure 8. The design cycle of hydrogen tanks begins with step no. 1, which defines the project general characteristics, such as the tank capacity, working pressure, material attributes and safety factors. The designer can use this information to compute other parameters that are required for the tank geometry definition, such as the cylinder radius, boss radius and tank length.

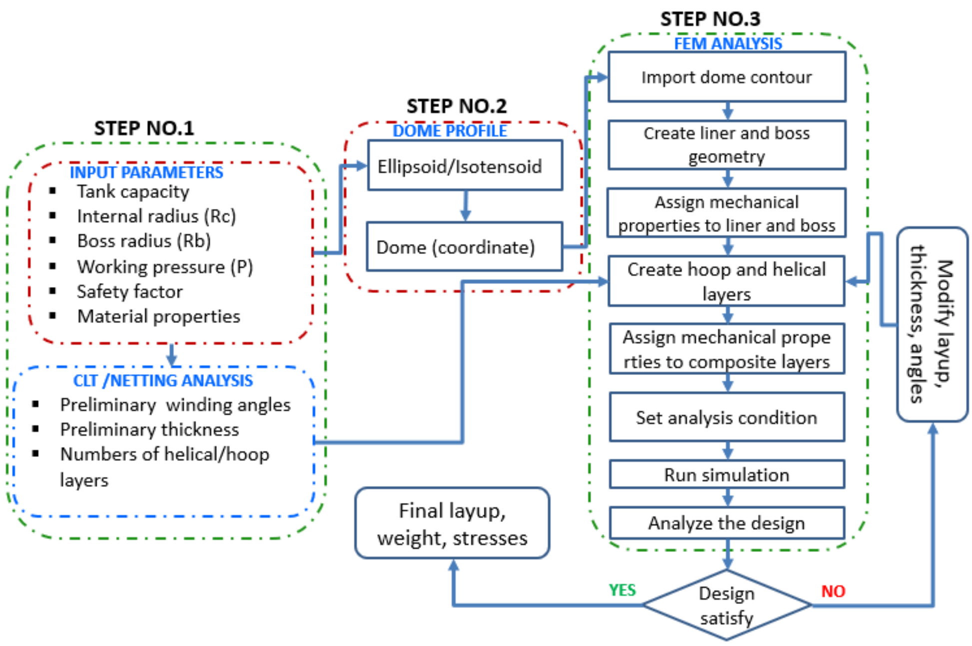


Figure 8. Flowchart of design and analysis of composite hydrogen tank.

An important phase of step no. 1 is to find out the preliminary sizes of the composite layup for the hydrogen tank, which can be accomplished using the composite laminate theory (CLT) or the netting analysis [153]. The layup sequence definition and the thickness of each layer are evaluated using CLT. Some researchers employed the netting analysis [151,152], which applies the principle of static equilibrium, assuming all fibers are loaded in tension and carry no shearing and bending stresses. It also neglects the contribution from the resin [154]. According to the netting analysis, helical ($t_\propto$) and hoop (t_{90}) layer thicknesses are given by Equations (1) and (2):

$$t_\propto = \frac{PR_c}{2\sigma_{f,\alpha} cos^2\alpha} \tag{1}$$

$$t_{90} = \frac{PR_c\left(2 - tan^2\alpha\right)}{2\sigma_{f,90}} \tag{2}$$

where P denotes the burst pressure, R is the tank radius and $\sigma_{f,\alpha}$ and $\sigma_{f,90}$ are the design allowable stresses of fibers in the helical layer and in the hoop layer, respectively.

In contrast with the netting analysis, CLT predicts the mechanical and structural performance of the composite structure with greater accuracy, as it considers the effect of the resin system as well. Based on the CLT calculation, finite element analyses can be conducted to obtain the optimized structure of the composite hydrogen tank.

4.3. Design of Dome Profile

The dome shape of composite tanks has a significant impact on its mechanical performance. The isotensoidal dome geometry, which is based on geodesic winding trajectories, is a common dome geometry. In this type of profile, the shear stress at the layer level is set to zero [154]. Vasiliev et al. also showed that to obtain maximum performance of the vessel, shear stresses must be zero [155].

Parameters defined in step no. 1, such as the tank capacity, working pressure and material characteristics, were the input parameters for the dome profile equation and are depicted in Figure 9a. These parameters could be converted into dimensionless parameters as below:

- $Y = \rho/R_b$, with $Y \geq 1$;
- $Y_{eq} = R_c/R_b$;
- $Z = z/R_b$, with $Z > 0$;
- $R = F_a/\pi P{R_c}^2$.

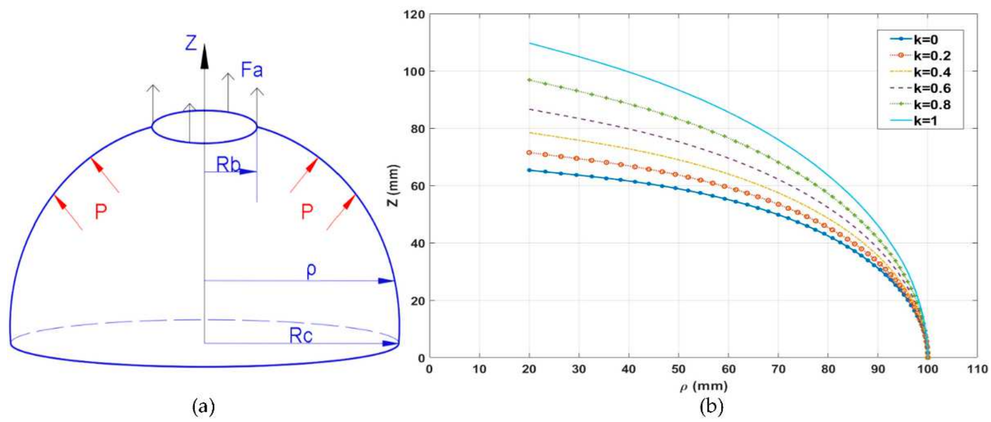


Figure 9. Dome design: (**a**) schematic representation of dome; (**b**) isotensoid dome contour generated with numerical integration.

The meridian profile of an isotensoid dome can be generated with the numerical integration of Equation (3) [156,157].

$$\dot{Z}(Y) = \pm \frac{Y\left(Y^2 + rY_{eq}^2\right)^2}{\sqrt{\left(\frac{k+Y^2-1}{k+Y_{eq}^2-1}\right)^{k+1}(1+r)^2 Y_{eq}^2 - Y^2\left(Y^2 + rY_{eq}^2\right)^2}} \tag{3}$$

where k is the dimensionless anisotropy defined by the mechanical properties of the composite, as shown in Equation (4).

$$k = \frac{E_2(1+\nu_{12})}{E_1(1+\nu_{21})} \tag{4}$$

The isotensoid dome meridian profile (Equation (3)) could be solved by using numerical integration techniques, and the results are plotted in Figure 9b. The parameter k represents the degree of the orthotropy of the material. For an isotropic material (k = 1), the meridian profile is almost hemispherical. When k = 0, the resin contribution on the mechanical properties was ignored, i.e., the transversal mechanical properties of the material were neglected.

The dome geometry of the composite pressure vessels can also be approximated to a traditional geometrical shape, most commonly hemispherical or ellipsoidal. Despite their high load capacity under internal pressure and low maximum stress due to their constant radius of curvature, hemispherical domes have a lesser volume for a given container length [158]. Thus, the initial dome profile can also be drawn using elliptical meridians, aiming for optimum shapes. Liang et al. [159] demonstrated that optimum dome shapes can be approximated as quasi-elliptic curves. The most important design parameter would be the depth of the elliptical dome. When the dome depths are between 0.6 and 0.775, designed domes present a stronger structure and greater internal volume.

4.4. Finite Element Analysis of Hydrogen Tanks

The analytical design solution of composite hydrogen tanks is based on broad assumptions about load and boundary conditions and does not account for stiffness discontinuities near the polar boss. The finite element analysis (FEA) must be used to correctly model these and other effects in order to accurately predict the behavior of filament wound pressure vessels. Most filament wound pressure vessels exhibit first-order non-linear geometry effects, which can only be captured via the FEA.

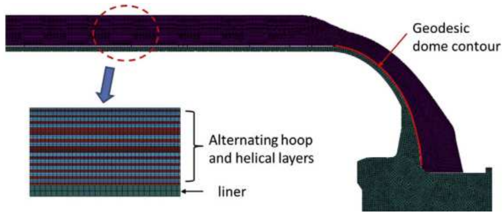
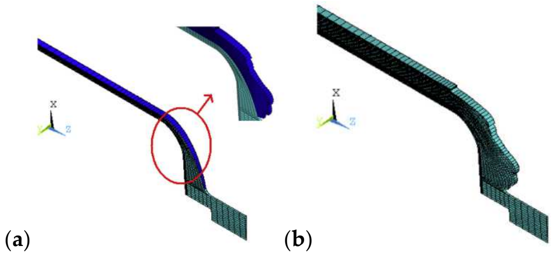
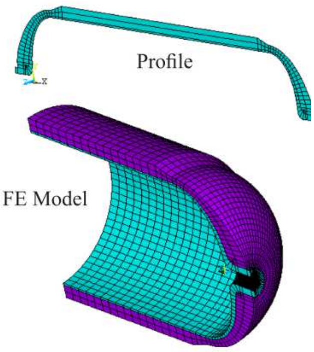
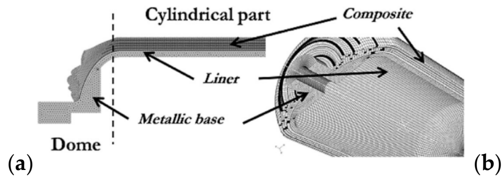
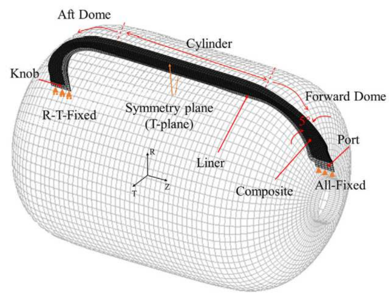
Wound Composite Modeler (WCM) [160] and WoundSIM [161] are software platforms used for the finite element analysis of hydrogen tanks. These tools allow users to create models with a detailed specification of the structural geometry and winding parameters, and also facilitate in the post-processing of the results. WoundSIM offers further advanced capabilities, such as optimization, a parametric design and design of experiment.

The translation efficiency in the FEA is defined as the ratio between the observed failure strain and the theoretical composite tensile strain. It is a result of the differences in fiber quality, winding characteristics and manufacturing variability between the actual structure and the model (e.g., voids, fiber misalignment, resin pockets, etc.). Each tank manufacturer's translation efficiency is unique and is determined empirically. It is essential to calibrate the FEA model to obtain the translation efficiency so that it implicitly contains all the variability described above.

The accuracy of the numerical analysis is mainly dependent upon the modeling technique and analysis conditions. Table 6 summarizes some approaches developed in the literature. Three-dimensional solid models are considered more accurate in the prediction of the burst pressure, but may not be efficient for the optimization, considering their simulation time. Shell models work best for thin to moderately thick structures. Axisymmetric models are fairly accurate and less computer time-consuming.

Hua et al. [152] used the axisymmetric model constructed by WCM (Wound Composite Modeler) [160]. Alternate hoop and helical winding was used. Each layer was modeled with a nominal thickness of 0.34 mm or 0.68 mm, and four-node axisymmetric elements were utilized. Tie constraints were applied between the liner and boss. A contact friction coefficient of 0.3 was applied between the liner and composite. Leh et al. [162,163] proposed two different finite element models to represent the tank's progressive failure. Model A was developed with shell and solid elements, while model B was fully constructed using solid elements. Due to computational efficiency, model A was better suited for design optimization.

Table 6. Summary of numerical studies for investigation of mechanical response of composite tanks.

Reference	Element	FEA Model
Hua et al., 2017 [152]	Software: ABAQUS/WCM Axisymmetric 2D elements Element type: CAX4	
Leh et al., 2015 [162]	Software Model (a): *Liner*, *boss*: solid elements *Composite layer*: shell element Model (b): All solid	
Alcántar et al., 2017 [164]	Software: ANSYS 3D solid element Element type: SOLID191	
Berro Ramirez et al., 2015 [13]	Model (a): *Liner*, *boss*, *composite layer*: 2D axisymmetric elements Model (b): *Liner*, *boss*, *composite layer*: solid elements	
Che et al., 2021 [165]	Software: ABAQUS Axisymmetric section Solid elements Element type:C3D8R	

4.4.1. Modeling of Winding Layers

Composite tanks are wound using a combination of alternate hoop and helical windings, whose main features are summarized in Table 7. An alternate helical/hoop winding scheme is used to remove the excess resin and to obtain the target fiber volume fraction during the winding process. Some researchers adopt a concentration of hoop winding in the inner layers due to the strength aspect [166]. However, such winding may be prone to delamination at the hoop/helical interface, a conclusion also reached by Hua [152].

Table 7. Main feature of different filament winding layers.

Winding Type	Feature
Hoop winding	- Filaments are placed nearly perpendicular to mandrel axis (α ≈ 90°). - Usually used with other strategies to resist circumferential stresses. - Creates high consolidation pressure. - Generally applied only to cylindrical section. - Placed at high speeds. - Used to describe geodesics, non-geodesics and combinations thereof.
Low helical winding	- Winding angle varies (5° ≤ α ≤ 30°). - Low helical angle is used to strengthen the dome regions. - Placed at moderate speeds. - Used to describe geodesics, non-geodesics and combinations thereof.
High helical winding	- Winding angle varies (60° ≤ α ≤ 80°). - High helical winding is used to strengthen the transition regions between the cylinder and dome. - Placed at moderate and high speeds. - Used to describe geodesics, non-geodesics and combinations thereof.

4.4.2. Helical Winding on Geodesic Path

The geodesic path is the shortest path between any two arbitrary points on a surface. Fibers on geodesic trajectories are stable and do not require an external force to avoid slipping. A geodesic path can be expressed with Clairaut's relation [167], as in Equation (5):

$$R \times Sin \propto = Const \tag{5}$$

where R is the vessel cylindrical radius and α is the winding angle.

4.4.3. Helical Winding on Non-Geodesic Path

Non-geodesic winding is a technique in which a fiber follows any path between two locations on a surface, excluding the shortest. There can be several non-geodesic paths that can cover a given surface, unlike the unique geodesic path. Zu et al. [168] presented a novel methodology for the design of filament-wound vessels based on non-geodesic winding patterns. In non-geodesic winding, to avoid the tendency for slippage, it is always recommended to determine the required friction between the liner surface and the fiber yarn. Koussios and Bergsma provided an empirical method to determine this friction [169].

Helical layers on the non-geodesic path can be placed using Equation (6). A detailed derivation can be found in [3]. Equation (6) is a non-linear differential equation that can be solved using numerical integration techniques such as the Runge–Kutta method, with the aid of the initial conditions of the winding process.

$$\frac{d\alpha}{dz} = \lambda \left[\frac{\sin\alpha \tan\alpha}{r} - \frac{r''}{1 + r'^2} \cos\alpha \right] - \frac{r' \tan\alpha}{r} \tag{6}$$

where α is the angle between the fiber tow and the meridian direction of the dome, r is the radius in the dome, z is the position along the vessel axis and r' and r'' are, respectively, the first and second derivatives of r with respect to z and λ (slippage coefficient of the fiber tows on the supporting surface).

By changing the values of λ, one can obtain different values of the turnaround radius on the dome surface, as shown in Figure 10. From this figure, it is evident that different non-geodesic trajectories on the same dome surface and with the same initial winding angle can be obtained by just changing the value of the slippage coefficient λ.

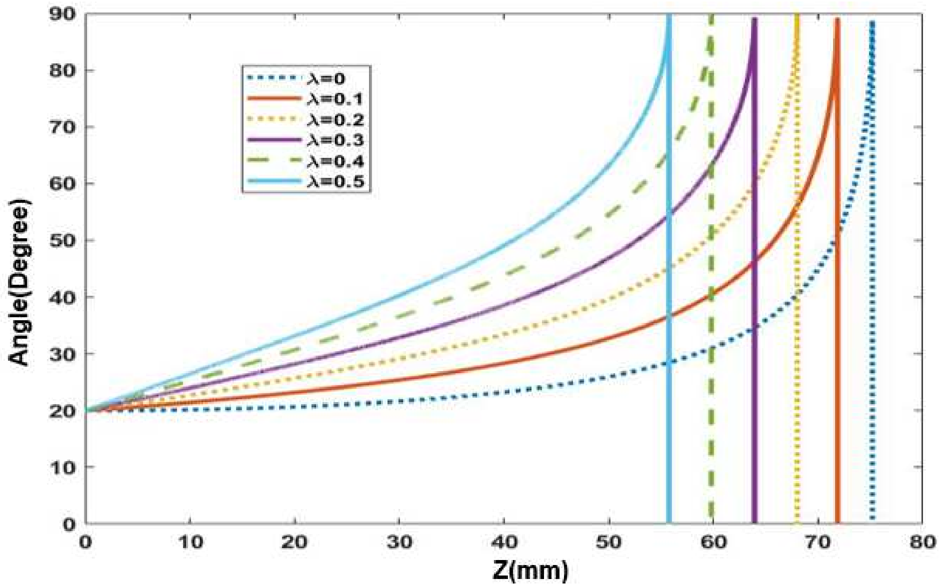


Figure 10. Influence of slippage coefficient on the turnaround radius of the non-geodesic path. By changing its value, turnaround radius of the helical path is changed.

However, for non-geodesic helical winding, ABAQUS® uses Equation (7). It is a linear interpolation of two different geodesic trajectories; by putting $\delta = 0$, it can be the same as the geodesic equation:

$$\alpha(r) = \sin^{-1}\left(\frac{r_0}{r}\right) \pm \delta\left(\frac{r - r_0}{R - r_0}\right)^n \tag{7}$$

In Equation (7), R is the radial distance from the pressure vessel axis to the current point in the layer, r_0 is the radial distance from the axis to the turnaround point and δ is a parameter controlling the winding geodesy. For modeling the non-geodesic helical winding in ABAQUS®, the value of the coefficient of fiction is not one of the input parameters, which is necessary to control the maneuverability of the fiber roving on the dome surface. Instead, only an initial winding angle and the turnaround radius are required. In such a way, it is up to the knowledge of the user to define a proper pair of these two parameters to ensure the windability without the slippage of the fiber yarn.

4.5. Working Pressure and Cylinder Dimensions

During the refueling of high-pressure hydrogen cylinders, the gas temperature may rise rapidly, causing the hydrogen storage tank to fail [170]. Furthermore, the high temperature affects the hydrogen density in the tank, resulting in a drop in the final mass delivery and, as a result, a reduction in the hydrogen vehicle operating range. The temperature increase during refueling is a significant concern regarding hydrogen safety [171]. To efficiently control the end tank gas and wall temperature to remain below 85 °C, initial pressure, initial gas temperature, ambient temperature, filling rate and cylinder dimensions are all critical. However, this review only dealt with the refueling pressure and the cylinder dimensions, as both parameters are related to the design of the hydrogen tank.

4.5.1. Effect of Working Pressure

Given their technical simplicity, reliability, cost-effectiveness and energy efficiency, high-pressure tanks appear to be the most suited mode of hydrogen conveyance. However, the initial pressure has a substantial impact on the final hydrogen gas temperature. According to the experimental study of Zheng et al. [172], the final temperature of the gas decreases approximately 4.5 K when the initial pressure increases 5 MPa. Similarly, Kim et al. [173] also confirmed that the maximum temperature drops practically linearly when the initial gas pressure rises. A higher pressure means that more hydrogen is stored in the tank at the start of the refueling process, as well as a lower pressure ratio between the final and initial pressures, both of which can help to reduce the temperature increase during refueling [174].

4.5.2. Effect of Cylinder Dimensions

Zheng et al. [172] studied the effect of the aspect ratio (length-to-diameter ratio) on the hydrogen temperature field inside the hydrogen tank. They compared the temperature profile of the hydrogen gas inside two different aspect ratio cylinders as shown in Figure 11. Tank A's aspect ratio was higher as compared to tank B. From the temperature profile, it was evident that the gas temperature in cylinder A was non-uniformly distributed, increasing gradually in the axial direction. The tail region presented the highest temperature, while the inlet region had the lowest. In contrast, the temperature homogeneity of cylinder B was evident, which also matched with the experimental findings. According to these results, a higher aspect ratio may cause a too high local temperature, thus, lowering the length-to-diameter ratio improves the tank safety.

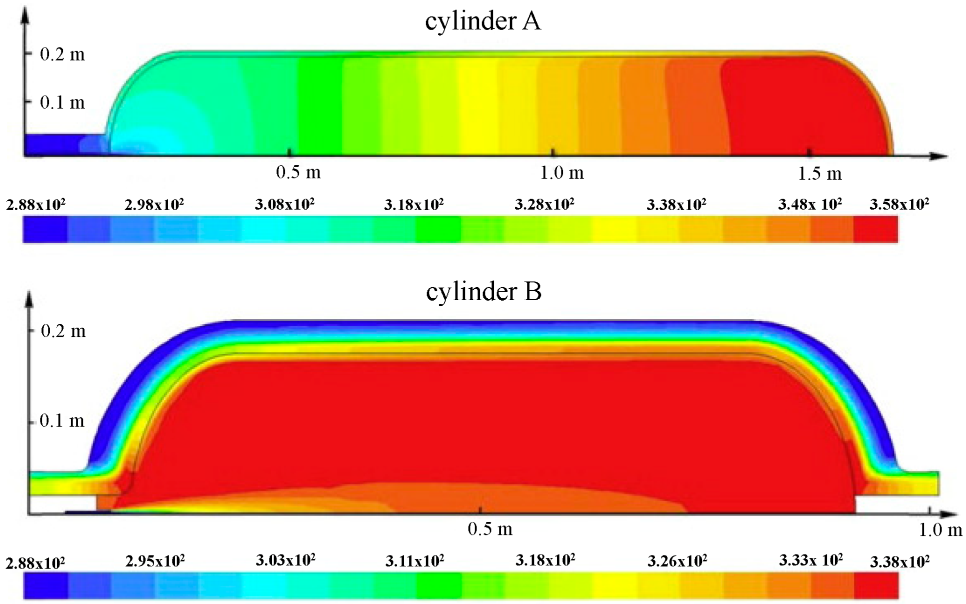


Figure 11. Hydrogen temperature distribution within the cylinder at the end of refueling [172]. Reprinted with permission from Zheng et al, International Journal of Hydrogen Energy, published by Elsevier, 2013.

5. Testing and Certification

Over the last decade, the international hydrogen community, which includes not only the countries driving the hydrogen economy, such as the European Union, the United States, Canada, Japan and China, but also the International Organization for Standardization (ISO) and the United Nations (UN), has worked hard to develop codes and standards for on-board gaseous hydrogen storage composite tanks [175]. These regulations and standards help overcome technological constraints to commercialization by ensuring the safety and dependability of hydrogen composite tanks. They also provide guidelines and specifications regarding their design, manufacturing, inspection, testing and certification. Currently, there are multiple available regulations and codes applicable to composite hydrogen tanks: EN 12245:2002 (E) [176], EC Regulation 406 [177], UN GTR 13 [178], ANSI HGV 2 [179], GB/T 35544 [180], SAE J2579 [181], ISO 19881 [182] and ASME Code [183].

The scope of this review paper did not allow for a comprehensive examination of all regulations and codes. However, some salient features of EN 12245:2002 (E) [176] were addressed briefly. This is a European standard, approved by CEN members in 2001. The goal of this standard was to establish a specification for the design, fabrication, inspection and testing of fully wrapped composite cylinders that are refillable and transportable. The following is a list of the tests required for the qualification of hydrogen tanks, with the most significant in terms of the safety highlighted **in boldface**:

(1) Composite material tests; (2) liner material tests; (3) liner burst test at ambient temperature; **(4) hydraulic (proof) test of finished cylinders at ambient temperature**; **(5) cylinder burst test**; **(6) resistance to pressure cycles at test pressure and ambient temperature**; (7) immersion in salt water; (8) exposure to elevated temperature at test pressure; **(9) drop test**; **(10) flawed cylinder test**; **(11) extreme temperature cycle test**; **(12) fire resistance test**; **(13) high-velocity impact (bullet) test**; **(14) permeability test of cylinders with non-metallic or without liners**; (15) test of compatibility of thermoplastic liners with oxidizing gases; (16) torque test; (17) neck strength; (18) cylinder stability; (19) neck ring.

5.1. Hydrostatic Burst Test

A hydrostatic burst test is conducted to determine the burst pressure of the tank. The determination of the burst pressure (BP) is critical for the composite tank's safety and reliability. It is a primary and most important qualification test for a hydrogen tank. Minimum values of the burst pressure ratio for different types of fibers are listed in Table 8.

Table 8. Minimum burst pressure ratio according to EC Regulation 406 [175]. Reprinted with permission from Wang et al., International Journal of Hydrogen Energy, published by Elsevier, 2019.

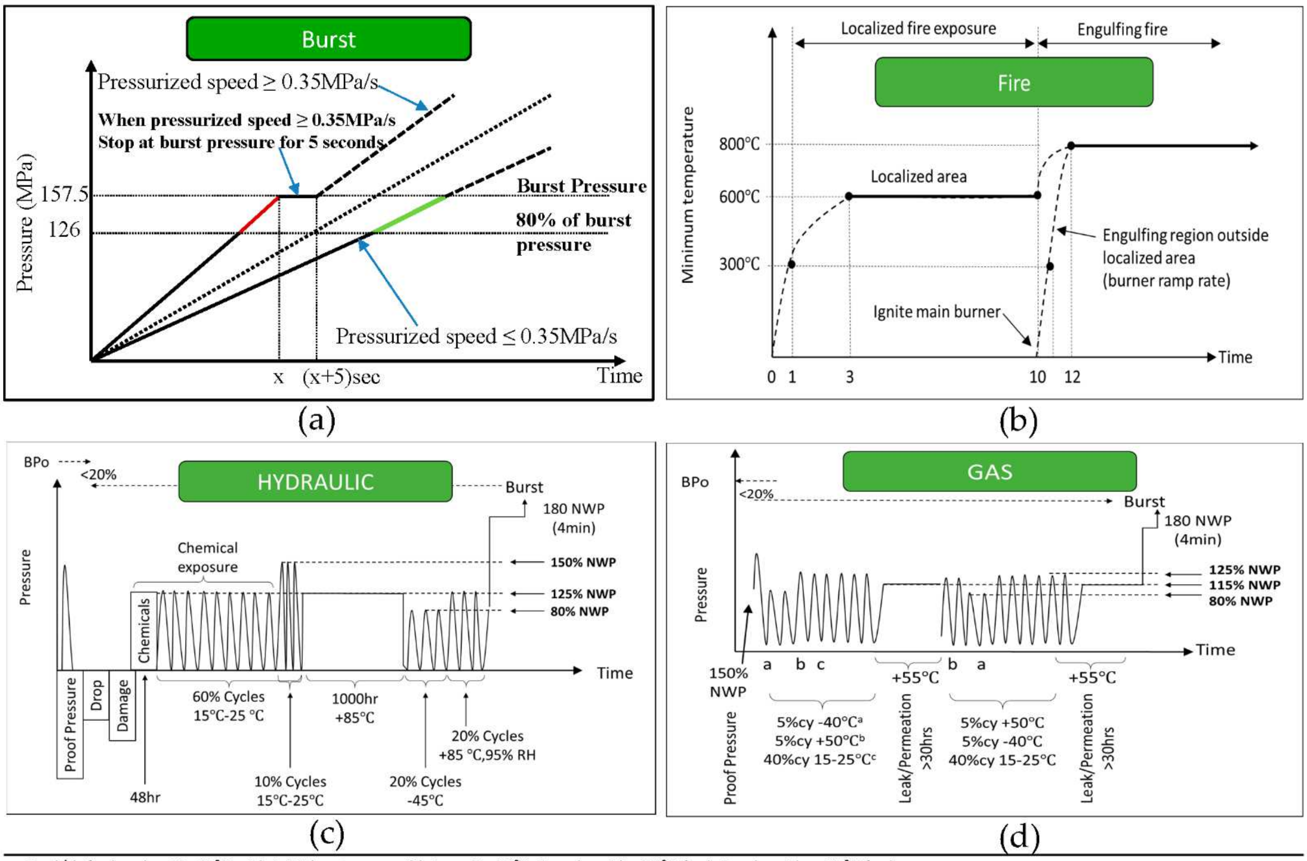
Material	Type III	Type IV
Glass	3.4	3.5
Aramid	2.9	3.0
Carbon	2.25	2.25
Hybrid	Stress analysis meets the corresponding requirements	

The test procedure of the hydrostatic burst test according to UN GTR 13 [178] is shown in Figure 12a. For the burst test, a non-corrosive fluid at 20 (5) °C is used. For pressures above 150% of the nominal working pressure, the rate of pressurization is less than or equal to 1.4 MPa/s. When the pressure rate is equal or greater than 0.35 MPa/s, then there must be a pause of 5 s at 157.5 MPa, as shown in Figure 12a. The burst pressure of the container should then be documented. The tested container should have a burst pressure greater than or equal to a minimum burst pressure (BPmin of 225% NWP).

5.2. Flame Exposure Test

The flame exposure test is performed to evaluate the ability of the hydrogen tank to withstand exposure to fire. The temperature profile for the fire exposure test according to UN GTR 13 [178] is shown in Figure 12b, and test procedure is as follows:

- Tank is pressurized up to the working pressure (70 MPa);
- Container assembly is positioned 100 mm above the ground;
- Tank is exposed to fire according to the fire-exposed cycle;
- In total, 1-to-10 min fire is applied at localized region (Temp $\leq$ 900 °C);
- In total, 10-to-12 min engulfing region exposed to fire (Temp $\leq$ 1100 °C);
- The tank should not burst and should vent by means of a pressure-relief device.



a Fuel/defuel cycles @ -40^{0}C with initial system equilibrium @ -40^{0}C ,5 cycle with +20^{0}C fuel; 5cycle with <-35^{0}C fuel

b Fuel/defuel cycles @ +50^{0}C with initial system equilibrium @ +50^{0}C ,5 cycle with <-35^{0}C fuel

c Fuel/defuel cycles @ 15-25^{0}C with service (maintenance) defuel rate, 50 cycle

Figure 12. Certification testing overview—UN GTR 13 [178]: (**a**) hydrostatic burst test; (**b**) flame exposure test; (**c**) durability test (hydraulic); (**d**) durability test (gas).

5.3. Performance Durability (Hydraulic/Gas Sequential Test)

The cyclic test or the performance durability test of hydrogen storage containers is performed according to Figure 12c,d. Three containers must be hydraulically pressurized for 22,000 cycles or until a leak occurs at (20 ± 5) °C to 125 percent NWP (+2/−0 MPa) without breakage. Considering a service life of 15 years, a leakage must be prevented within 11,000 cycles. Only one container is evaluated if the pressure cycle life measurements are greater than 11,000 cycles or if they are all within 25% of one another. If not, three containers should be examined. Further details can be found in R134CE [178].

6. Conclusions

Innovative applications employing fuel cell systems keep emerging across the transportation sector as part of a global environmental agenda. Academic and industrial attention has since been paid to overcome the multiple technical challenges associated with the storage of highly pressurized hydrogen, a vital issue for the development of fuel cell vehicles. Composite materials have since been used for lightweight tank design. Hydrogen tank solutions have demonstrated technological maturity and have been tested after the release of various prototypes.

Safety assessment studies have been vital in demonstrating that fuel cell vehicles can be as safe as their conventionally fueled pairs. A real-world evaluation has been proven to be crucial to ensure the reliability of hydrogen tanks, with proper focus on the installation, operation, maintenance and accident management. Today, the automotive industry's research revolves around achieving a longer fire resistance time interval, even in the event of failure regarding the temperature-activated pressure-relief device, and around further demonstrations of crashworthiness, ensuring the fuel cell system's integrity after different impacts.

Lightweight construction continues to be a goal in hydrogen tank development. Nonetheless, weight efficiency depends on the application in question. Mass sensitivity may be reduced for heavy-duty vehicles, but it cannot be overlooked. Meanwhile, it is paramount for sectors such as aviation, where it would greatly impact range performance.

Cost-effectiveness, however, remains a prime challenge, once hydrogen tank construction is dependent on the high utilization of expensive carbon fibers. Research efforts have since focused on the potential use of different material systems, such as different options of fibers and thermoplastics, and changes in design parameters. Further investigations regarding innovations in manufacturing such as the use of tape winding offer technological potential and economic advantages over current solutions employing thermoset resin and wet winding. In the end, a trade-off between weight and cost is the only path for deploying hydrogen tanks as a competitive technology.

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