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Review

A Review on the Cost Analysis of Hydrogen Gas Storage Tanks for Fuel Cell Vehicles

Hyun Kyu Shin [1,2] and Sung Kyu Ha [1,*]

[1] Department of Mechanical Engineering, Hanyang University, Seoul 04763, Republic of Korea; henryshin448@gmail.com
[2] Korea Carbon Industry Promotion Agency, Jeonju 54853, Republic of Korea
* Correspondence: sungha@hanyang.ac.kr

Abstract: The most practical way of storing hydrogen gas for fuel cell vehicles is to use a composite overwrapped pressure vessel. Depending on the driving distance range and power requirement of the vehicles, there can be various operational pressure and volume capacity of the tanks, ranging from passenger vehicles to heavy-duty trucks. The current commercial hydrogen storage method for vehicles involves storing compressed hydrogen gas in high-pressure tanks at pressures of 700 bar for passenger vehicles and 350 bar to 700 bar for heavy-duty trucks. In particular, hydrogen is stored in rapidly refillable onboard tanks, meeting the driving range needs of heavy-duty applications, such as regional and line-haul trucking. One of the most important factors for fuel cell vehicles to be successful is their cost-effectiveness. So, in this review, the cost analysis including the process analysis, raw materials, and manufacturing processes is reviewed. It aims to contribute to the optimization of both the cost and performance of compressed hydrogen storage tanks for various applications.

Keywords: hydrogen energy; hydrogen storage tank; carbon fiber; composites; carbon composites; storage tanks; cost analysis

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1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC), human activities are the most probable direct causes of rapid, abnormal global warming [1]. Signed by 196 countries in 2015, the Paris Agreement set a target to limit global warming to below 2 °C compared with pre-industrial levels, and preferably below 1.5 °C [2]. For example, South Korea approved the objective of a 35% reduction in greenhouse gas emissions by 2030 in comparison with the emission level for 2018 under Law No. 18469 [3]. Reducing greenhouse gas emissions is crucial in preventing global warming. A method to reduce greenhouse gas emissions is hydrogen energy utilization, which can play an important role in ensuring a low-carbon future. As a zero-carbon energy source that can be easily stored and transported, hydrogen energy can maintain electrical balance. By utilizing hydrogen energy, humanity can reduce its dependence on fossil fuels and enable ecofriendly energy systems that can be applied to the transportation, heating, industry, and electricity sectors, which account for two-thirds of the world's CO_2 emissions [4]. In particular, interest in the role of hydrogen energy in the transportation sector is growing [5]. For transportation applications [6], it is essential to store and transport hydrogen fuel according to demand, making the hydrogen storage technology essential for developing hydrogen energy and indispensable for achieving a sustainable hydrogen economy [7,8]. However, increasing the energy density of hydrogen storage tanks economically and safely while minimizing their size is a challenge owing to the high energy content per unit mass but low energy density per unit volume of hydrogen [9].

For vehicle end-users, although 1 kg of hydrogen produces 2.5–3 times more energy than burning conventional fossil fuels, its volumetric energy density in the same phase is generally lower, thus inevitably incurring a volume penalty for all hydrogen storage media [10,11]. Therefore, it is crucial to store hydrogen using the optimal method for each application, considering cost and performance [12]. Both mobile and stationary hydrogen storage systems are required for a thriving hydrogen economy [8]. In particular, mobile hydrogen storage tanks are already in operation [13–15] for passenger cars [16] manufactured by companies such as Hyundai, Toyota, and Honda [17] and have been partially commercialized or piloted for heavy-duty trucks by Hyundai, Hyzon, Dayun, Skywell, Nikola, MAN, and Scania, among others [18]. However, the cost of hydrogen storage tanks remains a barrier to their market expansion potential [19].

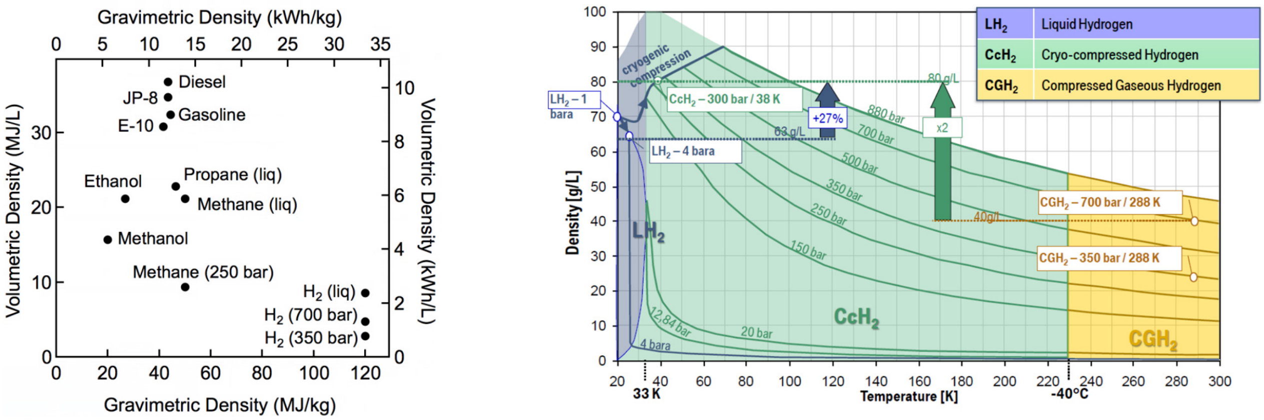
This critical review of the existing literature on the cost efficiency of various types of hydrogen gas storage tanks from passenger vehicles to heavy-duty trucks [20,21] including the process analysis, raw materials, and manufacturing processes is reviewed, aiming to contribute to the optimization of both the cost and performance of compressed hydrogen storage tanks.

2. Application of Hydrogen Storage Tanks

2.1. Hydrogen Storage Systems

Hydrogen storage systems can be classified into physical storage (compressed gas, cryogenic) and storage in solid materials (physisorption, chemical storage [22–24]). The gravimetric and volumetric energy densities of hydrogen are used to assess the suitability of the storage media [25,26].

Figure 1 compares the volumetric and gravimetric H_2 densities of the most common hydrogen storage methods. Although solid-state storage systems have a lower volumetric density and theoretical potential, additional system requirements must be met [27].



(**a**) (**b**)

Figure 1. (**a**) Density for various H_2 storage forms [28] ; (**b**) hydrogen density versus pressure and temperature from BMW [29].

Hydrogen storage is a key component of hydrogen energy systems, particularly in scenarios involving large-scale hydrogen utilization. In the context of the hydrogen economy, hydrogen storage applications can be divided into two groups [30]: stationary and mobile applications, as summarized in Figure 2.

Various hydrogen storage methods have been compared based on density, pressure, temperature, and cost [25,31], as summarized in Table 1. Among the various methods, the onboard hydrogen storage method used in passenger cars such as the Mirai, NEXO, and Clarity is a compressed gas method, with hydrogen storage tanks of 350–700 bar. Whiston et al. [32] predicted that compressed hydrogen storage methods will be predominantly used by 2035 and will account for 67% of all hydrogen storage methods, and the proportion will rise to 56% by 2050. Cerri et al. [33] predicted the cost of storing 1 kg of hydrogen in a tank using the compressed gas method to be USD400–700, as shown in Table 1.

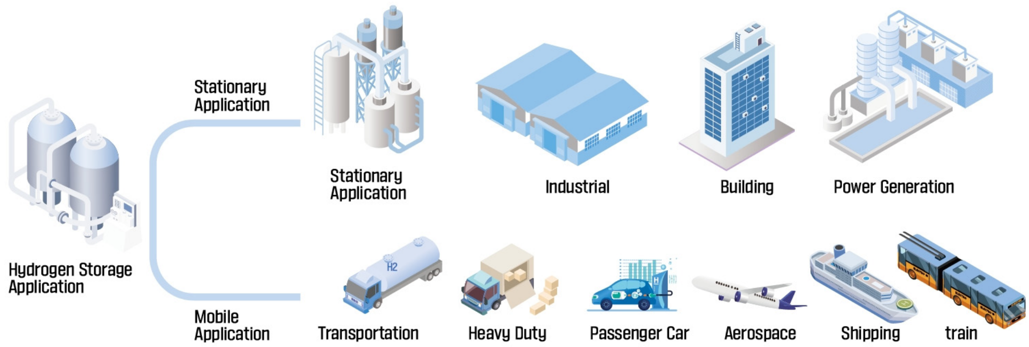


Figure 2. Types of hydrogen storage applications. Stationary includes on-site storage at the point of production or use and stationary power generation. Mobile applications include vehicle fuel and hydrogen transportation.

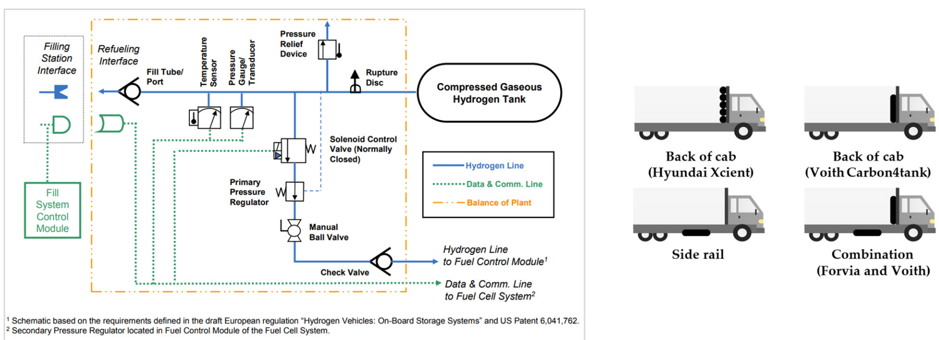
Table 1. Comparison of the main hydrogen storage media.

Storage Technologies	Volumetric Density (kg H_2/m^3)	Gravimetric Density (Reversible) (wt.%)	Operating Pressure (bar)	Operating Temperature (K)	Cost * (USD/kg H_2)
Compressed gas (H_2)	17–33	3–4.8 (system)	350 and 700	ambient	400–700 *
Cryogenic (H_2)	35–40	6.5–14 (system)	1	20	200–270 *
Cryo-compressed (H_2)	30–42	4.7–5.5 (system)	350	20	400
High pressure—solid	40	2 (system)	80	243–298	
Sorbents (H_2)	20–30	5–7 (material)	80	77	
Metal hydrides (H)	<150	2–6.7 (material)	1–30	Ambient-553	>500
Complex hydrides (H)	<120	4.5–6.7 (material)	1–50	423–573	300–450 *
Chemical hydrides (H)	30	3–5 (system)	1	353–473	160–270 **

* Cost estimates based on 500,000 units of production. ** Regeneration and processing costs not included.

The onboard compressed gas hydrogen system for fuel cell electric vehicles (FCEVs) is depicted in Figure 3 and is categorized into the hydrogen storage tank and the BOP (balance of plant). Passenger car hydrogen storage tanks are designed with 1–3 tanks, considering packing based on 5–6 kg of hydrogen storage capacity depending on the vehicle's layout. The BOP consists of a fill port, regulator, valves, and sensors. Heavy-duty truck hydrogen storage tanks have higher hydrogen storage capacity than passenger cars and use various mounting methods such as side rail, back of cab, combo, canopy, and top of the body [34].

In particular, development and demonstration of operations and initial commercialization are ongoing for heavy-duty trucks (classes seven and eight) [35], employing various hydrogen storage tank packing methods, as shown in Figure 3. While most passenger cars are designed with a hydrogen storage tank capacity of at least 5.6 kg per vehicle, heavy-duty trucks have a wide range of types and uses [36]. Kast et al. [34,37] calculated the required onboard hydrogen storage tank capacity for each class, as shown in Table 2.



(**a**) (**b**)

Figure 3. (**a**) Compressed gas hydrogen storage system [38]; (**b**) compressed gas hydrogen storage onboard trucks, shown in various potential locations.

Table 2. Representative vehicle range considerations from the aggregated drive cycle. Reprinted/adapted with permission from Ref. [34]. 2017, Elsevier.

Vehicle	Weight (lbs) [39]	Onboard Hydrogen Storage (kg) [34]	Tank Pressure (bar) [37]	Average Fuel Economy (km/kg of H_2) [34]	Average Range (km) [34]
Class 2 Van	6001~10,000	7.2	700	38	274
Class 3 Enclosed Van	10,001~14,000	8.9	700	25	222
Class 3 School Bus	10,001~14,000	9.1	700	31	285
Class 3 Service	10,001~14,000	6.7	700	25	169
Class 4 Delivery Van	14,001~16,000	19.1	350	19	365
Class 5 Utility	16,001~19,500	8.5	350	18	151
Class 6 Construction	19,501~26,000	13.5	350	22	293
Class 7 School Bus	26,001~33,000	11.3	350	18	201
Class 8 Construction	33,001~over	25.3	350	15	375
Class 8 Linehaul	33,001~over	63.7	350	9	563
Class 8 Refuse	33,001~over	18.2	350	10	187
Class 8 Tractor Trailer	33,001~over	56.6	350	10	565

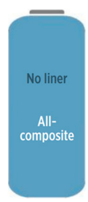
2.2. Types of Hydrogen Storage Tanks

Hydrogen storage tanks were previously one of four types [29,40,41]; recently, Type V [42–46], which is a linerless fully composite tank, was developed by Composite Technology Development Inc. [47,48]. The essential features of each type are as follows:

- Type I: All metal construction;
- Type II: Metal with hoop composite overwrap;
- Type III: Metal liner with full composite overwrap. Composite carries all load;
- Type IV: Polymer liner with a full composite overwrap;
- Type V: Linerless composite vessels.

Type I is an all-metal storage tank. Type II is a tank with a composite material overwrapped around the cylindrical part of the storage tank. In Type II, the internal pressure load is shared between the liner and composite layers. Type III consists of a metal liner fully overwrapped with carbon or glass fiber, whereas Type IV consists of a polymer liner fully overwrapped with carbon or glass fiber. Type V is a linerless structure, with the entire tank made of carbon or glass fiber. Carbon and glass fibers are commonly used as reinforcements in storage tanks, with epoxy or vinyl ester primarily used as the matrix system, as shown in Table 3.

Table 3. Type of hydrogen storage tank [43,48–53].

	Type I	Type II	Type III	Type IV	Type V
Schematic [54]					
Composition	All Metal	Metal Liner with Composites Layer	Metal Liner with Full composites Overwrapped	Metal Liner with Full composites Overwrapped	Full Composites
Tank price (USD/kg)	++ (83)	+ (86)	– (700)	– (633)	–
Gravimetric capacity	–	-	+	++	++
Composite layers load sharing		45% load bearing	80% load bearing	100% load bearing	100% load bearing

Type I is currently the most widely used vessel, accounting for approximately 90% of the market. However, Type I is more than three times heavier than Type III and Type IV, whereas Type IV costs over 300% more than Type I [55]. Type II is over 50% more expensive and 30–40% lighter than Type I. Type III is 50% lighter but costs more than twice as much as Type II, shown in Figure 4. Additionally, Type III and Type VI offer the advantage of hydrogen storage at higher pressures for higher energy storage density.

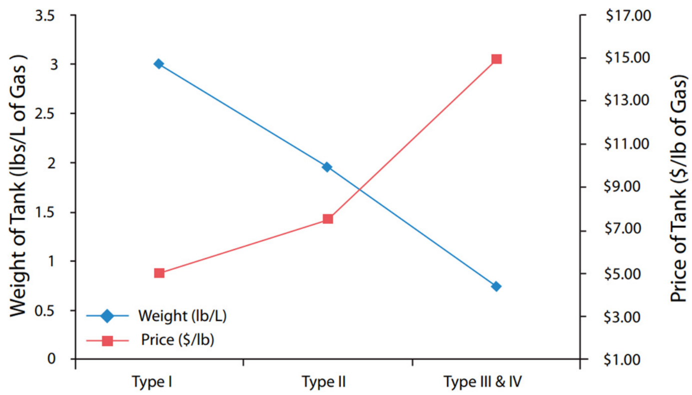


Figure 4. Weight of tanks per gas storage and price of the tank per pound of gas versus tank type. Reprinted/adapted with permission from Ref. [55]. 2014, Elsevier.

2.3. *On-Road Application*

Current commercially available passenger cars with hydrogen pressure vessels are summarized in Table 4. Some initial models used 350 bar hydrogen pressure vessels, but owing to hydrogen storage limitations, most models currently use 700 bar hydrogen pressure vessels; 1–3 pressure vessels are used depending on the vehicle layout. The hydrogen storage capacity of vehicles equipped with hydrogen pressure vessels ranges from a minimum of 4.4 kg to a maximum of 6.33 kg. Hydrogen storage tanks adopt the Type IV manufacturing method that uses polymer liners (HDPE, PA6, etc.), and the wet winding process is widely used as an essential filament winding method during production.

Table 4. Hydrogen vehicles and specification of hydrogen storage tanks.

	Hyundai NEXO (2018) [15,56–58]	**Hyundai ix35(2013) [57,59]**	**Toyota MIRAI II (2021) [13,60–63]**	**Honda Clarity (2016) [14,64,65]**	**Mercedes Benz GLC (2017) [66–68]**
Photos					
Pressure (bar)	700	700	700	700	700
Tank volume (liter)	156.6 (52/52/52)	140 (36/104)	142.2 (52/25.3/64.9)	141.3 (24/117)	117 (unknown)
Tank capacity (H_2 kg)	6.33	5.64	5.6	5.46	4.4
Tank weight (kg) estimation	111 kg (37/37/37)	104 kg (36/104)	unknown	unknown	unknown
Gravity capacity	7.18 wt%	6.43 wt%	5.7 wt%	unknown	5.64 wt%
Driving range(km)	609	415	650	589	478
Tank type	Type IV	Type IV	Type IV	Type III	Type IV
Liner materials	PA6	HDPE	PA 6	aluminum	unknown
Winding process	wet	wet	unknown	unknown	unknown

The Tucson ix35, manufactured by Hyundai Motor Company in 2013, was the first commercialized FCEV passenger car, storing 5.64 kg of hydrogen in two hydrogen pressure vessels (36 L/104 L) with a total volume of 140 L. Toyota began developing fuel cell systems in 1992 and started sales on a limited lease basis in 2002 [69]. The mass-produced Mirai was launched in 2014, and the 2021 model has a total hydrogen storage capacity of 5.6 kg in three hydrogen pressure vessels (52 L/25.3 L/64.9 L) with a total volume of 142.2 L. In 2016, Honda launched the Clarity, which stores a total of 5.46 kg of hydrogen in two hydrogen tanks with a capacity of 141 L. In 2017, the Mercedes Benz GLC, capable of storing 4.4 kg of hydrogen in a 117 L tank, was launched. The 2018 Hyundai NEXO model stores 6.33 kg of hydrogen in three identical-capacity (52 L) tanks with a total capacity of 156.6 L. As shown in Table 4, original equipment manufacturers (OEMs) efficiently packed hydrogen pressure vessels of the same or different sizes according to the vehicle's layout, securing adequate hydrogen storage capacity [70]. In the transportation sector, hydrogen energy is gaining importance for its application to heavy-duty trucks in Table 5, which have a driving range of more than 805 km, fast fuel supply, and shift operation [32,71]. According to an IEA report [18], as of 2022, 12 manufacturers have manufactured or plan to manufacture 16 types of fuel cell trucks by 2024. According to the Interreg North-West Europe H2-Share report [72], 15 types are currently in operation. Hydrogen storage tank suppliers, listed in Table 6, are developing or manufacturing Type III and Type IV hydrogen storage tanks for passenger cars, commercial vehicles, and transport tube trailers, with operating pressures ranging from 350 to 700 bar.

Table 5. Hydrogen heavy-duty truck models [18,73–75] in North America and Europe.

	Hyundai XCIENT (36 t) (2019) [76–78]	**Hyzon Hymax (24 t) [79]**	**Daimler GenH$_2$ [80]**	**DAF-VDL H2 Share Project (27 t) (2020~) [72]**	**MAN (35 t) [81]**	**Scania (27 t) (2019~) [82]**
Photos						
Operator	COOP	-	Testing	-	COOP	Akso
Pressure (bar)	350	350	Liquid	350	350	350
Range (km)	400	400	1000	400	400	500
Tank Capacity (H_2 kg)	31 [78]	30	80	30	31	33
No. of Tanks/Type	7/IV	10/Unknown	2/Liquid	Unknown	7/III	Unknown/IV

Table 6. The manufacturer of compressed gas hydrogen storage tanks.

Manufacturer	**Type [83]**	**Pressure (bar)**	**Water Volume (liter)**	**Application**
Advanced Structural Technologies, Inc. [84]	III	350–517	290–540	Off-road, mining, construction, marine, rail
Liaoning Alsafe Technology [85]	III	350–700	3–180	Hydrogen, medical, SCUBA, etc.
AMS composites cylinders [86]	III	300	1–10	Oxygen, UAV
Avanco (Hexagon) [87]	IV	300–381	350	Distribution, train
Cylinders Holding [88]	I	300	166	Trailer, container
CATEC [89]	IV	275	30~53 ft trailer	trailer
EKC [90]	IV	245	148–324	Medical, industrial, truck
Faber Industries [91]	I, II, III, IV	200–1100		SCBA, hydrogen, CNG, food, etc.
Hexagon Purus [92]	IV	250–950	193–1745	Stationary, distribution, etc.

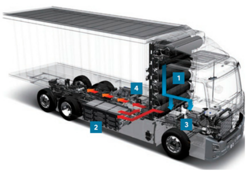
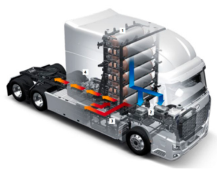
Table 6. *Cont.*

Manufacturer	Type [83]	Pressure (bar)	Water Volume (liter)	Application
Hanhwa [93,94]	IV	350–700	10.8–2078	Passenger cars, buses, and trucks
IlJin Hysolus [95]	IV	700	500	Transport, mobility
Infinite composites [96]	V	310	325	Spacecraft applications
Luxfer [97]	I, II, III	90–350	0.8–2250	SCBA, specialty, medical. CO_2, aerospace
Mahytec [98]	IV	60–500	300–850	Stationary storage
Nproxx [99]	III, IV	100–700	-	Stationary, railroad, passenger car
Plastic Omnium [100]	IV	200–700	-	Passenger car, truck
Quantum Fuel systems [101]	IV	350–700	26–994	Passenger car, truck, bus, transportable, aerospace
Steelhead composites [102]	III, IV	200–700	90–270	Storage and transport
Faurecia Ullit [103]	IV	350–700	120–691	Heavy truck
Toyoda Gosei [104]	IV	700	25.3–64.9 (w/o truck)	Passenger vehicle, truck
Voith composites [105]	IV	700	350	Heavy-duty trucks
Wiretough [106]	II (wire)	350–700	765–1750	Ground storage
Jiangsu Guofu Hydrogen Energy Equipment Co., Ltd. [107,108]	III	350	59–140	Passenger car, bus, logistic vehicle
Sinoma Science and Technology Co., Ltd. [107,109,110]	III	350–700	28–320	Bus, UAM

As shown in Table 4, passenger cars can store 5.4–6.33 kg of hydrogen in hydrogen storage tanks with volumes ranging from 25.3 to 117 L per vehicle and achieve a maximum driving range of 650 km. Class 8 heavy-duty trucks, as shown in Table 5, store 30–31 kg of hydrogen, with a driving range of 400–500 km.

The first heavy-duty FCEV vehicle, the Hyundai Xcient model, underwent test runs for 2 years and has covered 5 million km in Switzerland since October 2020. Full commercial sales of the hydrogen-powered fuel cell truck Xcient began in December 2022 [111]. At IAA Transportation 2022, FORVIA [112] exhibited a product that could store 80 kg of hydrogen by mounting five 700 bar XL Type IV hydrogen storage tanks in the cab module (diameter: 200–700 mm, length: up to 3300 mm) and two tanks in the module on the side (diameter: 700 mm, length: 2500 mm). Voith [113] developed a product with a 700 km driving range by storing 56–112 kg of hydrogen in 4–8 tanks; each hydrogen storage tank had 350 L and 14 kg of hydrogen capacity (7.4%) at 700 bar. Compared with passenger cars carrying 5.6 kg of hydrogen, heavy-duty trucks show an increasing trend of 5.5–20 times in the storage capacity, with a maximum storage of 112 kg, as shown in Table 7. Park, C. et al. [114] also reported that buses and trucks use 10–20 times more hydrogen than passenger cars.

Table 7. Compressed gas hydrogen storage tanks onboard trucks, shown by location.

	HYUNDAI XCIENT 2021 [76]	HYUNDAI XCIENT Tractor 2023 [115]	FORVIA XL-Type IV [112]	Voith Carbon4tank [113]
Tank Location				
Capacity H_2/No. of Tanks/Pressure	31 kg/7 tanks/350 bar	68.6 kg/10 tanks/700 bar	80 kg/7 tanks/700 bar	112 kg/6 tanks/700 bar

3. Cost and Cost Modeling

3.1. Definition of Cost and Cost Modeling

Cost refers to the resources sacrificed to achieve a specific goal, such as manufacturing a particular product, and can be categorized int o (1) recurring or non-recurring costs, (2) direct or indirect costs, and (3) fixed and variable costs [116]. Recurring costs include administrative costs, debt, and other long-term costs that support business functions, and are regular, routine, and part of the ongoing business operations. Non-recurring costs are infrequent costs that are unusual or one-time occurrences. Direct costs are those that can be specifically and easily identified for a particular product or activity, whereas indirect costs are incurred for common or shared objectives and cannot be easily and specifically traced to a particular product. Fixed costs remain constant regardless of production or activity levels, whereas variable costs differ depending on the level of activity or output [117]. Another distinction is between relevant and irrelevant costs [118]. Relevant costs are defined as costs associated with a specific decision. The cost period can be summarized using the cost breakdown structure (CBS) proposed by Fabrycky, W.J. et al. [119]. The total product cost or life cycle cost is divided into four components [120]: (1) research and development costs; (2) production and construction costs; (3) operation and maintenance costs; and (4) retirement and disposal costs. Costs must be calculated using a technology applicable to all options, i.e., a technology that can be applied to any material, form, or process [121]. Qualitative and quantitative cost estimation techniques are described in the tree diagram presented in Figure 5. Qualitative cost estimation techniques primarily identify similarities between new products based on a comparative analysis of new products and previously manufactured products. In contrast, quantitative techniques are not merely dependent on past data or estimators' knowledge but are based on the detailed analysis of the product design, functionality, and relevant manufacturing processes [122].

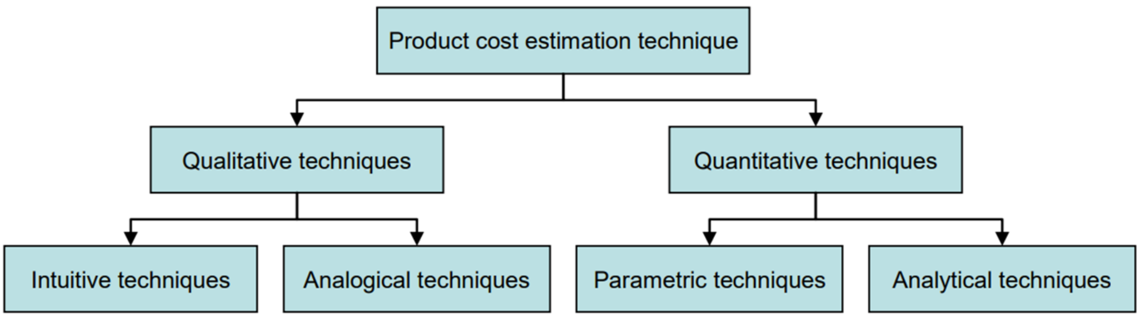


Figure 5. Classification of the cost estimation technique [123].

Process-based cost modeling (PBCM) was proposed by Bloch, C. et al. [124] and is suitable as a decision support tool for evaluating various technology and process choices, with the cost of each process calculated using the input data, as shown in Figure 6. The process parameters include the process flow, speed of each process stage, yield of each process stage, equipment costs, number of operations, machinery, and indirect labor requirement. The factory parameters include worker costs, indirect labor costs, overheads, space costs, and the number of operations. Shift and maintenance times and material and scrap costs are included, and the total cost is the sum of the abovementioned costs for each module. The PBCM framework introduced by Field et al. [125] indicates that costs can be considered as functions of technical factors such as cycle time, downtime, defect rate, equipment and tooling requirements, or materials used [126]. These technical factors, which include operational inefficiencies, determine the amount of factory resources required to produce a given level of output for a given type of technology.

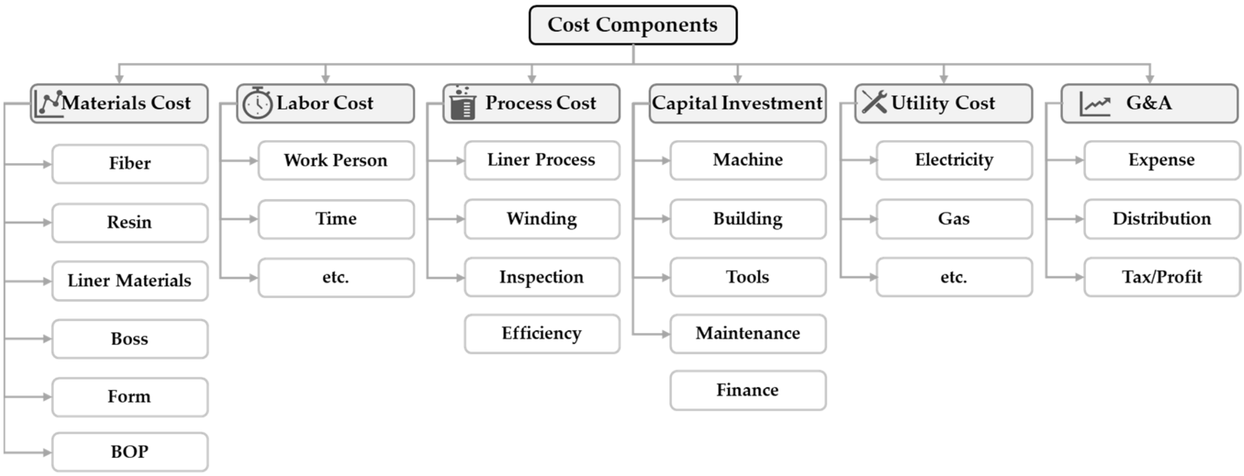


Figure 6. Components of cost modeling for compressed gas hydrogen storage tanks.

3.2. Cost Modeling of Composites

Cost modeling for composite material-based manufacturing processes is an emerging research area. Because the majority of the cost for hydrogen storage tanks is incurred for the carbon fiber and the filament winding process using it, a literature review on cost modeling of composite materials was conducted first, as shown in Table 8. One of the first attempts at cost estimation for composite materials [127] is the "Advanced Composite Cost Estimation Model (1976)", released for government contractors. Zallom et al. [128] reviewed four major cost models and estimated the cost of components made from advanced composite materials. These were used for the initial cost estimates for aircraft, but the early models had limitations in practical application owing to the lack of cost data and rapid changes in process technology. M. Akermo et al. [129] developed a cost modeling program for compression molding composites and sandwich components. The program separated the costs into fixed power costs and labor costs.

$$\text{Fixed power cost} = \frac{\text{Fuse(Equipment)}}{1200} \times 52{,}000 \text{ EUR/year}, \tag{1}$$

$$\text{Labor cost} = \frac{\text{Labour rate}}{1200} \times \sum\nolimits_{\text{process}} \text{Dedication(i)Time(i)}, \tag{2}$$

This program was used to investigate the cost comparison trends, such as size, complexity, and series length, between products made from steel components and those made from thermoplastic composites and sandwich materials, including glass fabric-reinforced PA12, unidirectional glass-reinforced polypropylene, and randomly glass-reinforced unsaturated polyester sheet molding compound (SMC). M. G. Bader [130] conducted cost modeling, as shown in Equation (3), to estimate the manufacturing costs for the components used for various composite materials and in various manufacturing techniques. It was proven that selecting "expensive" carbon fiber instead of "cheap" E-glass could provide a more economical solution.

$$\text{Total cost} = \text{feedstock} + \text{tooling} + \text{labor} + \text{plant cost}, \tag{3}$$

J. Verrey et al. [131] used a parametric technical cost model (TCM) to compare two resin transfer molding (RTM) variants for the production of full automotive floor pans using 12,500 to 60,000 parts per year. Research on alternate preforming strategies proved that the reduction in non-crimp fabric scrap, which is the raw material used in the process, is the most feasible solution for cost savings. Erica R. H. Fuchs et al. [132] concluded that considering the technological advancements in polymer composite body-in-white design compared with mild-grade steel bodies, polymer composite bodies used for light weighting had significant economic potential owing to the advantages of the composites and fuel efficiency improvements obtained from their use. They studied the cost estimation models for automotive body-in-white applications and applied the total cost analysis using two PBCM models, a component PBCM mode and an assembly PBCM model, which applied the model equation shown below.

$$C_{Tot} = \sum_q C_p, \text{ s.t. } q \in \text{Components; Assembly}, \quad (4)$$

C_{Tot} represents the total unit cost and C_p is the total unit cost output of one model, which are either the total body-in-white cost of producing all components ($C_{Components}$) or the total cost of assembly of a model ($C_{Assembly}$). The cost study showed that fiber-reinforced composite bodies-in-white have a greater likelihood of competing with steel products than in the past. Ye, J. et al. [133] conducted a manufacturing process-based manufacturing cost analysis and proposed a cost estimation model that included the material cost, labor cost, equipment cost, and tooling cost, as shown in Equation (5).

$$C_{cost\_per\_part} = C_M + C_L + C_E + C_T, \quad (5)$$

Table 8. Literature review about cost modeling of the composite-based manufacturing process.

Authors	Year	Application	Cost Process	Results
LeBlanc, D. J. et al. [127]	1976	Aircraft	Advanced composite cost estimating manual	Cumulative average cost estimate
Zaloom, V. et al. [128]	1982	Aircraft	Integrated computer-aided manufacturing program (ICAM)	Accuracy is unknown due to a lack of actual cost data
Åkermo, M. et al. [129]	2000	Tailgate	Thermoplastic composites	Composite and sandwich materials are cost-comparative with steel
Bader, M. G. [130]	2002	L stiffening ribs	different manufacturing routes	Economic solutions may often be realized by choice of carbon than E-glass
Verrey, J. et al. [131]	2006	Automotive floor pan	Thermoset RTM	A reduction in non-crimp fabric scrap yielded major solution cost savings
Fuchs, E. R. et al. [132]	2008	Automotive body	Injection molding	Composites have significant economic potential in the body-in-white design
Ye, J. et al. [133]	2009	Composites wave beam	Autoclave	Estimation variables and modifying parameters in the layup procedure
Schubel, P. J. [134]	2012	Wind turbine blade	Vacuum infusion	Investigates the influence of labor costs, component area, deposition/cure time, and reinforcement price
Weiland, F. et al. [135]	2013	Helicopter rotor	Prepreg/infusion	The manual prepreg manufacturing process and cost savings with the novel process
Hagnell, M. K. et al. [136]	2015	Aircraft parts	ATL/HDF	For higher production volumes, ATL followed by HDF is the most cost-effective choice
Ellringmann, T. et al. [137]	2016	Carbon fiber	24 K PAN fiber manufacturing process	Energy (34%), raw materials (19%), and capital costs for equipment (18%)
Soares, B. A. et al. [138]	2019	Aircraft parts	ATL/ATP	ATL is less expensive than AFP due to lower material costs
Hagnell, M. et al. [139]	2020	Aircraft parts	Design, materials	The sandwich-stiffened design has been shown to be the most cost efficient

For the cost model, they selected a weaved beam as the target product and the autoclave cure process for the method and studied the effects of the material cost (C_M), labor cost (C_L), equipment cost (C_E), and tooling cost (C_T). They also estimated the costs considering the effects of the geometric size, configuration complexity, time delay in operation, and running condition of the equipment. Schubel, P. [140] conducted a detailed technical cost analysis of 45 m wind turbine blades manufactured using the vacuum infusion process for high cost savings and presented the methodology and results of the TCM of wind turbine blades [134]. The process parameters and production variables reflected in the cost were interest and depreciation, maintenance, utilities, floor space and building, tooling, labor, materials, and transportation. According to the results, non-crimp fabric processes were found to be cost-effective materials. Although non-crimp fabric is a relatively high-cost material and has limitations in use, the study conducted TCM-based research and proved it to be more efficient.

Weiland, F. et al. [135] studied the manufacturing process and cost modeling of components that comprise the composite rotor blade pitch horn in the root section of the main rotor of a helicopter. The cost analysis was based on the ABC methodology, and the cost estimation results showed that the new semi-automated preforming process had 20% cost savings compared with the manual prepreg manufacturing process. However, the researchers discussed that accurate input data are necessary for successful process analysis, but collecting such data with new technological approaches is difficult and it must be carefully estimated in advance. Hagnell, M. K et al. [136] presented a novel composite-based production estimation model for aircraft. For the cost model, they evaluated the costs of a generic aeronautical wing composed of skin, stiffeners, and rib feet, and compared the costs for several common aviation manufacturing methods. For manual layup, the layup speed of the flat parts is generally 0.9–1.5 kg/h, whereas automatic fiber placement (AFP) ranges between 2 and 150 kg/h depending on the size and complexity of the part. Automatic tape layup (ATL) speeds range between 10 and 150 kg/h depending on the size of the components. The relationship between the total layup rate and maximum rate is as shown below.

$$r = \sum_{i=1}^{\text{no of face}} \delta(r_0 C), \tag{6}$$

r_0 is the maximum layup rate of a face of the lowest complexity, C is the complexity factor, and δ is its percentage with respect to the total surface area of the part. For the studied structures, manual layup was the most efficient method for producing less than 150 units annually, whereas for mass production, ATL and hot drape forming (HDF) were the most cost-effective options. This result served as a good case study for the application of composite materials in the aviation industry. Ellringmann, T. et al. [137] modeled the production cost of 24 K polyacrylonitrile (PAN)-based carbon fiber. The new carbon fiber cost model used a modular design with independently configurable process steps. The cost analysis results were ranked in order of energy (34%), raw materials (19%), and equipment capital costs (18%). The high (54%) cost share of carbon fiber PAN precursors is consistent with that obtained from most reviewed models. The important points to consider here are the limitations of the theoretical approach and the fact that energy costs have the highest sensitivity in carbon fiber production. Hence, it is crucial to reduce energy consumption or choose low-cost factory sites. Soares, B. A. et al. [138] found that current aircraft components are manufactured using the ATL and AFP processes, and analyzed the costs of the two processes using PBCM.

$$\text{Mat}_{\text{cost}} = C_{Kg} \times \rho_a \times \text{surfa} \times \text{n}\circ\text{l} \times \text{NP}_i, \tag{7}$$

$$\text{Labor}{=}\text{CT}_i \times \text{n}\circ\text{w}_i \times \text{ded}_i \times \text{w}_i \times \text{NP}_i, \tag{8}$$

$$\text{Labor cost} = \frac{\text{Labour rate}}{1200}, \tag{9}$$

$$\text{Building cost} = \frac{\text{a}^\circ\text{jEqCostji} \times \text{SfAreai} \times \text{Alloci}}{\text{SfArea} \times \text{NPi}}, \tag{10}$$

ρ_a is prepreg density per unit of area, surfa is the part surface area, n∘l is the number of layers, CT_i is the cycle time, and $n\circ w_i$ and ded_i are the number of workers and the percentage of their dedication to the process step i. NP_i is the number of parts produced in the process step i, $EqCost_{ji}$ is the residual value of buildings, SfAreai is the area occupied by the infrastructure of the manufacturing process, SfArea is the global shop-floor area i, and $Alloc_i$ is the percentage of occupied by the production of the part in required quantities. According to the results, ATL has lower material efficiency and slower cycle time owing to lower material costs than AFP but is more affordable. This study utilized data from both industry and academia and is significant in terms of cost analysis. Hagnell, M. K. et al. [139] conducted a case study demonstrating the importance of structural design and material selection. They performed a cost analysis on composites containing monolithic, u-beam, sandwich-insert, and sandwich-stiffened plates, and predicted that carbon, glass, recycled carbon, lignin, and hemp-fiber-reinforced composites and sandwich-reinforced designs would be efficient in terms of both weight and production cost, with a superior range of bending stiffness and overall torsional stiffness.

Although much effort has been made in the optimization of cost analysis for the application of composites in various fields (e.g., aerospace and automotive) over the past few decades, most studies have limitations due to the lack of field data and theoretical approaches.

4. Cost Analysis of Compressed Hydrogen Storage Tanks

4.1. Manufacturing Process

The manufacturing process for Type III [141] and Type IV [38] hydrogen storage tanks is shown in Figure 7. The manufacturing process is divided into three parts: the liner manufacturing process, filament winding process, and inspection and assembly process.

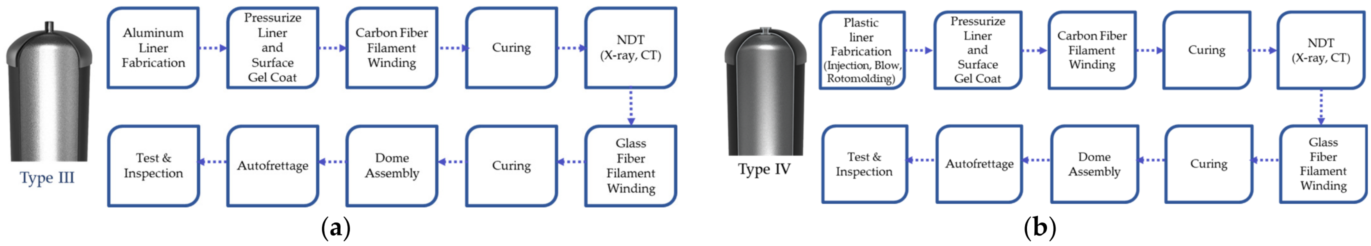


Figure 7. The manufacturing process of hydrogen storage tanks; (**a**) Type III; (**b**) Type IV.

Liners, as mentioned earlier, are made from various types of materials, both metal and non-metal, for Types III and IV. Types I and II are not suitable for use as hydrogen pressure vessels; they are made from metallic materials and are mostly applied in industries, such as liquid or chemical industries [142]. Type III liners are made from metal or aluminum alloys, whereas Type IV liners are made from polymer. The difference between Types III and IV liners is that Type III uses metal (generally aluminum) as the liner material and applies an autofrettage process after the manufacturing of the liner. Type IV uses a non-metallic polymer liner. The detailed processes for each are as follows. Type III and Type IV hydrogen pressure vessels, consisting of aluminum alloys or polymer liners and carbon fiber winding layers, are currently the most common means of storing hydrogen in vehicles [143]. First, the metal liner used in Type III is most commonly made of aluminum alloys 6061 and 7000, and Types I, II, and III metal liners are manufactured using the three methods shown in Figure 8a. The first method involves forming the shape using a deep-drawn aluminum plate from a steel plate, and the tank's neck is manufactured by a hot spinning process [144]. The second method is to use a billet in the manufacturing process, similar to the plating process. The third method involves using a tube of the same thickness as the final tank's hoop and connecting the dome through a hot spinning process [52,145].

Type IV polymer liners are made of high-density polyethylene (HDPE) [146] or polyamide (PA6) systems [147], which have nonstructural properties for high-pressure gas and serve as a hydrogen permeation barrier [148]. The various Type IV plastic liners [149] currently used by each manufacturer are listed in Table 9.

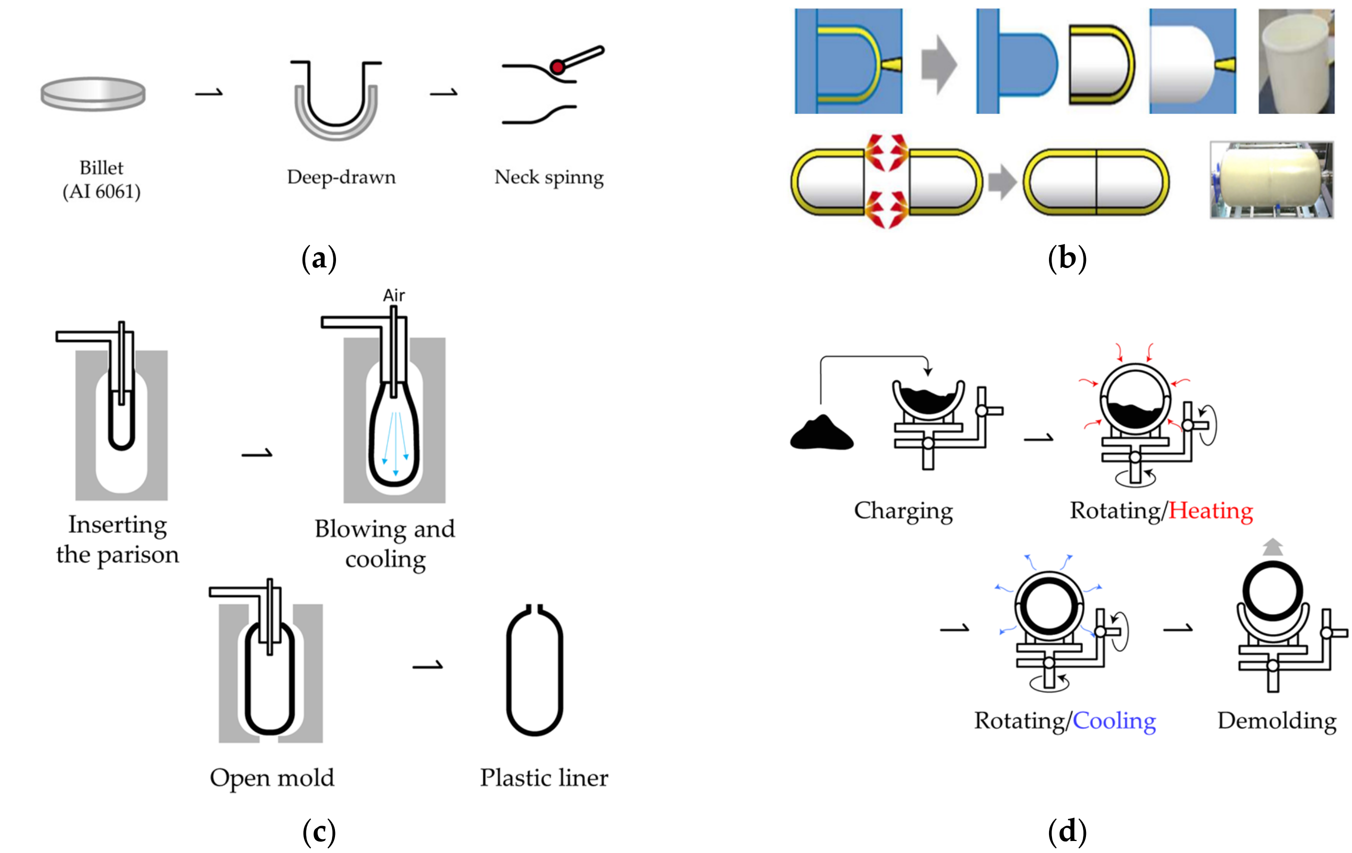


Figure 8. The manufacturing process of the liner; (**a**) Type III metallic liner from plates; (**b**) Injection molding of Type IV [150]; (**c**) Blow molding of Type IV; (**d**) Rotomolding of Type IV.

Hydrogen has small molecules, making diffusion and penetration important aspects of safety in hydrogen pressure tanks. Liner materials must consider both safety and cost-effectiveness [147,151–154]. Type IV polymer liners can be manufactured using injection molding and welding [150,155], blow molding [156], and rotomolding [157,158] techniques, as shown in Figure 8b–d. Injection molding and welding is a multi-stage molding process [49]. The head part is injection-molded, and the cylinder part is welded. This method offers high precision, stability, and excellent mechanical properties of the part but has the disadvantage of being a complicated welding process. Blow molding is a fast one-step molding process that produces good mechanical properties and high production efficiency but has relatively low uniformity. Rotomolding is a cost-effective method for producing hollow polymer parts. The process involves placing the polymer in a mold in the shape of the final liner, then rotating and heating the mold, followed by a cooling process [157,159].

Table 9. Liner materials for Type IV commercial hydrogen storage tanks.

Company	Liner Material	Raw Material Cost [160]
Hexagon Purus [161,162]	HDPE	USD0.72/kg
Toyota [61]	PA6	USD3.13/kg
Quantum [163]	Cross-lined polyethene PET	USD0.72/kg
French Atomic Commission (CEA) [147,164]	Thermoplastic (PA)and thermoset	USD3.13/kg
Ullit (France) [147]	PA6	USD3.13/kg
Kautex [165]	PA6	USD3.13/kg
DSM [161,166]	PA6	USD3.13/kg
Hyundai [167]	PA6	USD3.13/kg

EUR to USD exchange rate (USD1.0938/EUR).

As shown in Table 10, liner manufacturers and OEMs are conducting necessary research and devising suitable liner manufacturing methods. Additionally, unlike other types of tanks, Type V must be linerless; hence, either no liner is used or a washable liner or composite hard tooling [42,168,169] is used, which is removed during the later stages of the process. Linerless filament winding processes are under development [43]. Technical studies are underway to overcome limitations related to permeability and manufacturing processes, such as matrix modification and research using AFP [170]. After liner production, the most important process in hydrogen storage tank manufacturing is the filament winding process. Filament winding reinforces the liner using glass, aramid, or carbon fibers, which are characterized by high tensile strength, modulus, and elongation [171]. Carbon fibers exhibit excellent mechanical properties as reinforcements in the filament winding process owing to the very high pressures at which hydrogen is stored. Carbon fibers can be classified into low-modulus and high tensile strength types (HT) with strengths over 3 GPa, intermediate-modulus type (IM) with moduli below 300 GPa, high-modulus type (HM) with moduli above 300 GPa, and ultra-high-modulus type (UHM) with moduli above 500 GPa [172].

Table 10. Comparison of the liner molding process. Reprinted/adapted with permission from Ref. [148]. Copyright 2022, Elsevier.

	Injection Molding and Welding Molding	**Blow Molding**	**Rotational Molding**
Manufacturer	Toyota, Hyundai, IlJin, NPROXX	Quantum, Plastic Omnium, General Motors, Impco, and Hexagon Purus	Quantum, CEA, and Hanhwa solutions
Molding step	Multistep molding	One-step molding	One-step molding
Advantages [148]	• The product has high precision, stabilized size, and good mechanical properties • Suitable for the molding various complex BOSS structures and can be employed to form large liner • The length of the cylinder can be arbitrarily changed	• Good mechanical properties • High production efficiency • Low equipment cost • Small residual stress • Products have high-impact toughness and environmental cracking resistance	• It is simple and can form a large liner • No internal stress • Suitable for forming liners with different wall thicknesses
Disadvantages [148]	• The welding process is difficult • There are more forming steps • A high requirement for melt fluidity and extrusion molding is needed when the aspect ratio increases • Large residual stress	• Poor wall thickness uniformity • A high requirement for melt fluidity • Only suitable for forming the liner with a simple BOSS structure • The increase in liner structure will improve the difficulty of forming	• High equipment cost • Low molding density • Low production efficiency • The raw material needs to be powder

Filament winding is a major composite manufacturing process that manufactures composite parts by placing fibers in a predetermined pattern [173]. There are three types of filament winding technologies: wet winding [174], dry fiber winding [175], and towpreg winding [176]. A schematic of the process is shown in Figure 9. Generally, most hydrogen pressure vessels are manufactured using the wet winding process. In this process, a stationary rotating mandrel is used, and the carriage moves horizontally with the mandrel. Carbon fibers are impregnated in a resin bath before winding. The impregnated carbon fibers are grouped and dispensed with a payout eye that includes an arm with the carbon fibers wrapped around it [51]. After this process is complete, all assemblies are placed in a curing oven and heated to the necessary temperature for curing. After full curing, the mandrel is removed from the composite part [177,178].

The dry filament winding process is similar to the wet winding process but does not involve a resin impregnation process during filament winding. The dry winding process has various advantages, such as low cost and production speed, but requires an additional impregnation process [179] after winding. Towpreg winding involves controlling the towpreg at the desired temperature before guiding it under constant tension onto the mandrel. Final compaction occurs on the mandrel by applying sufficient heat and pressure.

Towpreg winding offers benefits such as precise control of the resin content, reduced variability, increased production throughput due to high-speed mandrel winding, reduced scrap, and easier workplace cleanup. However, it has drawbacks, such as limited shelf life and high raw material costs. In the above study, towpreg winding was planned to be used as a dry winding method with the objective of using fibers pre-impregnated with resin.

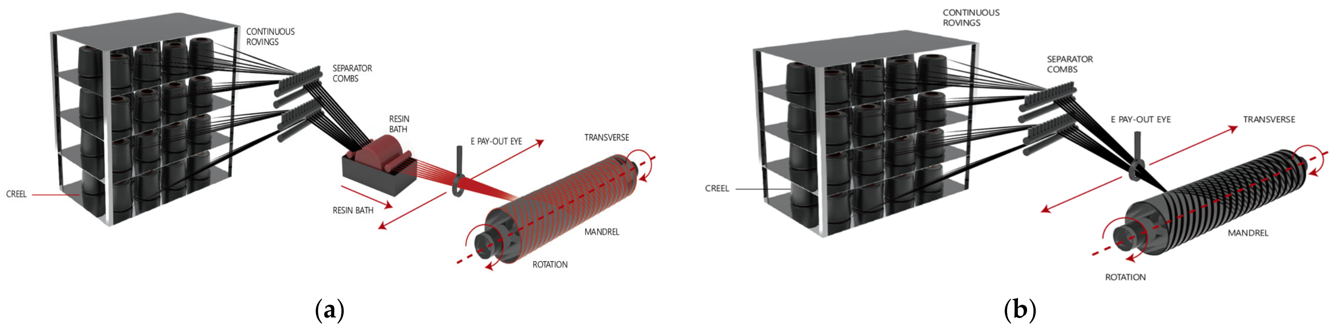


Figure 9. A schematic of the filament winding process: (**a**) wet filament winding; (**b**) filament winding with in situ consolidation.

Filament winding processes generally involve three winding patterns [180,181]. The winding pattern primarily used in hydrogen pressure vessel manufacturing is a combination of circumferential angle (hoop) and helical and polar wrapping, as shown in Figure 10 [69,176,182]. The pattern also significantly affects the winding speed and cost.

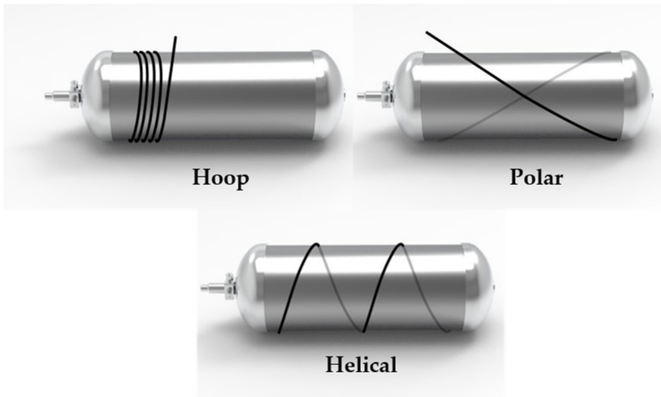


Figure 10. Filament winding pattern and strategies.

4.2. Cost Analysis

From a vehicle perspective, safety, performance, cost, technical adaptation for infrastructure, and scalability must be considered for hydrogen storage tanks [183]. The US Department of Energy (DOE) operates a hydrogen cost reduction program [184] and reports achievements in comparison with targets. Several other publications have also provided cost analysis and directions for cost reduction. Various approaches can be taken to reduce the cost of hydrogen storage tanks. The most effective methods are reducing carbon fiber usage, which accounts for the largest share of costs, or reducing the filament winding process, which incurs significant processing costs [141]. The cost for the main raw material, carbon fiber, varies depending on the cost analysis method, hydrogen storage tank capacity, and design, but more than 75% of the total cost is attributed to the carbon fiber composite layer, with 50% attributed to carbon fibers [141,185]. Research and a literature review on reducing carbon fiber usage are presented in Section 4.2.3. Currently, the filament winding process during hydrogen storage tank manufacturing is time-consuming. The introduction of a high-speed filament winding process has the greatest potential to reduce the cost of hydrogen storage tanks and increase the fiber throughput in the curing ovens [141]. The speed of the wet filament winding process is inevitably limited by the fiber impregnated with resin, and typical process speeds range from 1 to 2 m/s to a maximum of 10 m/s, depending on the shape, size, and complexity of the manufactured parts [186]. However, the dry towpreg filament winding process can achieve ultra-high speeds of 20 m/s [141]. The second cost reduction method is to change the structure of the hydrogen storage tank or optimize it from a cost perspective. Lastly, the cost can be lowered by changing the overall design and manufacturing method to an alternative process, such as conformable hydrogen tanks.

4.2.1. Cost Analysis and Forecasting of the DOE's Hydrogen and Fuel Cells Program

The cost-related reports of the DOE's hydrogen program can be found in the program records [184], which are divided into six categories; the hydrogen storage tank cost related to this study is related to the last category, that is, storage. Research on hydrogen storage tank costs began in 2006 as a part of a study on hydrogen materials and became a more focused study on onboard storage systems in 2010. Detailed analysis of the performance and costs of Type IV tanks has been conducted since 2013. The goals for the hydrogen storage tank system [187] by the DOE and US DRIVE [188] were updated in 2009 [189] and 2017 [190], with the target objectives as shown in Table 11.

Table 11. The target cost of the hydrogen storage system.

Storage System Target	2010 [191]	2015 [191]	2020	2025	Ultimate
System Gravimetric Capacity (wt%)	4.5	5.5	4.5	5.5	6.5
System Volumetric Capacity (g H_2/L)	28	40	30	40	50
Cost (USD/kWh)	4	2	10	9	8
Cost (USD/kg H_2)	133	67	333	300	266

Constants: 0.2778 kWh/MJ; lower heating value for H_2 is 33.3 kWh/kg H_2; 1 kg H_2 ≈ 1 gal gasoline equivalent (gge) on an energy basis.

The 2010 DOE report "On-Board Hydrogen Storage Systems - Projected Performance and Cost Parameters" summarized the research on technical assessments and projected the manufacturing costs for hydrogen storage tanks based on an annual production volume of 500,000 units [192]. In 2009, the DOE changed its 2010 targets for system gravimetric capacity (wt%) from 6% to 4.5% and system volumetric capacity (g H_2/L) from 45 to 28. The revised targets showed insufficient results but generally provided good directions for hydrogen storage tank costs and technology. According to the 2013 DOE report [193], the costs for manufacturing 500,000 units of 350 and 700 bar, 147.3 L hydrogen storage tanks per year were predicted to be USD12–16.0/kWh and USD16–20.0/kWh, respectively. The costs applied were USD28.67/kg for carbon fiber, USD7.09/kg for resin, and USD1.77/kg for liners. The calculated costs of hydrogen storage tanks per kg of hydrogen were USD532.8–666/kg H_2 for 700 bar and USD399.6–532.8/kg H_2 for 350 bar, showing a cost reduction of approximately 50% compared with the 2010 analysis. The BOP cost was calculated using a learning curve factor. Brian D. James et al. [194] provided a detailed calculation of the cost of a 700 bar, Type IV hydrogen storage tank based on a single 147 L tank with a length-to-diameter ratio of 3, containing 5.6 kg of usable hydrogen and produced at an annual capacity of 500,000 systems. The estimated cost was calculated as the sum of the material, manufacturing, and assembly costs. Throughout the analysis, the costs were normalized in terms of USD/kWh to allow comparison with the DOE targets and were used as indicators of the total available onboard fuel storage. The energy content of hydrogen was calculated based on the lower heating value (LHV), with the LHV of hydrogen assumed to be 33.3 kWh/kg H_2. The main reasons for the comparative results of the 2015 and 2013 analyses were the reduction in cost due to the lower unit price of epoxy resin after switching to low-density resin, the application of low-cost carbon fiber (USD23.43/kg) instead of high-volume carbon fiber, integration of BOP components by changing the hydrogen storage tank design, and optimization of variables and doilies during the process. In 2013, the cost for a 700 bar, Type IV tank storing 5.6 kg of H_2 was estimated at USD16.76/kWh when producing 500,000 units per year. In 2015, the expected cost for an equivalent system was predicted to be USD14.75/kWh. In addition, a provisional cost of USD14.07/kWh was proposed for a single tank system in 2016, with a production of 500,000 units. The cost breakdown for each component was as follows: 62% for carbon fiber, 25% for BOP, 6% for wet winding, 4% for resin, 1% for liner, and 2% for other elements. Fullenkamp, P. et al. [195] calculated the cost of a hydrogen storage tank with a capacity of 147 L, 5.6 kg H_2 at 700 bar. The production quantity was based on an annual production of 100,000 vehicles using the DFMA® program, and international prices were applied for carbon fiber, resin, and HDPE liner materials. Selling, General, and Administrative Expenses (SGAs) were set at 3%, engineering at 3%, and profit at 5%. T-700 carbon fiber and vinyl ester resin were used, and a safety factor of 2.25 was applied. The cost analysis showed that material costs accounted for 73%, direct labor costs 6%, burden 8%, SGAs 2%, engineering 4%, and profit 6%. The burden included equipment payment, tooling, maintenance, electricity, and facility costs. The report used a blow molding method with HDPE to produce the liner and a wet winding method to manufacture the storage tank. The main cycle times were assumed to be 148 min for wet winding, 2.45 min for full cure, and 1 min for blow molding. Investment amounts were estimated based on hydrogen storage tanks for 100,000 vehicles annually: USD74.0 million for facilities, USD32.8 million for capital equipment, and a workforce of 78 people. The report's detailed cost analysis for storage tanks by investment amount and country for mass production is significant but requires a review of the material cost and cycle time assumptions.

In 2019 [196], the projected cost of a 700 bar Type IV compressed hydrogen system was reduced by 30% to USD15.7/kWh compared with the 2013 cost target of USD22.1/kWh for 100,000 systems. For 500,000 systems per year, the cost was USD14.2/kWh. The main considerations were lower costs of carbon fiber and resin and the integrated balance of plant components. The gravimetric energy density was 1.48 ± 0.04 kWh/kg system, and the volumetric energy density was 0.83 ± 0.01 kWh/L system. As shown in Figure 11, the system cost for 100,000 systems per year was USD22/kWh in 2013, USD18/kWh in 2015, and USD16/kWh in 2019, whereas for 500,000 systems per year, it was USD18/kWh in 2013, USD16/kWh in 2015, and USD14/kWh in 2019. Thus, the DOE's 2020 target of USD9/kWh could not be achieved, as shown in Table 11.

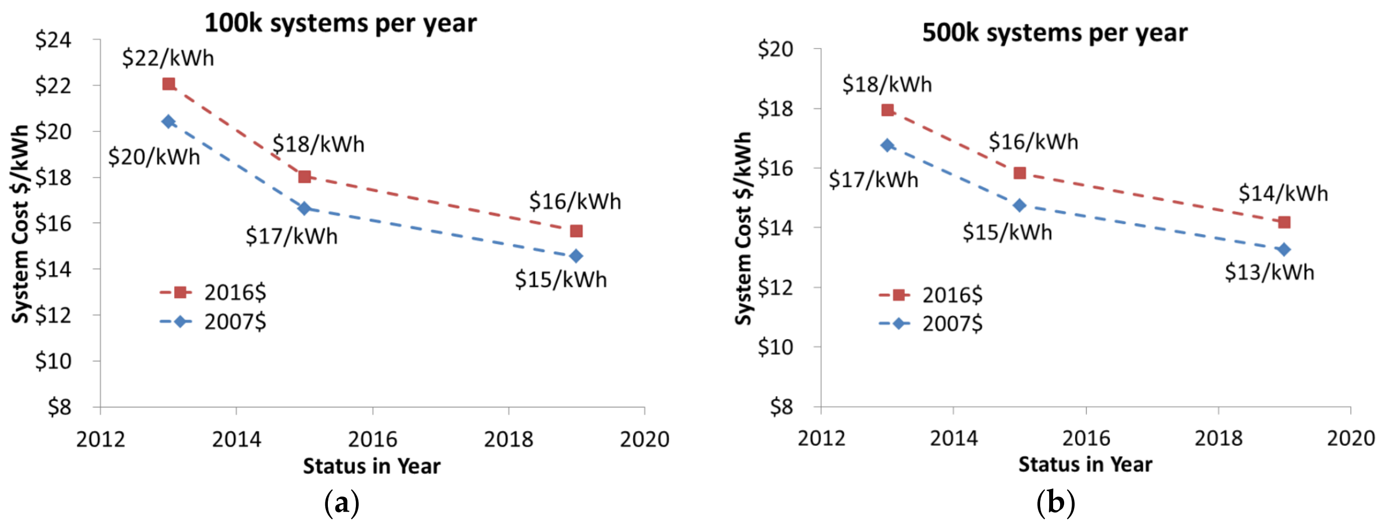


Figure 11. Comparison of storage system cost status in 2007, 2016, and 2019; (**a**) costs are for annual productions of 100,000 units; (**b**) 500,000 units [196].

The DOE has been making efforts to analyze and reduce the cost of hydrogen storage tanks using various methods and strategies. Their research appears to be the most comprehensive among the literature and reports reviewed here. However, there are some discrepancies between the raw material unit prices and the actual values used by companies. Notably, according to the 2014 DOE report, the hydrogen storage performance matrices show that the unachieved performance indicators were fuel lifecycle cost, volumetric density, gravimetric density, and system cost, and the lowest performance was observed for the system cost, as shown as Figure 12.

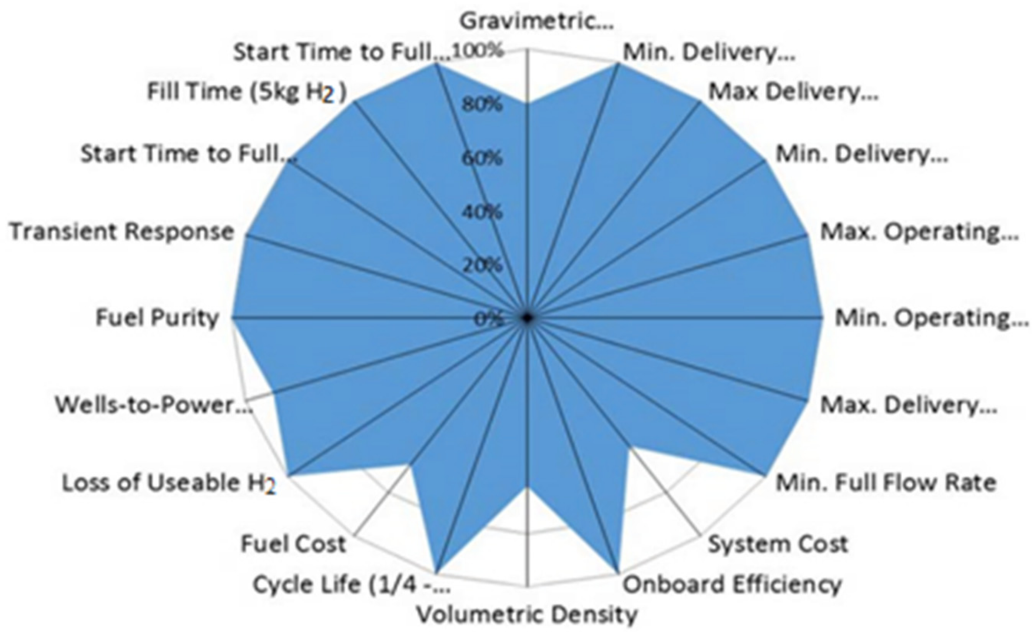


Figure 12. Spider hart comparing performance of 700 bar Type IV single tank system with 5.6 kg usable hydrogen storage with the 2020 onboard automotive target [197].

The DOE announced a target cost for storage tanks intended for heavy-duty trucks (class 8) in 2020 [198]. The 2030 target is USD9/kWh (USD300/kg H_2), and the ultimate goal is USD8/kWh (USD266/kg H_2). The target cost includes the cost of BOP components. Additionally, the National Clean Hydrogen Strategy and Roadmap [71] includes a strategy for the period between 2024 and 2028 to reduce the unit price of carbon fiber by 50% compared with 2020, thus securing economical costs.

4.2.2. Cost Target, Analysis, and Estimation

The previous section reviewed the DOE's target costs and cost reduction strategies for hydrogen storage tanks. This section discusses the relevant academic literature on this topic, as shown in Table 12. Berry, G.D. et al. [199] analyzed the cost of a hydrogen storage tank capable of storing 5 kg of hydrogen at 34.4 MPa. Their analysis compared the costs of cryogenic, liquid, and LH_2 hybrid storage tanks based on the vessel parameters. Although the paper lacks detailed input data for cost analysis, it provides a good comparison of the costs for each type. The authors predicted that the cost for a 34.4 MPa compressed gas type storage tank would be USD2000 for limited production and USD600.4 for mass production. Although their data lacked specific criteria for the classification of limited and mass production, their study is noteworthy for defining target values. Lipman, T. E [200] conducted a cost analysis [201] for vehicles with a 300-mile driving range. In the case of Gen 4 vehicles, if the hydrogen storage system pressure is 350 bar and the hydrogen weight is 6.94 kg, the entire system weight is 71.7 kg. Assuming an annual production of 2000 units, the cost of the hydrogen pressure vessel is projected to be USD500–600/kg H_2, whereas the corresponding cost for production of 200,000 units per year is USD84–163/kg H_2. Carbon fiber costs of USD8.8–22/kg were assumed in the study.

Table 12. Literature review on hydrogen storage tanks.

Authors	Year	Type	Volume (liter)	Pressure (bar)	H_2 Mass (kg)	Cost
Berry, G. D. et al. [199]	1998	III	216	344	5.0	USD2000/5 kg H_2 (low vol.) USD600/5 kg H_2 (high vol.)
Mitlitsky, F. et al. [202]	1999	IV	-	345	3.58	USD841/vessel (500 K)
Lipman, T. E. [200]	1999	-	-	350	-	USD500~600/vessel (10 K units)
Frederick W. DuVall [203]	2001	III, IV	12(D) × 37 in	350	-	USD580.23/vessel (wet) USD817.87/vessel (dry)
Riis, T. et al. [204]	2006	IV	-	350–700	-	USD500~600/kg H_2
Chalk, S. G. et al. [7]	2006	-	-	-	-	USD18/kWh (690 bar) USD15/kWh (345 bar)
Felderhoff, M. et al. [205]	2007	IV	260	700	4.2	USD2188
Villalonga, S. et al. [147]	2009	IV	37	700	1.5	USD650/vessel (100 K units)
Sun, Y. et al. [206]	2010	IV	-	700	-	USD25.9/kWh (1 K units) USD12.2/kWh (2.5 M units)
Leavitt, M [207]	2011	IV	125	700	-	USD20.80/kWh (10 K/year)
Propfe, B. et al. [208]	2012	-	-	700	-	USD383/kg
Fayaz, H. et al. [209]	2012	-	-	-	-	USD2188/vehicle (system)
K. Law et al. [38]	2013	III, IV	149	700	5.6	USD3490 (IV, 1-tank) USD3569 (IV, 2-tank)
Greene, D. L. et al. [210]	2013	-	-	-	5.3	USD8000~10,000
von Helmolt, R. et al. [201,211]	2014	IV	260	700	6.0	USD3600
Eudy, L. et al. [212]	2015	III	-	350	50	USD50,000/400 kg (American fuel cell bus)
Das, S. et al. [213]	2016	IV	-	700	5.6	USD1927
Johnson, K. et al. [214,215]	2017	IV	147.3	700	5.6	~USD2790/unit (100 K)
COPERNIC report [216]	2018	IV	149	700	5.0	USD656/kg H_2 (>8 K)
J. Adams et al. [196]	2019	IV	147	700	5.6	USD1100/tank (10 K) USD550/tank (100 K)
Silverman, L. [217]	2019	III, IV	80	350	-	USD930 (III, winding) USD932 (III, AFP) USD805 (IV, winding) USD827 (IV, AFP)
Villalonga, S. et al. [218]	2021	IV	-	700	-	USD766/kg H_2 (>10 K)
Yaïci, W. et al. [219]	2021	IV	-	700	-	USD15,000~17,500
Li, J. et al. [107]	2023	III, IV	-	350~700	-	USD3085 (III, 350 bar) USD3920 (III, 700 bar) USD2685 (IV, 350 bar) USD3488 (IV, 700 bar)

DuVall performed a cost analysis for Types II and IV hydrogen storage vessels [203]. The author quantified the cost parameters of wet filament winding, a process that impregnates resin during the manufacturing process, and dry filament winding, which uses towpreg fiber pre-impregnated with resin. In particular, the costs of wet and dry filament winding for Types II and IV vessels are detailed in the study. Although dry filament winding had lower labor costs, the material costs were higher. However, after considering profitability over a certain period, it was concluded that the dry filament winding process using pre-impregnated towpreg generates an additional profit of USD9000 per month compared with the wet process. Although there are limitations in the direct comparison between Type II and Type IV, as well as limitations related to the process variables, the study is significant for being the first to compare the costs of the wet and towpreg filament winding processes. Riis, T. et al. [204] analyzed the cost of hydrogen storage to be USD500–600 per kg of hydrogen stored. Chalk, S. G. et al. [7] analyzed the current cost levels of various storage methods, with 350 bar compressed gas storage tanks costing USD15/kWh and 700 bar tanks costing USD18/kWh. Von Helmolt, R. et al. [211] conducted a comparative cost analysis of the FCEV Chevrolet Equinox Fuel Cell vehicle, gasoline powertrains, and battery electric vehicles. In their opinion, FCEVs were inferior in many respects in 2007 but could become viable if renewable energy sources were used. Villalonga, S. et al. [147] estimated the cost of producing 100,000 units per year of a 1.5 kg hydrogen storage, 37 L, Type IV, 700 bar hydrogen storage tank to be USD650, but did not provide detailed costs. Sun, Y. et al. [206] calculated the cost of a hydrogen storage tank under scenario 3, in which a hydrogen pressure vessel needs to store approximately 4 kg of hydrogen to achieve a driving range of 300 miles according to the Federal Urban Drive Schedule. The derived cost was USD1900, that is, approximately USD12/kWh. They also proposed an equation to calculate the cost for a pressure vessel operating at 690 bar.

$$H_2 \text{ tank cost (2005 constant USD)} = 467.76 \times \text{full tank } H_2 \text{ fuel (kg)} + 50, \quad (11)$$

According to the report [220] by the COPERNIC (COst and PERformaNces Improvement for Cgh2 composite tank) project, which started in 2013 and ended in 2016 [198], the current cost of the hydrogen storage tank system is USD3281/kg H_2. It is predicted that through the optimization of composites to reduce the cost of the hydrogen storage tank system, a cost reduction of 13% and an increase in the tank's internal volume by 40% from 37 L to 61 L can be achieved. If the annual production reaches 8000 units, the target value of USD656/kg H_2 can be achieved. Here, the gravimetric capacity is 4.99%, and the volumetric capacity is 0.0221 kg/L. Greene, D. L. et al. [210] studied the cost of automotive fuel cells through various paths. Interviews with automotive OEMs showed that the power train accounts for 80% of the total cost of the vehicle. The cost composition of the power train is as follows: 30–35% for the stack, 15% for the BOP, 20% for the motor/controller, 5% for the battery, and 20–25% for the hydrogen tank and pressure regulator.

For example, if the vehicle price is assumed to be USD50,000, the cost of the tank and pressure regulator is estimated to be 20–25% of the total, which is USD8000–10,000. They also mentioned that the cost of a 5 kg hydrogen capacity pressure vessel is USD3828, according to BMW's public data, which is approximately USD766/kg H_2 when converted to 1 kg of hydrogen. Johnson, K. et al. [214] conducted a detailed cost analysis of an onboard 700 bar compressed hydrogen tank for the annual production of 30 K, 80 K, 100 K, and 500 K. Amica, G. et al. [221] predicted the tank cost to be USD5300–6700/vehicle in a critical review, and Villalonga, S. et al. [218] estimated a cost of USD766/kg H_2 based on an annual production of 10 K, as shown in Table 13.

Table 13. European FCH-JU target for the compressed H_2 storage system (CHSS) [218].

Key Performance Indicators for Onboard Compressed H_2 Storage System (CHSS)	Unit	2012	2017	2020 (Old)	2020 (Revised)	2024	2030
Cost	USD/kg H_2	>3281	875	656	547	438	328
Cost reduction/2020 revised cost	%	<−500%	−60%	−20%	-	20%	40%
Volumetric capacity	kg H_2/L of CHSS	0.02	0.022	0.023	0.23	0.033	0.035
Gravimetric capacity	kg H_2/kg of CHSS	<4	4	5	5.3	5.7	6

EUR to USD exchange rate (USD1.0938/EUR).

Mourad, N. et al. [222] compared the costs by type. According to the 2015 International Energy Agency (IEA) technology roadmap, as shown in Table 14, the cost of hydrogen storage tanks was predicted to be USD600/kWh (USD4300/vehicle) in 2015, USD14/kWh (USD3100/vehicle) in 2030, and USD13/kWh (USD2800/vehicle) in 2050, based on a storage capacity of 6.5 kg per vehicle. Based on the literature review of the cost of hydrogen storage tanks, it is difficult to make a fair comparison owing to differences in the range of analysis depending on the cost source, but as of 2020, the DOE target cost was USD333/kg H_2, and the COPERNIC standard was USD547/kg H_2. The 2020 DOE target cost of a hydrogen storage tank that stores 5.6 kg of H_2 per passenger car based on the normalized cost per vehicle was USD1864.8/vehicle, whereas the COPERNIC standard was USD3063/vehicle. According to Johnson, Kenneth, et al. [214], the cost was estimated to be USD2950/vehicle based on an annual vehicle production of 100 K, whereas J. Adams et al. [196] estimated it at USD2950/vehicle. However, the cost analysis results may vary depending on whether the BOP part or other parts are included, but the difference should not be significant.

Table 14. Techno-economic parameters of FCEVs as computed for the model in the United States [223].

		2015	2030	2050	Unit
FCEV costs		60,000	33,600	33,400	USD
Thereof	Glider *	23,100	24,100	25,600	USD
	Fuel cell system **	30,200	4300	3200	USD
	H_2 tank **	4300	3100	2800	USD
	Battery **	600	460	260	USD
	Electric motor and power control **	1800	1600	1400	USD
Specific costs	Fuel cell system (80 kW)	380	54	40	USD/kW
	H_2 tank (6.5 kg H_2)	20	14	13	USD/kWh
	Battery (1.3 kWh)	460	350	200	USD/kW
Other parameters	Tested fuel economy	1.0	0.8	0.6	kg H_2/100 km
	Lifetime	12	12	12	Years

Note: The USA DOE Fuel Cell Technology Office Record 13010 suggests total system costs of the 70 MPa hydrogen tank of USD33 per kWh at annual production rates of 10,000 vehicles, dropping to about USD17 per kWh at annual production rates of 10,000 vehicles. A tested fuel economy of 0.8 kgH_2 per 100 km has been reported for the Toyota Mirai (Toyota, 2015). The assumed tested fuel economy for today's FCEVs in the United States is higher based on the assumption that PLDVs are generally larger in the United States compared to Japan. They are in line with the results provided in the NREL FCEV demonstration project report (NREL, 2012). * Future cost increase is due to lightweighting, improved aerodynamics, low-resistance tires, and highly efficient auxiliary devices. ** Future costs are based on learning curves with learning rates of 10% (H_2 tank), 15% (electric motor, power control, battery), and 20% (fuel cell system) per doubling of cumulative deployment.

The application cost of the hydrogen storage tank for heavy-duty trucks is still in the early stages; hence, there is limited literature available. However, Vijayagopal, R. [224] predicted it to be similar to light-duty vehicles, including passenger cars. According to Sharpe, B. et al. [73], 59% of the total truck cost is accounted for by fuel cell propulsion and 18% by the hydrogen storage system cost. This suggests that a cost reduction in the hydrogen storage tank is necessary for its wide applicability.

4.2.3. Reduce Raw Materials

A large part of the cost components of a hydrogen storage tank comprises material costs, with carbon fiber being the costliest. The carbon fiber cost varies depending on usage, physical properties, country of production, and technological advancements, but its proportion of the total hydrogen storage tank cost has been analyzed to be 62% by Stetson, N.T. [225], 45% for 10 K production and 62% for 500 K production by James, B.D. et al. [194], 52% for 100 K production by Adams, J. et al. [196], and approximately 50% by Winter. Methods to reduce the cost proportion of the hydrogen storage tank include using low-cost carbon fiber to manufacture the tank and optimization of the design to reduce absolute usage. Design optimization will be covered in Section 4.2.4; this section will review the literature related to the trends in low-cost carbon fibers and cost reduction studies according to the type of carbon fiber.

A cost analysis of the currently produced Type IV hydrogen storage tanks shows that the carbon fiber layer, which accounts for more than 75% of the tank's cost, has the highest cost expensive, and 50% of the manufacturing cost of carbon fiber originates from the precursor [141,185]. Carbon fibers are produced by companies such as Toray Industries, Inc., SGL Carbon, MCCF, Teijin Ltd., and Hexcel Corp. [226,227], and their market price varies based on the manufacturer, performance, and country [137,228].

Choi et al. [229] reviewed the technological advancements for reducing the cost of carbon fiber precursors and new precursor materials. The proposed precursor materials are textile PAN [230], meltable PAN [231], lignin [232], polyethylene [226], and pitch [233]. As shown in Table 15, the authors proposed that textile PAN could reduce the carbon fiber cost by 31–39%, lignin cost by 41%, and polyethylene cost by 38%. The DOE and ORNL have run programs to reduce the carbon fiber cost [234], and achieved a 50% reduction in the overall cost and a 60% reduction in the energy cost [235]. However, there have been no cases of the application of these cost-reduced carbon fibers to hydrogen storage tanks.

Table 15. Low-cost carbon fiber precursor materials.

	Textile PAN	Meltable PAN	Lignin	Polyethylene	Pitch
Cost reduction relative to commercial PAN carbon fiber (USD25.7/kg) [227].	31–39%	-	41%	38%	-

Toyota initially used expensive carbon fibers employed in aviation and other applications for manufacturing its hydrogen storage tanks but subsequently reduced the tank cost by replacing the material with a new type of carbon fiber with aero-grade performance [60].

Researchers found that during the manufacturing process of the hydrogen storage tank, optimizing the hoop winding can reduce the composite material layer cost by 5%, using doilies [43,236,237] can decrease the weight of 10% of the composite material layers, and using separately manufactured endcaps fabricated using the RTM method can reduce the weight of the composite material layer by 10% [238]. This will be discussed in greater detail in Section 4.2.4. Although these processes have the problem of requiring endcaps or doilies during the liner manufacturing process and filament winding process, they provide an effective way to reduce the cost-heavy composite layer. The use of towpreg, where resin is impregnated into the carbon fibers in advance, is a viable option. Several studies have analyzed hydrogen pressure vessels made with towpreg [239,240]. However, the high cost [241] remains a challenge compared with the process advantages. DuVall, F. [203] assumed the price of towpreg to be 1.27 times that of carbon fiber, but reducing the cost is key [55,241,242]. Although the manufacturing process of low-cost towpreg is being studied in various ways [242,243], the currently available towpreg is not economical because the company's mark-up is added to the cost of the carbon fiber. Therefore, there are efforts to mass-produce hydrogen tanks by manufacturing towpreg within the facility and using it immediately to fabricate the tank [244]. Sofi, T. et al. [176] divided the filament winding types into dry, wet, and prepreg winding, but in this paper, we classified the method using towpreg as dry and summarized the advantages, disadvantages, and main features in Table 16. Weisberg, A. et al. [186] found that using dry towpreg can reduce the time spent during traditional wet filament winding from 3 h to 10 min.

Another approach is to use low-density, low-cost resin [214,245]. The density of commonly used epoxy resin is 1.25 g/cm^3, and when made into a composite layer, the density is 1.58 g/cm^3 [240]. By applying polyester, which is relatively low in density (1.25 g/cm^3) and cost, as the resin system [245] and manufacturing it into a full-sized tank, the resin requirement decreases by 6.08–8.7 kg, and the total weight reduction is 9%, which leads to cost savings for the hydrogen storage tank.

Table 16. Comparison of dry and wet winding.

	Dry (Towpreg) Winding	Wet Winding
Impregnation with resin	• Impregnated during the winding process	• Prior to the winding process
Advantage [176]	• Lower raw material costs • Simplified material storage	• Lower raw material costs • Simplified material storage
Disadvantage [176]	• Higher material costs • Material storage and handling	• Less control over resin content variability • Resin dripping and resin accumulation • Trade-off between quality and speed • Poor external finish
Winding speed [246]	1 m/s, 0.02 kg/s	20 m/s
Composite costs [240]	USD18 per kg composites	USD37 per kg composites

4.2.4. Structural Design Optimization and Alternative Process Approach

Design optimization through numerical simulation can achieve an optimal weight reduction in the hydrogen storage tank and significantly reduce its cost [247]. Table 17 summarizes the literature related to cost reduction through design optimization.

Hydrogen pressure vessels must have two important features: burst pressure and better weight performance [247]. FCEV manufacturers have increased the operating pressure of the initial onboard hydrogen storage tanks from 350 bar to 700 bar, thereby reducing the weight by more than 20% and increasing the energy content by more than 55%, resulting in cost savings [248,249]. Zhou, W. et al. [237] attempted to optimize the design of the hydrogen storage tank by optimizing the liner, boss, and composite layer. Liner optimization involved considering the types of materials used, the radius of the cylinder, thickness, and dome shape depending on the type of hydrogen storage tank. The parameters of the composite layer for fabricating the cylinder were thickness, sequence, winding angle, and winding technology, whereas those for the dome were geometry, thickness, and structure. In addition, optimization methods using doilies and the like during reinforcement were studied. In this section, the results of the optimization study were quantified from a cost perspective.

The liner is an essential component of hydrogen pressure vessels, except Type V. To meet the sealing and fatigue performance requirements of hydrogen storage vessels, Type III uses aluminum and Type IV uses polymer materials. There has been limited research on the cost reduction for liners. He, C. et al. [250] suggested that a lightweight optimal design of the liner based on the shear field theory through a digitalized 3D auto fiber placement technique could enable lightweight design and reduce the production cost of hydrogen storage tanks. However, there are no reports on the extent of cost savings compared with conventional methods.

Table 17. The summary of design and cost optimization work.

Authors	Year	Purpose (Model, Optimization Parameter, Software)	Results
Xu, P. [251]	2010	The weight minimum optimization (3D eight-node solid element SOLID95, ANSIS)	The optimal configurations are h: 1.38 mm, r: 30 mm, w: 7.73 kg, and P: 164.52 MPa
Yumiya, H. et al. [69,252]	2015	(1) The shape of the liner (2) The boundary regions were strengthened (3) Hoop winding lamination was concentrated in the inner layers	Reduced the amount of CFRP by 20 wt%

Table 17. *Cont.*

Authors	Year	Purpose (Model, Optimization Parameter, Software)	Results
He, C. et al. [250]	2016	Metal lining reinforcement with shear field theory (1/4 finite element mode) (ANSYS)	Lightweight optimization design largely at a round section hydrogen storage tank
Alcantar, V. et al. [253]	2017	Weight minimization of Type IV 1400 mm(L), 465 mm(D), 5.6 kg H_2 (SOLID191, ANSYS)	Reducing the weight by up to 9.8% and 11.2% compared to previously published vessel optimization research
Sharma, P. et al. [254]	2020	Netting analysis (1) Clairault equation (2) Maximum principal stress (3) Manufactured prototype (4) (ANSYS)	Models 1, 2, and 3 have reduced the composite from 35 kg to 30.5 kg, 23 kg, and 28 kg, respectively (Type III, 350 bar)
Hu, Z. et al. [255]	2021	Dome reinforcement (DR) technology to reduce carbon fiber (ABAQUS)	The dome reinforcement (DR) technology can help to reduce the consumption of carbon fiber by up to 5.5% in composite material
Cevotec [256]	2021	Automated dome reinforcements with fiber patch placement yield 15% improvements in weight and cost (ABAQUS)	Weight: −16% Cost: −11% Process time: −16%
Sharma, P. et al. [257]	2022	Dome shape on burst pressure, failure characteristics, and weight performance of the vessel (Type III) (ABAQUS, ANSYS)	Hydrogen storage kg per 1 kg vessel (hemispherical 0.03116, paraboloid 0.03094, ellipsoid (I) 0.03142, ellipsoid (II) 0.03143, ellipsoid (III) 0.03116, and isotensoid 0.03138)

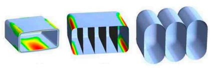
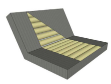
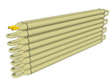
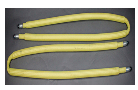
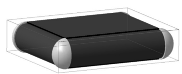
Regarding cost reduction for the composite layer, Sharma, P. et al. [257] studied the volume, weight, and weight performance after classifying it into six types (hemispherical, paraboloid, ellipsoid(I), ellipsoid (II), ellipsoid (III), and isotensoid) based on the dome shape. Although detailed cost data are not available, they proposed an approach to increase the weight performance of hydrogen storage tanks. Research has been conducted to save carbon fiber by introducing doilies, which provide local reinforcement in the dome part [193]. By applying AFP reinforcements to the dome part in a separate line and integrating them with the second stage of producing the main vessel, an 11% cost reduction and 15% material savings were achieved [258]. Kartav, O. et al. [259] did not report on cost savings through the use of doilies but improved the burst pressure by 29%.

Cevotec [260] developed and commercialized a process that reduced material use by 15% using the fiber patch placement (FPP) method. Leh, D. et al. [261] reduced the weight by 30% through the optimization of the composite stacking sequence. Alcantar, V. et al. [253] reduced the weight of a 700 bar Type IV vessel with a diameter of 521 mm by 9.8–11.2% by applying a genetic algorithm (GA) and simulated annealing (SA). Hu, Z. et al. [255] reduced the use of carbon fiber by 5.5% by researching dome reinforcement (DR) technology. Additionally, research is being attempted on low-cost alternative methods for the filament process. Dionoro, G. et al. [262] researched Robotic Filament Winding (RFW) methods, which have high process costs. Further, the US DOE hydrogen program achieved a 20% cost reduction with general filament winding and hybrid AFP/FW methods [258]. Recent research trends have proposed hydrogen pressure vessel-based methods that use environmentally friendly thermoplastic tape [263] in laser-assisted tape winding (LATW) [264], which has replaced the filament winding method, the braiding method that creates a carbon fiber layer on the liner and uses resin impregnation, and the HP-RTM method [179,265].

Moreover, Air, A. et al. [43] stated that the cost could be affected if the above methods are combined with the AFP method of the linerless hydrogen storage tank (Type V).

In comparison with the FCHV-adv [266] sold in 2002, Toyota has reduced the cost by 15% for the Mirai [266] released in 2014 by optimizing [69,252] the composite layer and boss [60]. In the filament winding process, low helical winding, high helical winding, and hoop winding account for 72%, 17%, and 9%, respectively, of the total winding time [267]. Accordingly, they eliminated the high-angle helical winding in the composite lamination method and focused on the inner layers where the generated stress is high. Thus, they reduced the weight of the composite layer by approximately 20% and achieved up to 5.7 wt% of hydrogen storage capacity. Additionally, they examined the possibility of boss optimization and managed to reduce the helical winding layer by approximately 5%. Regarding alternative process approaches, the existing strategies for increasing the gravimetric and volumetric storage capacities of hydrogen storage tanks from their current levels involve two approaches [191]. The first approach, the "cryo-compressed" or "liquid hydrogen tank" storage method, is not discussed in this review paper. The second approach is the development of a conformable tank. The conformable tank allows improved space utilization [268,269] and is attractive for its compatibility with existing EV vehicles and platforms [270]. According to a study on space utilization of cylindrical tanks and conformable tanks depending on the aspect ratio [271], a conformable tank can achieve over 80% space utilization, making it an effective method for increasing hydrogen density. As shown in Table 18, research on conformable tanks has been ongoing since the late 2000s, but it remains in the conceptual research stage or prototype stage of TRL 3–4. Recently, active research has been conducted as part of the BRYSON project in Europe.

Table 18. Development status of conformable hydrogen storage tanks.

Authors	Year	Tank	Pressure	Concept	Results
Haaland, A. [272]	2000		345 bar (5000 psi)	Two-cell comfortable tank	Burst pressure of 755 bar (10,950 psi)
Weisberg, A. et al. [273]	2005		345 bar (5000 psi)	Flat ends (pillow tank)	Volumetric efficient over 75%
Aceves, S. M. et al. [268]	2006		690 bar (10,000 psi)	Macro lattice and replicant concepts	20~40%
Erik Bigelow [274]	2015		700 bar	Conceptual conformable storage	Target (5.6 kg, 140 L); cost: USD8.40/kWh
Aceves, S. M et al. [275]	2016		700 bar	Kevlar over-braided coiled vessel	Improved packaging onboard vehicles; bust test: 2345 bar
Bigelow, E. et al. [276]	2018		700 bar	Kevlar over-braid	Manufacturing time: 38 min; cost: USD1424 (cylinder type: 7~10 h)
BRYSON project [277]	2020		700 bar	Based on the braiding of thermoplastic tapes	-
Öztas, K. A. et al. [270]	2022		-	Box-shaped type with inner tension struts	5.71 kg H_2, 1.78% 322 kg (material)
Forvia company [278]	2023		~700 bar	Hydrogen storage in a box "cartridge" system	Prototype stage

5. Conclusions

With growing interest in global climate change, governments, organizations, and institutions worldwide are increasingly adopting agreements such as the Paris Agreement. An attractive fuel option for addressing climate change and realizing a green economy is hydrogen energy, which can greatly reduce our carbon footprint.

The main aspects of the hydrogen economy are production infrastructure, distribution networks, storage technology, and power converter technology. Thus, a major challenge for the hydrogen economy is the well-to-wheel cost from production to final power conversion. In this regard, hydrogen storage technology is a core technology that enables essential and sustainable hydrogen energy development for achieving a hydrogen economy in the future. Both mobile and stationary hydrogen storage systems are necessary for the hydrogen economy to thrive. In particular, onboard hydrogen storage tanks, representing mobile hydrogen storage technology, are already being applied to passenger cars by automotive companies such as Hyundai, Toyota, and Honda. Moreover, in the transportation field, they have great potential for application to heavy-duty trucks and other vehicles that have less spatial constraints and can carry more load than vehicles with batteries. For the sustainability and diverse expansion of hydrogen storage tanks, they must be safe and inexpensive. As discussed in this review, the literature survey results on the cost analysis and reduction strategies for hydrogen storage tanks reveal that the cost structure of hydrogen pressure tanks depends on the utilization of expensive carbon fiber, and the filament winding process remains a major cost driver and a key challenge.

In particular, hydrogen is stored in rapidly refillable onboard tanks, meeting the driving range needs of heavy-duty applications, such as regional and line-haul trucking. Customers might need hydrogen's rapid refueling advantage and hydrogen fuel cells, which are currently the closest alternative to diesel engines for heavy-duty truck applications. Nevertheless, fuel cell vehicles are not yet commercially attractive, and there are opportunities to enhance the market penetration and expand the market share in the future. One of the most important factors for fuel cell vehicles to be successful in commercialization is their cost-effectiveness. At the mobility system level, the cost is low, and the technological development of lighter storage solutions is a critical point. However, most research is focused on technological development for hydrogen storage. Therefore, technology development must be performed simultaneously with technology, safety, and cost reduction research. In addition, the whole-life cost analysis and the application of sustainable circular economy-based materials, such as recycling carbon fiber, towpreg, and thermoplastic polymers, are essential in the field of materials that account for most of the cost. In order to solve these problems, it is expected that additional research will be conducted to optimize the cost of storage tanks and performance to improve processes. Ecofriendly, advanced, and next-generation materials have a notable effect on cost.

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