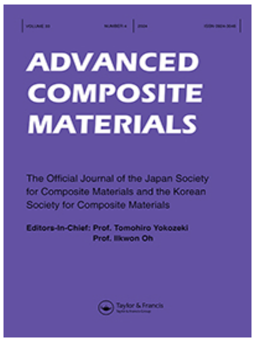

Advanced Composite Materials

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tacm20

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To cite this article: Hyun Kyu Shin & Sung Kyu Ha (2024) Techno-economic analysis of type III and IV composite hydrogen storage tanks for fuel cell vehicles, Advanced Composite Materials, 33:4, 527-559, DOI: 10.1080/09243046.2023.2278258

To link to this article: https://doi.org/10.1080/09243046.2023.2278258

Published online: 01 Dec 2023.

Advanced Composite Materials, 2024
Vol. 33, No. 4, 527–559, https://doi.org/10.1080/09243046.2023.2278258

Techno-economic analysis of type III and IV composite hydrogen storage tanks for fuel cell vehicles

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(*Received 31 August 2023; accepted 27 October 2023*)

The hydrogen gas storage tank market includes passenger cars and heavy-duty trucks. However, there is insufficient economic analysis of these tanks, which is the key element for achieving market expansion. Theoretical studies have investigated the cost of carbon composites in automotive and aerospace applications and hydrogen storage tanks. However, there is insufficient analysis based on actual technological and cost data. Moreover, there is limited analysis of the material, labor, and expense costs and equipment investments based on production quantities. The objective of this study is to analyze the costs related to hydrogen tanks in passenger cars and heavy-duty trucks on the basis of the manufacturing technologies, tank volume, type, and annual production. Furthermore, this study uses a cost – profit modeling approach to identify the cost, price, investment, and key cost drivers and provide target costs, effective manufacturing technologies, and strategies to meet the demands of the hydrogen tank market.

Keywords: Cost analysis; cost modeling; carbon composites; hydrogen storage tank; fuel cell vehicles

Introduction

Reduction in greenhouse gas emissions is a crucial aspect of preventing global warming. Hydrogen has significant potential as a zero-carbon energy source, and it is easily stored and utilized in various applications, particularly transportation. Hydrogen energy can be used to reduce reliance on fossil fuels and develop green energy systems in the transport, thermal, industrial, and electrical sectors, which account for two-thirds of the global CO_2 emissions [1].

Hydrogen-based energy systems have emerged as alternatives to fossil fuels, particularly for transportation, including hybrid electric vehicles, electric cars, and other forms of transportation, and for portable applications [2,3]. Hydrogen fuel cells provide a viable solution for heavy-duty vehicles that require high energy densities and fast refueling capabilities, making them suitable for long-range and high-utilization scenarios [4,5]. The global hydrogen industry experienced a growth rate of 3.06%, where the total number of hydrogen units increased from 51,089 in 2014 to 59,403 in 2019. The hydrogen storage tank market is projected to reach a value of $3.5 million by 2027, exhibiting a compound annual growth rate of

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21.4% from 2020 to 2027 [6]. Hydrogen gas storage tanks are important components of hydrogen fuel cell systems. The earliest recorded design of such storage tanks dates back to Leonardo da Vinci's basic experiments in 1495, as documented in Codex Madrid [7]. Currently, most storage tanks are constructed using steel, although there is a growing trend toward utilizing composite materials reinforced with glass, aramid, and carbon fibers. Composite storage tanks fabricated from carbon fibers provide the advantage of being lightweight compared to conventional metal pressure tanks owing to the exceptional physical properties of carbon fibers. However, their manufacturing processes are challenging and complex [8,9]. Filament winding is a viable method for producing cylindrical structures using continuous carbon fiber composites [10]. This cost-effective and automated technique can reduce production costs, particularly in mass-production scenarios [11]. Consequently, cost analysis plays a critical role in the effective utilization of carbon fiber composite materials.

Costs are categorized into recurring, nonrecurring, direct, indirect, variable, and fixed costs [12]. Recurring costs are incurred as part of regular and ongoing business operations. They include administrative costs, debt, and other long-term costs that support business functioning. Nonrecurring costs are infrequent and occur because of extraordinary circumstances. Direct costs are specific and easily identifiable for a particular product or activity. Indirect costs are incurred for common purposes, and they are not easily or specifically identifiable for a particular product. Fixed costs are constant, regardless of the level of output or activity, whereas variable costs depend on the level of activity or output [13]. Costs are also categorized into relevant and irrelevant costs [14]. Relevant costs are pertinent to a specific decision, and the cost breakdown structure presented by Fabrycky et al. [15] can be used for cost classification. The total product cost, or life cycle cost, can be divided into four parts [16]: research and development, production and construction, operation and maintenance, and retirement and disposal costs. Moreover, costs should be derived based on the technology applicable to all options, regardless of the shape, process, or material used [17]. Qualitative cost estimation involves the comparison of existing and new products. In contrast, quantitative cost estimation does not rely solely on existing cost data or estimator knowledge but is based on a detailed analysis of product design, features, and manufacturing processes [18].

Process-based cost modeling (PBCM) was proposed by Cal Bloch in 1991. It is a suitable decision support tool for evaluating different technologies and processes. In this model, the costs for each process are calculated using input data such as the process flow, speed and yield of each process step, equipment cost, number of operations, machines, indirect labor, and plant parameters, including operator cost, indirect labor cost, overhead cost, space cost, number of shifts, and maintenance time [19]. The PBCM framework introduced by Field et al. [20] suggests that costs can be considered as a function of technical factors such as the cycle time, downtime, scrap rate, equipment, maintenance, tooling, or materials. These technological factors, including operational inefficiencies, determine the number of resources required to produce an output for a given technology input [21]. As the market for hydrogen tanks has expanded in recent years, the production of various materials and methods is being investigated. However, there is a lack of cost analysis studies.

This study aims to conduct a comprehensive cost analysis of hydrogen storage tanks with various volumes, types, and annual production capacities in the transportation field. It applies cost models to actual manufacturing data; identifies key cost drivers through parametric studies; evaluates materials, labor, energy, and investment costs; and presents fixed-cost investment costs and profit based on the annual production volume.

Literature review of cost analysis modeling

Cost analysis modeling for composites

The field of cost modeling for composite-based manufacturing processes is relatively small. Several models have been developed to estimate the costs of components fabricated from advanced composites, as shown in Table 1. These models include the 'Advanced Composites Cost Estimation Model (1976)' for government contractors [32]; the model developed by M. Akermo et al. [22] to estimate the cost of compression molded composites and sandwich components; and studies by Bader [23], Verrey et al. [33], Fuchs et al. [24], and Ye et al. [25], which explore the cost estimation and comparisons of different composite materials and manufacturing processes. Schubel [34] conducted the detailed technical cost analysis of a wind turbine blade [35] manufactured using the vacuum infusion process. Weiland et al. [36] developed a cost model for a helicopter rotor blade component based on the principles of activity-based costing. Hagnell et al. [27] developed a composite production cost estimation model for aeronautics wings. Ellringmann et al. [37] modeled the production cost of polyacrylonitrile-based carbon fibers using a modular design approach. In the context of filament winding, DuVall [38] conducted cost analysis for wet resin and preimpregnated tow fiber winding. Dionoro et al. [39] presented a cost estimation model for robotic filament winding, and Centea et al. [28] studied manufacturing cost relationships for vacuum-bag-only prepreg processing. Other studies have addressed topics such as carbon fiber recycling [29], automated tape layup, automated fiber placement processes [30], structural design trade-off, life cycle assessment [31] and costing frameworks for composite doors [40].

In summary, various researchers have developed cost estimation models and conducted cost analyses for different aspects of composite manufacturing, considering factors such as material, labor, equipment, energy, waste disposal, and transportation costs. These studies contribute to the understanding of cost implications and optimization of the manufacturing processes for composite-based products.

Cost analysis and target cost of hydrogen gas storage tanks

Various cost analyses and target cost proposals have been made for hydrogen storage tanks through modeling and parametric studies conducted by the US Department of Energy (DOE) and projects in Europe, such as the compressed H_2 storage system (CHSS) and COst & PERFormaNces Improvement for CGH2 (COPERNIC) composite tanks. The DOE [41] operates a hydrogen cost reduction program and has reported [42–46] its achievements in comparison to set targets. Since 2013, detailed analyses have been conducted on the performance and cost of type IV tanks. The goals for hydrogen storage tank systems [47], as estimated by the DOE, US DRIVE [48], and Villalonga et al. [49], were updated in 2009 [50] and 2017 [51], and the target objectives are shown in Table 2.

According to the COPERNIC project [53], which was conducted from 2013 to 2016, the current cost of a hydrogen storage tank system is €3,000/kg H_2. The cost is predicted to be reduced by 13% by optimizing composites, and the internal volume of the tank can be increased by 40% (from 37 L to 61 L). The target cost of €600/kg H_2 can be achieved

Table 1. Recent studies on cost modeling of composite-based manufacturing processes.

Authors	Year	Product	Cost modeling	Modeling, strengths and limitations
M. Akermo et al. [22]	2000	Tailgate	Fixed power cost = $\frac{Fuse(Equipment)}{1200} \times 52{,}000$ EUR/year, Labor cost = $\frac{\text{Labourrate}}{1200} \times \sum_{process} Dedication(i) Time(i)$,	• Modeling: Microsoft excel 5.0 modelled subprocesses. • Strength: thermoplastic cost analysis. • Limitation: material price is held constant a level corresponding to the current price.
Bader, Michael G. [23]	2002	Stiffening ribs	C_T (tool price) = P_T/N_T, C_L (total labor cost) = $t_h P_L/60$, C_P (operation cost) = t_p (P_p $(1/w + R_I/100)/(250 \times t_o) + P_o$), P_T: number of parts, N_T: a single tool set, t_h: total labor time, P_L: hourly labor rate, P_p: capital value, w: write off period, R_I: interest rate, t_o: daily operation time, P_o: hourly cost of plant, power etc.	• Modeling: cost as a sum of direct costs without specifying the methods. • Strength: cost analysis of various raw materials and processes. • Limitation: Indirect costs were not taken into consideration.
R. H. Fuchs et al. [24]	2008	Body-in-white	$C_{Tot} = \sum_q C_p$, s.t. q, ∈ Components; Assembly, C_{Tot}: the total unit cost, C_p: total unit cost output of one model.	• Modeling: two process-based cost modeling(component and assembly PBCM). • Strength: cost-feasibility of a new FRP BIW against to the steel. • Limitation: cost-of-ownership analysis for automotive application was not conducted.

(*continued*)

Table1. (*Continued*).

Authors	Year	Product	Cost modeling	Modeling, strengths and limitations
Ye, J. et al. [25]	2009	Wave beam	$C_{cost\_per\_part} = C_M + C_L + C_E + C_T$, C_M: material cost, C_L: labor cost, C_E: equipment cost, C_T: tooling cost.	• Modeling: manufacturing based cost model. • Strength: working procedure model has been presented. • Limitation: indirect costs were not taken into consideration.
Shehab, E. et al. [26]	2013	Skin Panel	Manufacturing cost = $(\sum Material\ Cost + \sum Support\ Material\ Cost) + (\sum DirectLabour\ Cost + \sum Indirect\ Labour\ Cost) + \sum Energy\ Cost + \sum Equipment\ Cost + \sum Tooling\ Cost + \sum Facility\ Cost$	• Modeling: Composites manufacturing Cost Estimator. • Strength: covered quality inspection(NDT). • Limitation: cost based on quantity was not analyzed.
Hagnell, M. K. et al. [27]	2015	Aircraft parts	$C_{Material} = C_{kg}W(1 + r_{waste})$, $T_{Cost}=T_{Base\ cost}\ C_M$, $t = L/r$, W: weight, r_{waste}: percent material waste rate, C_{kg}: prepreg cost/kg, $T_{Base\ cost}$: cost of a simple mold of the part projected area, C_M: average milling factor of involved part features, t: process step time, L: characteristic dimension (area, volume, length etc.), r: layup rate.	• Modeling: production cost by summarizing the cost of each process step. • Strength: cost analysis based parts size using AFP and ATL. • Limitation: only low-volume production.
Centea, T. et al. [28]	2016	Bag-only prepreg processing	$C_{total} = C_{labor} + C_{material} + C_{equipment}$ $C_{material} = C_{m,\ prepreg} + \sum_i t_{activity}$ $C_{labor} = W_{hourly}\sum_i t_{activity}$ $C_{equipment} = C_{depreciation} + C_{maintenance} + C_{electiricity}$	• Modeling: technical cost modeling. • Strength: a variety input data was utilized. • Limitation: no cost analysis based on production quantity.

(*continued*)

Table1. (*Continued*).

Authors	Year	Product	Cost modeling	Modeling, strengths and limitations
Meng, F. [29]	2017	Recycle carbon fiber	$MSP\ (minimum\ selling\ price) = \frac{OPEX+ACAPEX-OR}{AO}$ OPEX: operational cost ($/yr), ACAPEX: annualized capital cost (%/yr) OR: other revenue ($/yr), e.g. heat sales AO: annual output (t/yr)	• Modeling: life cycle costing. • Strength: cost and price analysis of carbon fiber composites. • Limitation: cost based on CF production quantity was not conducted.
Soares, B. A. et al. [30]	2019	Aircraft parts	$Mat_{cost} = C_{Kg} \times \rho_a \times surfa \times n°l \times NP_i$ $Labor = CT_i \times n°w_i \times ded_i \times w_{€i} \times NP_i$, $Building\ cost = \frac{a^{O}j\ EqCostji \times SfAreai \times Alloci}{SfArea \times NPi}$, ρ_a: prepreg density per area, $surfa$: part surface area, $n°l$: number of layers, NP_i: number of parts, CTi: part cycle time, $n°w_i$: number of workers, ded_i: percentage of their dedication, $w_{€i}$: average wage per time, $EqCost_{ji}$: residual value of building, $SfAreai$: area occupied by the infrastructure of the manufacturing process i $Alloc_i$: percentage of occupied by production of the part, $SfArea$: global shop-floor area.	• Modeling: process based cost modeling. • Strength: a detail cost analysis was conducted regarding the scrap during process. • Limitation: limitation to the cost analysis for small quantities per year.
Wu, M. et al. [31]	2023	Composite door	Production cost = $\sum Material\ Cost + \sum Labour\ Cost + \sum Energy\ Cost + \sum Scrap\ treatment\ Cost + \sum Equipment\ Cost + \sum Tooling\ Cost + \sum transport\ Cost$	• Modeling: integrated life cycle assessment (LCA) and life cycle costing (LCC). • Strength: integrated environmental and economic performances. • Limitation: limitation to the cost analysis for small quantities(100 parts).

Table 2. Target cost of hydrogen storage system of DOE and European FCH-JU target for CHSS.

Storage system target	DOE [52]			CHSS [49]		
	2020	2025	Ultimate	2020	2024	2030
System gravimetric capacity (wt%)	4.5	5.5	6.5	5.3	5.7	6.0
System volumetric capacity (g H_2/L)	30	40	50	23	33	35
Cost ($/kWh)	10	9	8	16	13	10
Cost ($/kg H_2)	333	300	266	547	438	328

if the annual production reaches 8,000 units. The gravimetric and volumetric capacities are 4.99% and 0.0221 kg/L, respectively. It should be noted that although various attempts have been made to analyze the cost of composite materials and hydrogen storage tanks over the past few decades, there is limited application of these findings to actual production costs because they are mostly theoretical studies focused on manufacturing costs.

Types and manufacturing process of hydrogen storage tanks

Types of hydrogen storage tanks

There are four types of hydrogen tanks in vehicles [54,55], as listed below. Another type has been recently introduced by Composite Technology Development, Inc.: i.e. composite pressure tanks without liners [56–59]. In this study, we classify type IV tanks into type IV-a and IV-b tanks according to the overwrap material.

- Type I: All metal construction.
- Type II: Metal with a hoop composite overwrap.
- Type III: Metal liner with a full composite overwrap. Composite carries all load.
- Type IV: Polymer liner with a full composite overwrap.
- Type IV-a: Polymer liner with a full composite overwrap (wet winding process).
- Type IV-b: Polymer liner with a full composite overwrap (dry winding process).
- Type V: Liner-less composite.

Type I refers to fully metal pressure tank. Type II represents a metal tank with composite overwraps on its cylindrical portion. Type III is a metal liner tank with full carbon fiber or glass fiber overwraps. In type II and III tanks, the load is shared between the liner and composite layers. Type IV features a plastic liner tank with full carbon fiber and/or glass fiber overwraps. In this study, type IV tanks are divided into types IV-a and IV-b according to the filament winding process. Type IV-a tanks use a wet filament winding process to fully apply carbon fibers over the plastic liner, whereas type IV-b tanks use a dry filament winding process. Finally, type V tanks are entirely fabricated from carbon or glass fibers without any liner, as shown in Figure 1.

Common reinforcement materials used in tanks include carbon fibers, glass fibers, and hybrid structures with epoxy or vinyl ester resins. All tank types are suitable for use as hydrogen tanks, and the selection depends on the technical performance, cost considerations, and application. Type I tanks are suitable for industrial gases with pressures ranging

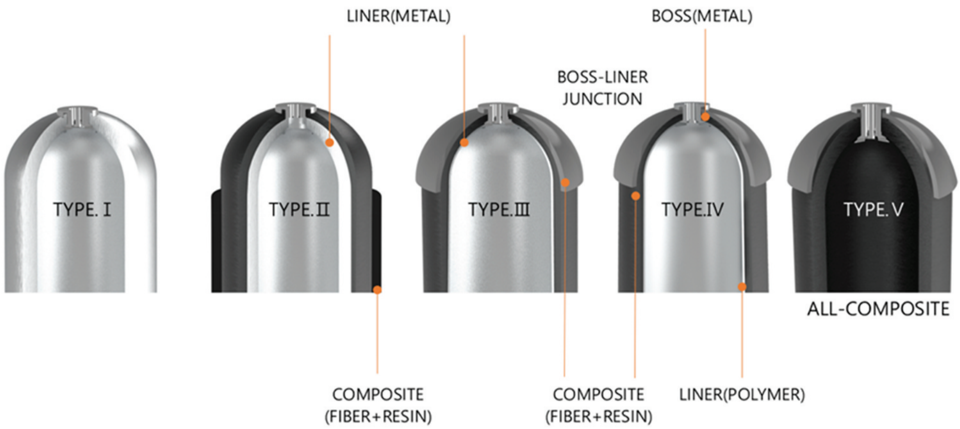


Figure 1. Types of hydrogen storage tanks.

from 150 bar to 300 bar. These tanks are the most inexpensive but the heaviest. Type II tanks are preferred for higher pressures compared to Type I, and they are suitable for stationary applications owing to their weight. Type III and IV tanks are mainly used in portable applications, where low weights are crucial. The low density and high strength of carbon fibers allow for the fabrication of thin and strong hydrogen storage tanks. However, carbon fibers have the drawback of being expensive, and the high-speed composite fabrication process poses challenges [60]. Type III and IV tanks are considerably expensive [61]; this has led to ongoing research on cost-effective approaches for manufacturing tanks. Currently, hydrogen storage tanks are commercially used in passenger cars. Tanks with a pressure of 700 bar are typically used in the initial stage. The number of tanks depends on the vehicle layout, and two or three tanks are used. Type IV tanks manufactured using the wet winding method are generally used for this purpose [62]. Several fuel cell vehicles have been introduced, such as Hyundai Tucson i×35[63] (produced in 2013), which stores 140 L and 5.64 kg of hydrogen in two tanks. The 2021 model of Toyota Mirai [64–66] (produced in 2014) stores 142.2 L and 5.6 kg of hydrogen in three tanks. Honda Clarity [67–69] (launched in 2016) stores 5.46 kg of hydrogen in two tanks. Mercedes-Benz CLS (launched in 2017) [70,71] stores 4.4 kg and 117 L of hydrogen. The 2018 model of Hyundai Nexo [72,73] stores 156.6 L and 6.33 kg of hydrogen in three tanks [62,72–74]. Hyundai Xcient, which is a hydrogen-powered fuel cell truck, underwent a 2 year test run starting from October 2020 and covered 5 M km in Switzerland. Full commercial sales of Xcient commenced in December 2022 [75–78]. Figure 2 shows the schematic of hydrogen gas storage tanks.

Manufacturing process

The filament winding process is crucial for manufacturing hydrogen tanks. Glass, aramid, and carbon fibers can be used in this process. Carbon fibers are preferred as reinforcing fibers in hydrogen tanks because of their high tensile strength. Carbon fibers can be categorized into different types based on their moduli and strength [67]. In this study, high-tensile-strength type (HT) carbon fibers with a strength more than 3 GPa are utilized for manufacturing type III and IV-a tanks. In addition, a towpreg fabricated from HT-type carbon fibers is used [82]. The general manufacturing process for a hydrogen tank is shown in Figure 3.

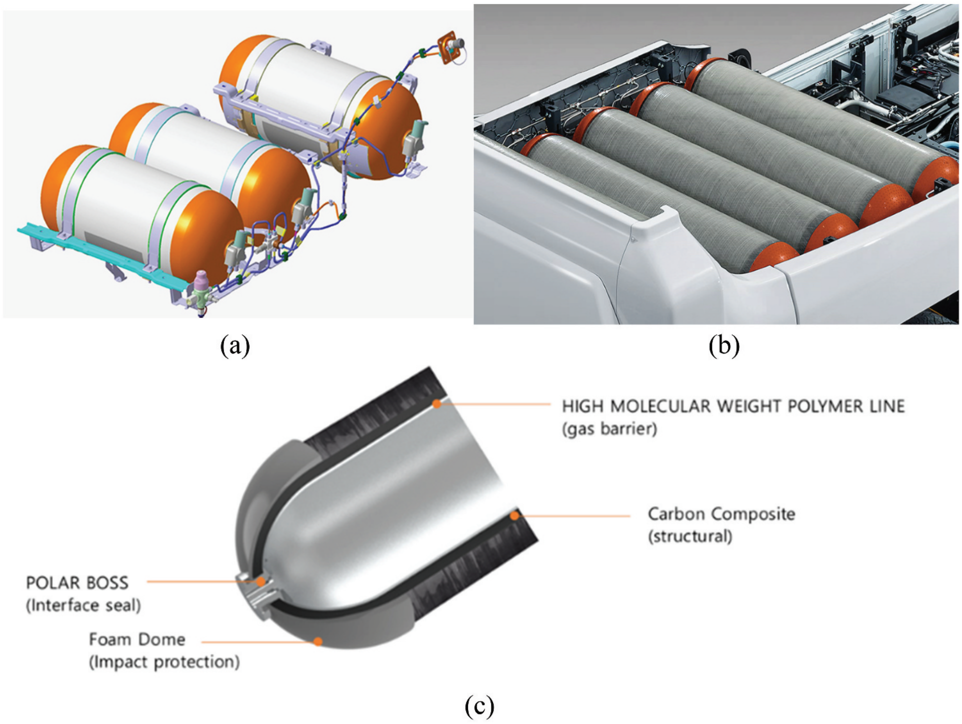


Figure 2. Fuel cell vehicle and hydrogen gas storage tanks: (a) 52 L tank for passenger cars [79]; (b) 175 L tank for heavy-duty trucks [80]; (c) schematic of hydrogen gas storage tanks [81].

The initial step is the fabrication of a metal or plastic liner. Type III tanks employ aluminum 6061 alloy as the liner, whereas type IV-a and IV-b tanks use plastic materials such as high-density polyethylene (HDPE) or polyamide (PA6) [83,84]. The next step is to prepare a stationary rotating mandrel. Carbon fibers are wound around the mandrel using a combination of hoop, helical, and polar winding at a specified speed. The most effective approaches for reducing costs include minimizing the use of expensive carbon fibers, which constitute a significant portion of the cost, and reducing the winding time, which is a high-cost process. High-speed winding provides the highest potential for cost reduction by increasing fiber throughput in manufacturing and curing machines [42]. In type IV-a tanks, the speed of the wet winding process is limited by resin absorption by fibers. Winding speeds vary from 1–2 m/s to 10 m/s depending on the part [75]. However, type IV-b tanks employ towpregs and achieve extremely high winding speeds (20 m/s) [42]. The composites are placed in a curing oven and heated to the appropriate temperature for resin curing, and then, the mandrel is removed. The finished tank undergoes inspection and testing to ensure its quality and safety, such as hydraulic and gas leak tests, followed by the assembly of the final balance-of-plant (BOP) components.

Liner manufacturing process

Metallic and nonmetallic liners are used in hydrogen tanks. Type I, II, and III tanks contain liners fabricated from metal or aluminum alloys, whereas type IV tanks

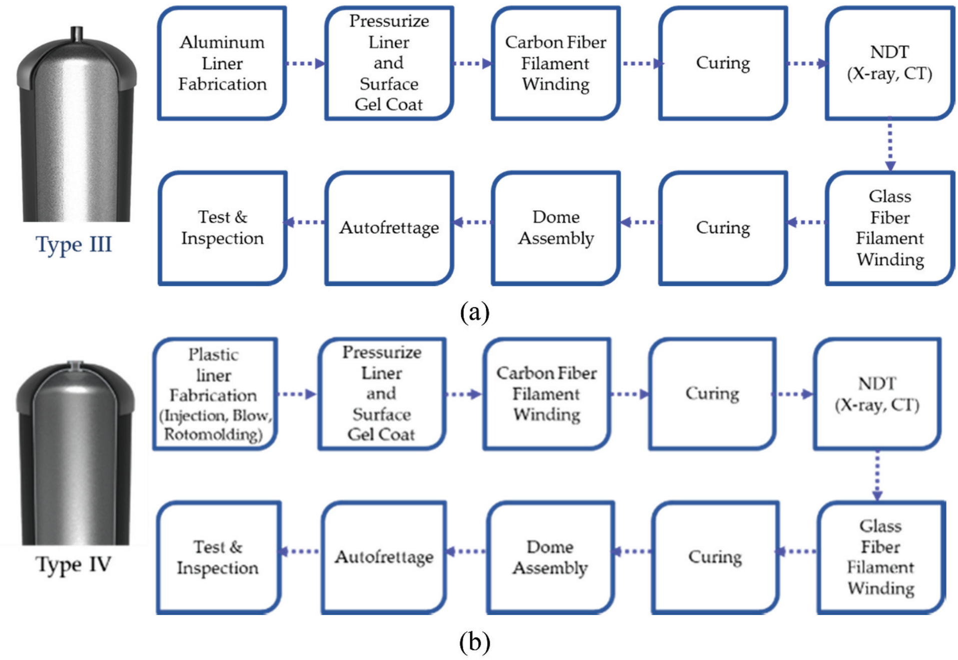


Figure 3. Manufacturing process diagram of hydrogen tanks: (a) type III; (b) type IV-a; type IV-b.

contain plastic liners. Type III and IV tanks are the most commonly used for hydrogen storage in vehicles [76]. The 6061 and 7000 aluminum alloy grades are generally used for type III tanks. HDPE or PA6 liners are typically used in type IV tanks, and they serve as nonstructural hydrogen permeation barriers for gases under high pressure [77].

Metal liners are manufactured using three different methods. The first method shapes a deep-drawn aluminum plate into a desired shape and forms the tank neck through a hot-spinning process [78,85]. The second method uses a billet-like plate process. The third method uses a tube with the same thickness as the hoop and connects the dome through hot spinning. The materials used for plastic liners must meet safety and economic requirements because of the importance of diffusion and penetration in ensuring the safety of hydrogen pressure tanks [83,86–89]. Polymer liners for type IV-a and IV-b tanks can be manufactured through injection and welding molding, blow molding, and rotational molding processes. Injection and welding molding is a multistep process [90] in which parts are welded after head injection molding. This process provides high precision, stable size, and good mechanical properties; however, welding can be challenging. Blow molding is a one-step rapid molding process; however, it may result in low uniformity. Rotational molding is a cost-effective method for producing plastic parts, where a polymer is placed in a mold in the shape of the final liner and rotated while heating and cooling the mold [91,92]. Liner manufacturers are currently exploring and implementing their liner manufacturing methods [77].

Dry towpreg and wet filament winding process

Filament winding is a commonly used mass-production method in composite manufacturing. It involves winding fibers in a predetermined pattern to create composites [93]. Type III, IV-a, and IV-b tanks use a combination of circumferential (hoop), helical, and polar angles to wrap composites [94]. Two filament winding techniques are commonly used: wet and dry fiber winding [95]. As shown in Figure 4(a), wet winding is primarily used for manufacturing hydrogen storage tanks. In this process, a stationary rotating mandrel is used for winding while the carriage moves horizontally with the mandrel. The arm of the carriage dispenses preimpregnated fibers, which are typically carbon fibers [96]. The roving is wrapped around the mandrel, thereby creating a carbon fiber composite winding. The carbon fibers are impregnated with the resin before winding. The mandrel is cured in an oven and then removed [97]. As shown in Figure 4(b), dry winding involves guiding the towpreg onto the mandrel under controlled tension and temperature. The final consolidation is achieved in the mandrel under the desired pressure using a heater. Towpreg winding provides advantages such as the precise control of the resin content, reduced variability, higher production throughput owing to high-speed winding, and reduced scrap and cleaning requirements. However, it has limitations in terms of the shelf life and high raw material cost.

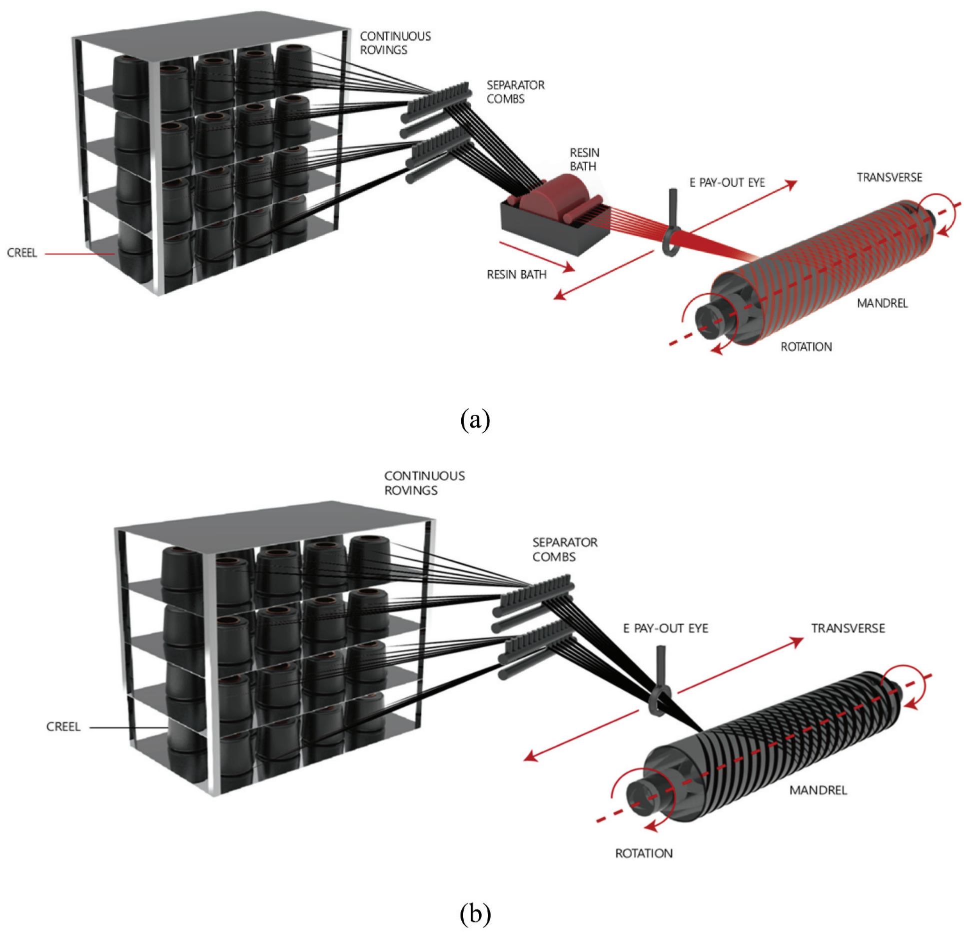


Figure 4. Schematic of filament winding: (a) wet winding; (b) dry (towpreg) winding.

Cost modeling of hydrogen gas storage tanks

Geometry, material properties, and design of hydrogen storage tanks

Hyundai Motor, Toyota, Honda, and others produce the hydrogen tanks that are used in fuel cell electric vehicles. Specifically, the Toyota Mirai model is equipped with two 700 bar hydrogen tanks with capacities of 60 L and 62.4 L, i.e. a total capacity of 122.4 L and 5 kg of hydrogen [64,98]. Hyundai Nexo (2018) features three 700 bar tanks with a capacity of 52 L, providing a total capacity of 6.33 kg hydrogen [73,99,100]. Moreover, heavy-duty trucks, such as Hyundai Xcient, Daimler, and MAN, use 350–700 bar hydrogen tanks with capacities of 175–200 L.

We selected two types of 700 bar hydrogen tanks for cost analysis: one with a capacity of 52 L for passenger cars and another with a capacity of 175 L for heavy-duty trucks. Type III, IV-a, and IV-b tanks were modeled using identical parameters. The 52 L tank was designed with an inner diameter of 310 mm, liner thickness of 5 mm, and operating pressure of 700 bar. The 175 L tank was designed with an inner diameter of 386 mm, liner thickness of 5 mm, and operating pressure of 700 bar. The aspect ratios of the 52 L and 175 L tanks were 2.17 and 4.39, respectively, as shown in (Figures 5a and b). The type III tank consisted of an aluminum liner (6061-T6) integrated with a carbon/epoxy composite material. The type IV-a tank employed a PA6 liner combined with a carbon/epoxy composite material, whereas the type IV-b tank incorporated a PA6 liner with a towpreg. The specifications, constituent materials, and capacities of each tank are listed in Table 3.

In the initial conceptual design stage, the angle of the spiral is based on the shape of the liner. The thicknesses of the helix and hoop can be obtained using the netting theory. However, when only a single helical layer is applied, the boss section in the tank became

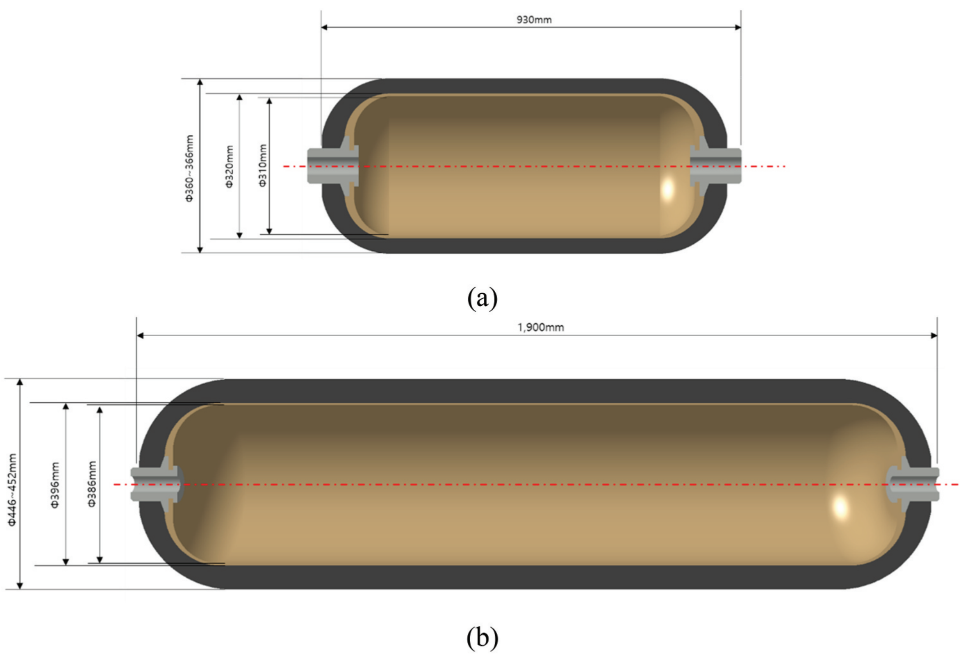


Figure 5. Dimensions of hydrogen gas storage tanks: (a) 52 L and 700 bar for passenger cars; (b)175 L and 700 bar for heavy-duty truck.

Table 3. Comparison of type III, IV-a, and IV-b hydrogen storage tanks.

	Unit	Type III	Type IV-a	Type IV-b
Pressure	Bar	700	700	700
Tank volume	L	52/175	52/175	52/175
Hydrogen capacity	kg	2.1 (52 L)/ 7.0 (175 L)	2.1 (52 L)/ 7.0 (175 L)	2.1 (52 L)/ 7.0 (175 L)
Liner materials	kg	Al6061-T6	PA6	PA6
Reinforced Fiber	-	Carbon Fiber	Carbon Fiber	Carbon Towpreg

excessively thick, resulting in an increased overall weight. Therefore, multiple helical layers are used to reduce the thickness of the boss section and decrease the overall weight of the tanks. In this study, three helical and hoop layers were employed, resulting in six layers. The physical properties of aluminum 6061-T6 and PA6 were used to analyze the hydrogen tanks on the basis of the information provided in the literature. The liner of the type III tank exhibited a Young's modulus of 68.26 GPa, Poisson's ratio of 0.33, ultimate tensile strength of 325.79 MPa, and yield strength of 269.85 MPa [101–107]. The liners of the type IV-a and type IV-b tanks had a Young's modulus of 2.4 GPa and Poisson's ratio of 0.43 [87,89], as shown in Table 4.

H2550 carbon fiber/epoxy (Hyosung Advanced Materials Ltd.) specimens were used to determine the orthotropic properties of the carbon/epoxy composites [108]. The carbon fiber volume fraction in the filament winding structure was 65%, which adhered to international test standards. The towpreg (TCR Composites) had a weight of 290 g/m^2, width of 38 mm, fiber volume content of 60%, and density of 1.58 g/cm^3. The reinforcement material used in the composites was 12K H2550 carbon fiber [109–111].

The properties of the composites used in the wet filament winding [112] (types III and IV-a) and dry filament winding processes were determined through tensile, compression, and shear tests. Tests were conducted on the towpreg (dry) and carbon/epoxy (wet) composites according to ASTM D3039, ASTM D6641, and ASTM D3528. The elastic moduli of fiber direction (E11) were 150.0 GPa and 139.0 GPa for the towpreg and carbon/epoxy composite, as shown in Table 5.

The finite element method was employed in the analysis model using 2D axisymmetric elements. Symmetric conditions were applied in the axial direction. The design criterion for the tanks was to maintain a strain of less than 1.56% in the fiber direction. The aluminum liner of the type III tank could withstand 10% of the internal pressure load [42,103,113,114]. The remaining 90% of the load was carried by the carbon composite. The carbon composite thickness for the type III tank was selected to achieve a strain of 1.6% under 90% load. The thicknesses of the hoop and helical layers were 0.3 mm and 0.6 mm, respectively. A carbon fiber composite stacking pattern of [(±14.2°)/(90°)/(±17.2°)/(90°)/(±20.2°)] was applied.

Table 4. Material properties of an aluminum (Al6061-T6) and PA6.

	E (GPa)	v	σ_{yield} (MPa)	$\sigma_{ultimate}$ (MPa)	$\varepsilon_{ultimate}$
Aluminum	68.26	0.33	269.85	325.79	0.0682
PA6	2.4	0.43	80	-	-

Table 5. Material properties of carbon/epoxy (H2550/epoxy) and towpreg composites.

	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	G_{13} (GPa)	v_{12}	v_{13}
Carbon/epoxy [112]	139.00	8.61	8.61	5.02	5.02	0.33	0.33
Towpreg	150.00	9.20	9.20	5.00	5.00	0.31	0.31

Figure 6(a) illustrates the shapes of the types III, IV-a, and IV-b tanks. Figures 6(b), 6(c), and 6(d) show the strain distribution under the maximum internal pressure. Structural analysis was performed to identify the thickness that satisfied the allowable strain under a load of 1,610 bar, considering a safety factor of 2.3 based on an operating pressure of 700 bar. The thicknesses, weights, and volumes of the type III, IV-a, and IV-b tanks are presented in Table 6.

Cost analysis modeling

The cost is calculated by adding the cost of material selection, manufacturing, inspection, and assembly. The total cost is the sum of the material cost, labor cost, energy cost, and capital investment.

$$C_T = C_M + C_L + C_E + C_P \tag{1}$$

C_M, C_L, and C_E are the material, labor, and energy costs, respectively, and C_p is the capital investment.

C_M is the cost of feedstock materials, and it is given by

$$C_M = m P_f/(1 - s) \tag{2}$$

m is the mass (kg) of the part, P_f is the cost of feedstock per unit mass (kg), and s is the percentage of material scrap or the waste rate. C_L is the labor time required to fabricate the part, and it is calculated as

$$C_L = P_{wage} \times \sum_i t_{Li} \tag{3}$$

P_{wage} is the hourly labor wage rate, and t_{Li} is the labor time for process *i*. C_E is the electricity cost consumed by the liner, filament winding, and curing processes. The energy cost is proportional to the power capacity of the equipment and operation time in part production.

$$C_E = \sum\nolimits_i E_{Li} \times t_{Ti} \times P_{Ei} \tag{4}$$

E_{Li} is the energy intensity of machine time for process *i*, t_{Ti} is the required operation process time, which consists of the operation cycle time and setup time, and P_{Ei} is the unit price of electricity (kWh).

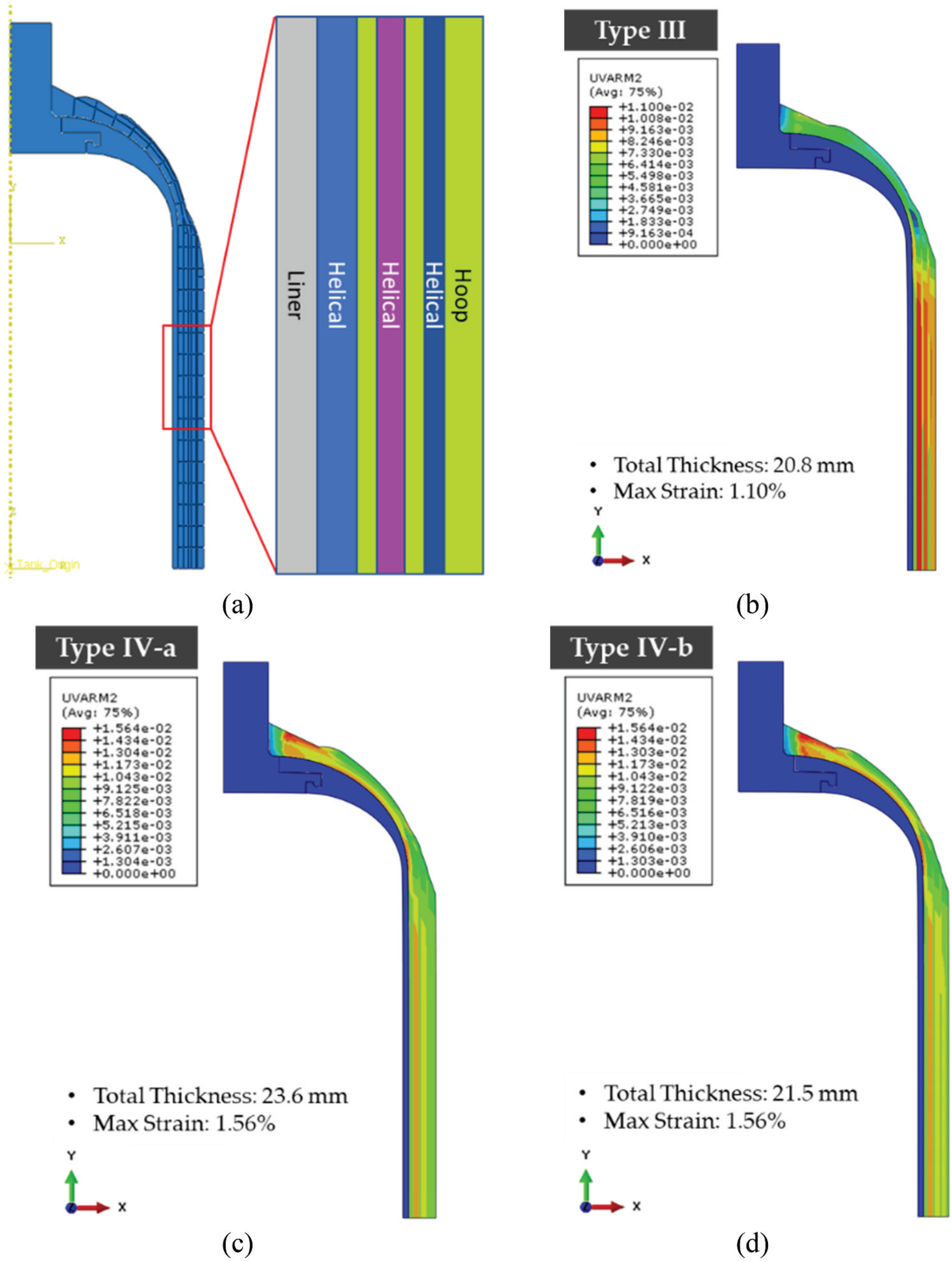


Figure 6. Hydrogen gas storage tanks (52 L): (a) winding configurations for types III, IV-a, and IV-b; (b) maximum strain and stress for types III, (c) IV-a, and (d) IV-b.

For each process step, C_P is divided into tooling, equipment, and building costs.

$$C_P = C_t + C_e + C_b \tag{5}$$

Table 6. Composites thicknesses, weights, and volumes of type III, IV-a, and IV-b tanks (52 L and 175 L).

	Type III [1]		Type IV-a [2]		Type IV-b [2]	
	52 L	175 L	52 L	175 L	52 L	175 L
Thickness (mm)	20.8	24.6	23.6	28.5	21.5	27.7
Weight (kg)	24.3	86.5	27.7	100.7	25.1	98.2
Volume (m^3)	1.5×10^{-2}	5.5×10^{-2}	1.8×10^{-2}	6.4×10^{-2}	1.6×10^{-2}	6.2×10^{-2}

[1]52 L: Al 6061-T6 liner (14.7 kg), 175 L: Al 6061-T6 liner (38.9 kg)
[2]52 L: PA6 liner (6.15 kg), 175 L: PA6 liner (16.3 kg)

C_t, C_e, and C_b denote the tooling, equipment, and building costs, respectively. The capital investment is distributed over time on the basis of the initial investment. A financial model is used to distribute the capital investment over the useful life (*n*) of tooling, equipment, and building and apply a common discount rate (*r*). The capital recovery factor used to determine the annual payment is given by

$$CRF = \frac{r(1+r)^n}{(1+r)-1} \tag{6}$$

The annual capital cost (C_p) used to allocate non-uniform cash flows to appreciative activities is calculated for a given initial capital investment (C_{teb}), as follows:

$$C_p = \sum\nolimits_{tep} C_{teb} \frac{r(1+r)^{n_{tep}}}{(1+r)-1}, tep = tool + equipment + building \tag{7}$$

where n is the number of periods over which the investment is distributed (here, n_{tool} is 3, $n_{equipment}$ is 10, and $n_{building}$ is 30) and r is 10%. This study assumes that all tools, equipment, and buildings used by the current part are not shared with the other parts. One of the most important variables in the cost analysis model is the process rate [24]. This is calculated by dividing the desired annual production volume for process i (PV_i) by the available line time (LT_{ai}).

$$Rate_i = PV_i/LT_{ai}(No.of parts/day) \tag{8}$$

The available line time for process i is calculated as follows:

$$LT_{ai} = \text{operationday/year}(24 - \text{idle time}) \tag{9}$$

$$\text{Idle time} = \text{break time} + \text{down time} \tag{10}$$

The cost calculation considered various factors, including the initial investment, energy consumption, and process-based, material, labor, building, equipment, tooling, and maintenance costs. The manufacturing process involved liner manufacturing, inspection, filament winding, curing, and assembly inspection. Liner manufacturing was categorized into an aluminum or polymer liner process, and filament winding was categorized into wet and dry winding. Figure 7 shows the cycle time, idle time, cavity, and workforce for each process for the 52 L and 175 L tanks. The liner manufacturing, curing, and filament winding processes required the most time and workforce in the manufacturing flow.

We developed an Excel-based cost calculation program, referred to as 'Hycost,' to predict the manufacturing cost of the hydrogen tank, as shown in Figure 8. Hycost serves as a comprehensive tool for modeling the cost and investment related to hydrogen tanks. It allows for economic analysis and decision making during the development and investment processes of actual companies. Additionally, it considers investment requirements such as land and other capital costs for facility construction. The goal of this program was to determine the cost, profit, and investment required to manufacture a hydrogen tank according to the requirements of actual companies, identify waste or inefficiency, and provide detailed cost information for each tank type. It considered the tank type, volume, annual production quantity, manufacturing type, material cost, labor cost, manufacturing expenses, capital investment, utility cost, and general expenses as inputs, and the outputs were the investment cost, sales revenue, profit, and unit cost. The cost for the 52 L and 175 L type III, IV-a, and IV-b tanks were estimated on the basis of annual production volumes of 3,000 units 30,000 units 60,000 units, 100,000 units, and 500,000 units. The results obtained using Hycost were adjusted with a markup of 10%–20% depending on the annual production volume and circumstances to facilitate a direct comparison with price quotations.

Table 7 presents the input data for manufacturing the hydrogen tanks, including the material, labor, energy, building, equipment, tooling, maintenance, overhead, and testing costs. In addition, general administrative expenses, interest rates, research and development costs, and profit were considered to predict the selling price. These factors were determined through interviews with raw material and equipment manufacturers.

Cost, price, and investment results

The cost is significantly influenced by the materials, including the carbon fibers, epoxy resin, towpreg, and liner [124]. For the purpose of comparison, the cost of the carbon fibers was discussed with manufacturers for low production volumes in 2022, and a price of \$24.0/kg was applied for low annual production volumes. We selected the KFR series (Kukdo Chemical) for the epoxy resin, with a price of \$4.6/kg. We assumed that the manufacturer of the hydrogen tank would purchase the towpreg at a price 1.27 times that of the carbon fibers [38,44,125]. We assumed the price of the towpreg as \$30.50 because current commercial hydrogen tanks do not use towpregs. As the annual production increased from 3,000 units to 500,000 units, the costs of the carbon fibers and the purchasing power based on the quantity were considered. The final assumed cost of the carbon fibers was \$20.0/kg, based on the discussion with carbon fiber manufacturers. The material cost of the aluminum liner was set as \$6.04/kg [115]. The price of the PA6 liner was set as \$1.43/kg [116].

The form and boss prices were considered as \$20 and \$50, respectively, based on low-volume purchases from manufacturers. In the material cost analysis of producing 30,000 units of the type III (52 L) tank, the costs of the carbon fibers and aluminum liner were \$436 and \$97, respectively. The aluminum liner carried a part of the load on the tanks [42,113], and the winding amount of the composite was 24.3 kg, which was 87.7% (27.7 kg) of that for the type IV-a tank. As a result, the carbon fiber cost for the type III

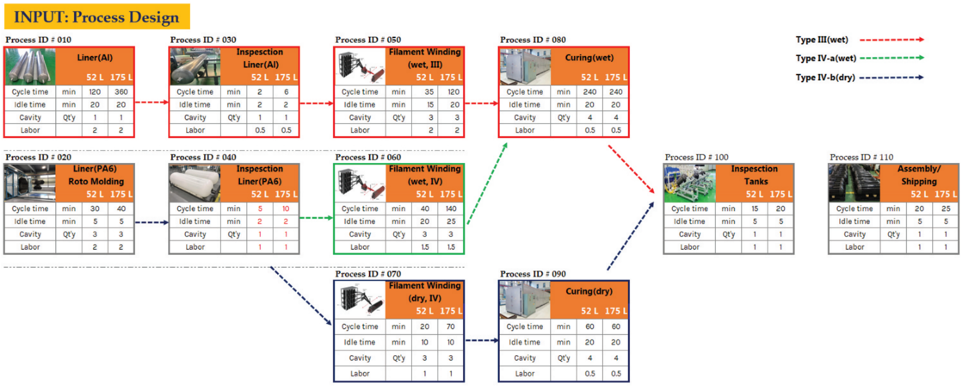


Figure 7. Manufacturing process map of hydrogen gas storage tanks.

tank was lower than that for the type IV-a tank. For the type IV-a tank, the costs of the carbon fibers and epoxy resin were $497 and $42, respectively. The towpreg cost for the type IV-b tank was $741. The material costs for the tanks that used the carbon fibers (types III and IV-a) were lower than those for the tank The form and boss prices were considered that used the towpreg (type IV-b). As shown in Figures 9(a and b), the material costs of the 52 L (30,000 units) tank were as follows: type III: $601, type IV-a: $668, type IV-b: $883.

The following factors are important for calculating the labor cost: the winding speed based on the process design, optimization of the labor time considering the learning curve, characteristics of the type of tank, and minimum wage requirements. The relationship between the labor time and production can be measured using a learning curve, which is also known as a product improvement curve [31,126–129]. The key assumption of the learning curve is that the manufacturing process remains unchanged as production increases, and the learning curve rate is 0.9 [130]. The speed for wet winding (types III and IV-a) was 60 m/min and that for dry winding (type IV-b) was 120 m/min [131]. A high winding speed can enhance the productivity of the winding machine, resulting in increased production and decreased labor cost. Two workers are involved in the wet winding process, whereas one worker performs the dry winding process. The total winding time for the type IV-a (52 L) tank was 60 min considering the standard idle time. As three spindles operated simultaneously, the production time per tank was approximately 20 min. The total winding time for the type IV-b (52 L) tank was 30 min considering the three cavities and standard idle time, resulting in a production time of approximately 10 min per tank. The curing time for the type III and IV-a tanks was set as 240 min on the basis of industrial production and 60 min for the type IV-b tank. The actual work time included 5 min for inserting and removing the curing oven and an additional 5 min for the three tanks. The curing time depended on the type of resin used, liner thickness, and working environment. The minimum wage is the legally mandated minimum amount that workers must be paid, and it depends on the country. In the case of South Korea, the Minimum Wage Council has set the minimum wage for 2023 as 9,620 Korean Won ($7.45) per hour [117]. However, as manufacturing requires skilled workers, this study applied an average labor cost of $16.00 per hour for equipment, machine operation, and assembly workers in the manufacturing industry based on the Korean employment and labor statistics from 2021 [118]. As shown in Figure 9(c and d), for an

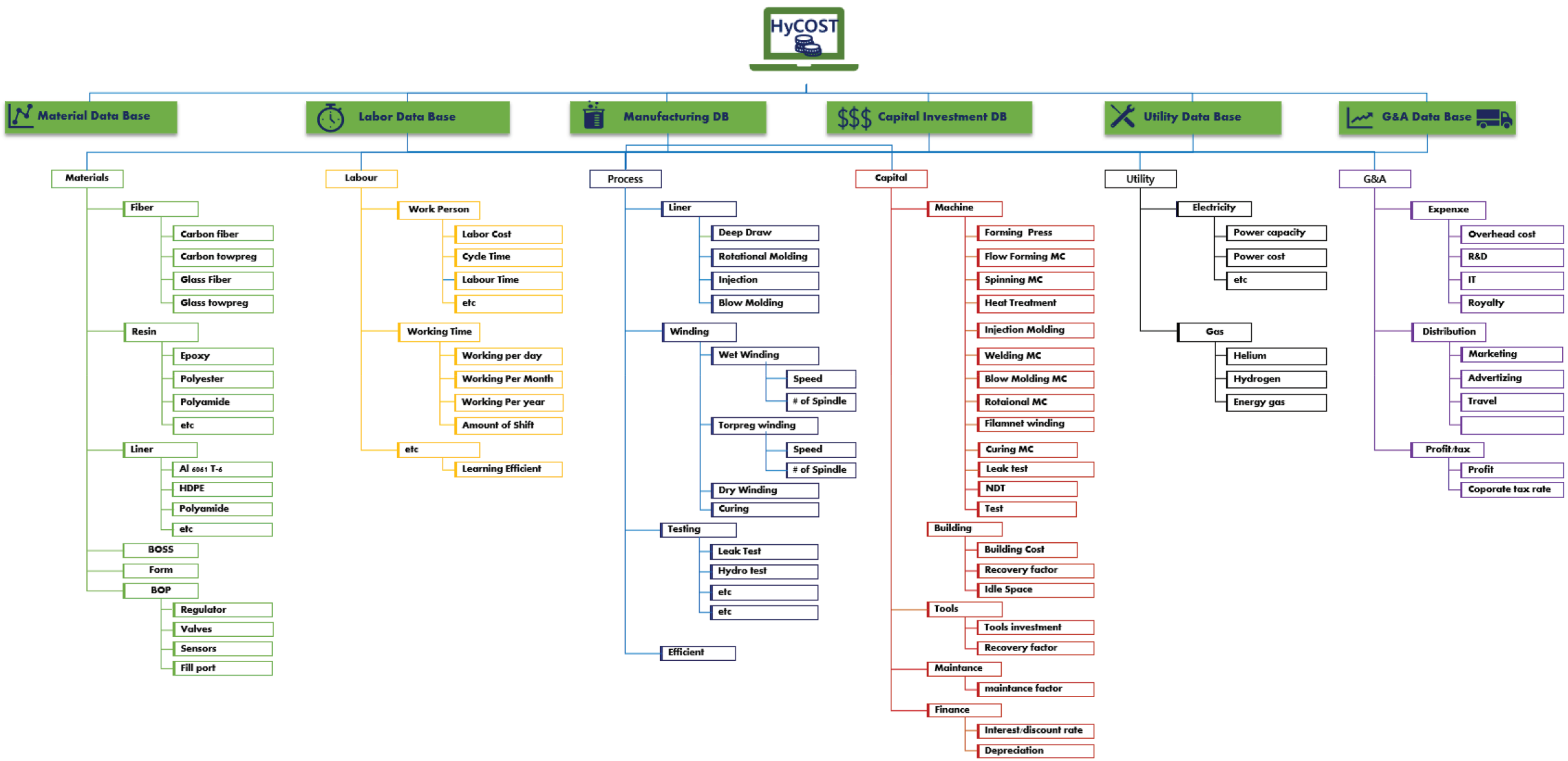


Figure 8. Cost tree obtained using Hycost for hydrogen gas storage tanks.

Table 7. Cost input data for manufacturing hydrogen gas storage tanks.

Input		Unit	Value					Reference
Quantity per year		No./year	3,000	30,000	60,000	100,000	500,000	
Material cost	Liner (Al)	$/kg	6.04	5.98	5.92	5.86	5.80	[115]
	Liner (PA6)	$/kg	1.43	1.41	1.40	1.38	1.37	[116]
	Carbon fiber[1]	$/kg	24.00	23.00	22.50	22.00	20.00	
	Carbon towpreg[2]	$/kg	30.48	29.21	28.58	24.20	20.00	[36]
	Glass fiber	$/kg	1.0	1.0	1.0	1.0	1.0	
	Glass towpreg	$/kg	15.0	15.0	13.5	12.2	8.5	
	Resin[3]	$/kg	4.60	4.49	4.41	4.26	3.87	
	Form	$/set	20.0	18.0	16.2	14.6	13.1	
	Boss	$/set	150.0	100.0	90.0	81.0	57.0	
Labor cost	Labor cost	$/h	16	16	16	16	16	[117,118]
	Working per day	Hours	8	8	8	8	8	
	Days per month	Days	20	20	20	20	20	
	Days per year	Days	240	240	240	240	240	
	Amount of shift	No.	2	2	2	2	2	
	Dedication	%	100	100	100	100	100	
Energy cost	Energy Cost	$/kWh	0.094	0.094	0.094	0.094	0.094	[119]
Equipment cost	Acquisition price	$	-	-	-	-	-	
	Amount	units	-	-	-	-	-	
	Recovery factor	year	10	10	10	10	10	[29]
	Efficiency	%	100	100	100	100	100	
	Dedication	%	100	100	100	100	100	
Building cost	Building area	m^2	-	-	-	-	-	
	Space cost	$\$/m^2$	615	615	615	615	615	[120]
	Idle space	%	30	30	30	30	30	
	Recovery factor	year	30	30	30	30	30	[30]
Tooling cost	Tooling cost[4]	$	-	-	-	-	-	[26,27,31]
	Recovery factor[5]	parts	50,000	50,000	50,000	50,000	50,000	
Maintenance cost[5]		%	10	10	10	10	10	[30]

(*continued*)

Table7. (*Continued*).

Input	Unit	Value					
Quantity per year	No./year	3,000	30,000	60,000	100,000	500,000	Reference
Overhead cost[6]	%	65	65	65	65	65	[121–123]
Sample test[7]	%	2	2	2	2	2	
Exchange rate	Won/$	1292	1292	1292	1292	1292	[79]
Interest rate	%	10	10	10	10	10	
General Expense[8]	%	25	25	25	25	25	
R & D[9]	%	5	5	5	5	5	[29]

[1]Carbon fiber coat: $23.0 (<30,000), $22.0 (>100,000), $20.0(> 500,000)
[2]Carbon towpreg cost: Carbon fiber price × 1.27 (<100,000), carbon fiber price × 1.10 (100,000), carbon fiber price × 1.00 (500,000)
[3]Resin cost: $4.64 (<30,000), $4.26 (>100,000), $3.87 (>500,000)
[4]Tooling cost: 2% × (equipment acquisition price)
[5]Recovery factor: approximated from OEM data (depreciation of 50,000 units)
[6]Overhead cost: 65% × expenses × expenses: energy, equipment, building, tooling, and maintenance
[7]Sample test: 2% (cycling and burst test) out of production
[8]General expense: 25% × (labor cost + expense)
[9]R&D: 5% × (expense)

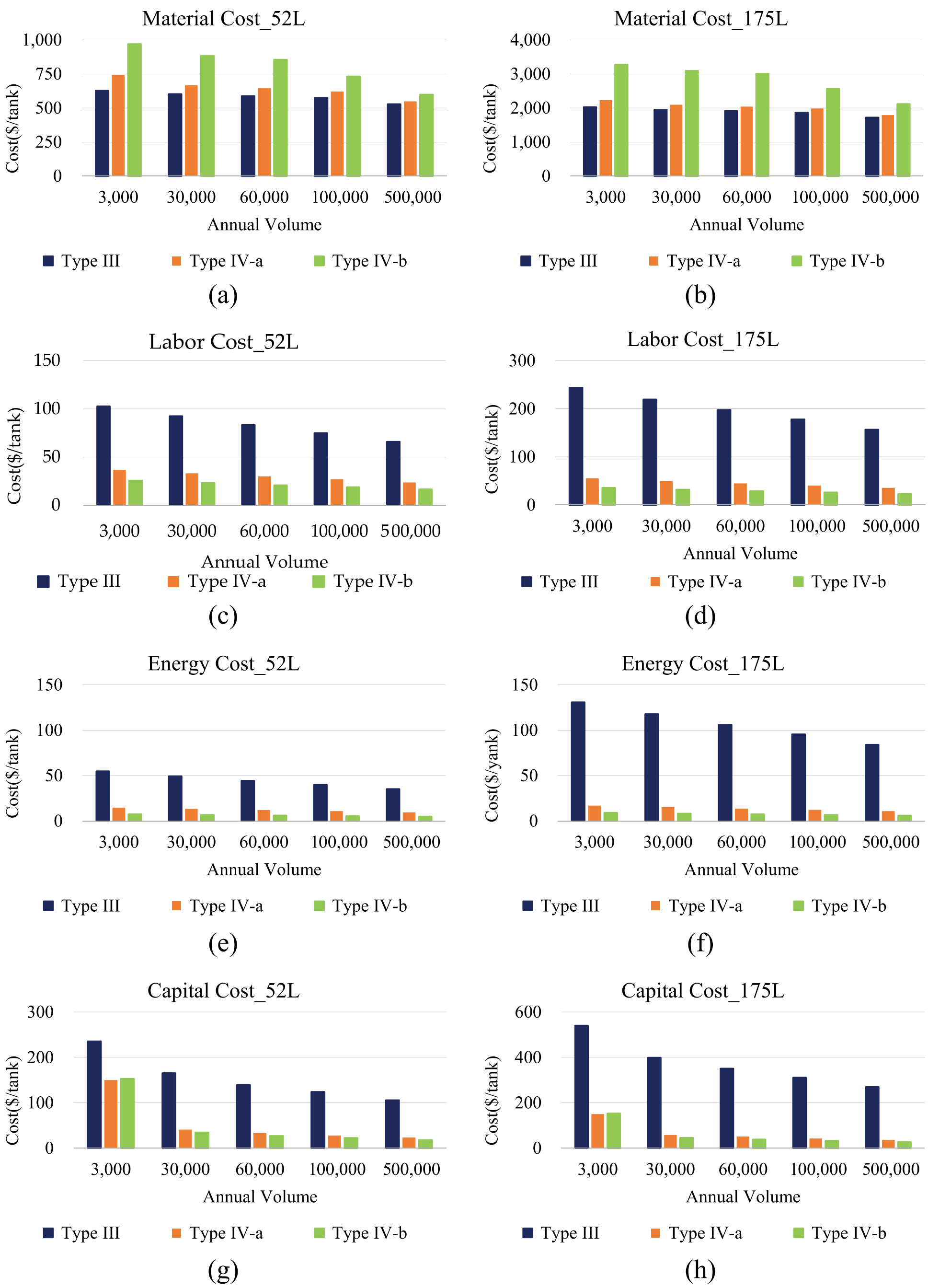


Figure 9. Cost for 700 bar hydrogen gas storage tank according to annual production volumes: (a) material cost for 52 L; (b) material cost for 175 L; (c) labor cost for 52 L; (d) labor cost for 175 L; (e) energy cost for 52 L; (f) energy cost for 175 L; (g) capital cost for 52 L; (h) capital cost for 175 L.

annual production of 30,000 units, the estimated labor cost for the type III tanks was the highest at $92.3 for 52 L and $219.3 for 175 L. The labor cost for the type IV-b tanks was $22.9 for 52 L and $31.7 for 175 L.

Energy consumption data were obtained from the 'Energy Prices and Taxes Statistics' report published by the Korea Electric Power Corporation, which is a part of the OECD-IEA [119]. Based on an average of 100 for all OECD countries, residential and industrial electricity consumption in Korea is 61 and 88, respectively. Based on the industrial electricity usage in 2020, the cost of electricity is $0.094/kWh. Equation 3 was used to determine the energy cost. The aluminum liner process incurred the highest energy cost owing to its demanding high-temperature process. This was followed by the curing and winding processes. The energy cost for the 52 L type III tank (30,000 units) was $49.3. This was attributed to the substantial amount of energy required to manufacture the aluminum liner. In comparison, the energy cost of the type IV-a tank with the same capacity was $13.2. It should be noted that the 52 L type IV-b tank, had a relatively lower energy cost of $6.6. This was attributed to the shorter cycle time involved in the dry winding and curing processes employed in the type IV-b tank, as shown in Figures 9(e and f). This analysis demonstrates the significant impact of different manufacturing processes on energy consumption and highlights the requirement for the careful consideration and optimization of energy usage in production.

Capital investment costs comprised the equipment, building, maintenance, and tooling costs. The annual capacity of the facilities was based on an 8 h work duration in two shifts. The initial facility investment costs were calculated by considering a 10 year depreciation period and 10% interest rate. The initial capital investment costs, including building and equipment costs, for each tank type (52 L 30,000 units) were as follows: type III: $31 million, type IV-a: $7 million, type IV-b: $6 million. The production of the 52 L type III and IV-a tanks (30,000 units) required three filament winding machines and three curing ovens. However, only two filament winding machines and three curing ovens were required for the type IV-b tank. The equipment costs for each type of tank (52 L 30,000 units) were as follows: type III: $82.5, type IV-a: $23.4, type IV-b: $19.2. Building costs were calculated on the basis of a 30 year building recovery rate and 30% idle space, and the construction cost of the factory building was $615/m^2 [132]. The average annual cost of land acquisition, which was assumed as $300/m^2 according to the Korean Industrial Complex [120] sites, was excluded from this study. The building costs for each type of tank (52 L 30,000 units) were as follows: type III: $55.7, type IV-a: $10.6, type IV-b: $9.3. Tooling costs were determined by dividing the depreciated tooling price over the lifespan of the tool by the number of components produced during the lifespan [26,27]. In this study, the tooling costs are calculated on the basis of the depreciation of 50,000 tanks. The tooling costs of each type of tank (52 L 30,000 units) are as follows: type III: $10.1, type IV-a: $2.9, type IV-b: $2.4. Maintenance costs refer to the one-time or recurring costs associated with maintaining a company's facilities or equipment. These costs are influenced by the equipment type, working conditions, total usage time, and useful lifespan. In this study, maintenance costs were considered to be 10% of the annual equipment costs [30]. The maintenance costs for each type of tank (52 L 30,000 units) were as follows: type III: $16.6, type IV-a: $4.1, type IV-b: $3.4. In the annual total capital cost analysis, the liner manufacturing, filament winding, and curing processes had the highest costs. The capital investment costs for each type of tank (52 L 30,000 units) were as follows:

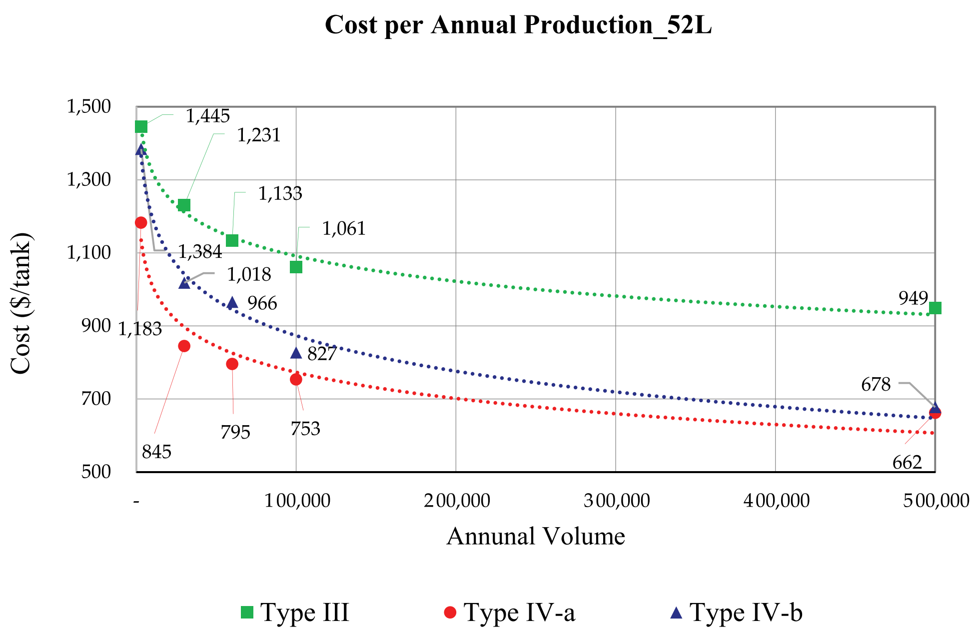
type III: \$165.0, type IV-a: \$40.7, type IV-b: \$34.2. These results are shown in Figure 9(g), and the results for the 175 L tanks are shown in Figure 9(h).

Indirect costs refer to various expenses associated with individual employees, in addition to direct wages. The application of indirect cost rates varies across countries and industry sectors, and it is based on detailed information. For example, Denmark, Norway, and Sweden typically apply an indirect cost rate of 25%. The standard rate in the Netherlands is 25%; however, it increases to 50% for regulatory measures in the financial sector. The initial overhead rate in the UK is set as 30% [121]. Different industries may employ different ratios of indirect and direct labor times for cost calculations. For example, Ma et al. [122] applied a ratio of 40% for the aerospace industry, whereas Bernet et al. [123] applied ratios of 75%–115%. In this study, we allocated 65% of the labor costs based on actual practices in automotive companies. The indirect costs of the 52 L tanks (30,000 units) were \$150.0 for type III, \$37.7 for type IV-a, and \$28.6 for type IV-b. These findings emphasize the importance of accurately determining indirect costs by considering country-specific rates, industry characteristics, and labor allocation ratios. Companies can improve cost efficiency and financial effectiveness by comprehensively evaluating and optimizing these factors.

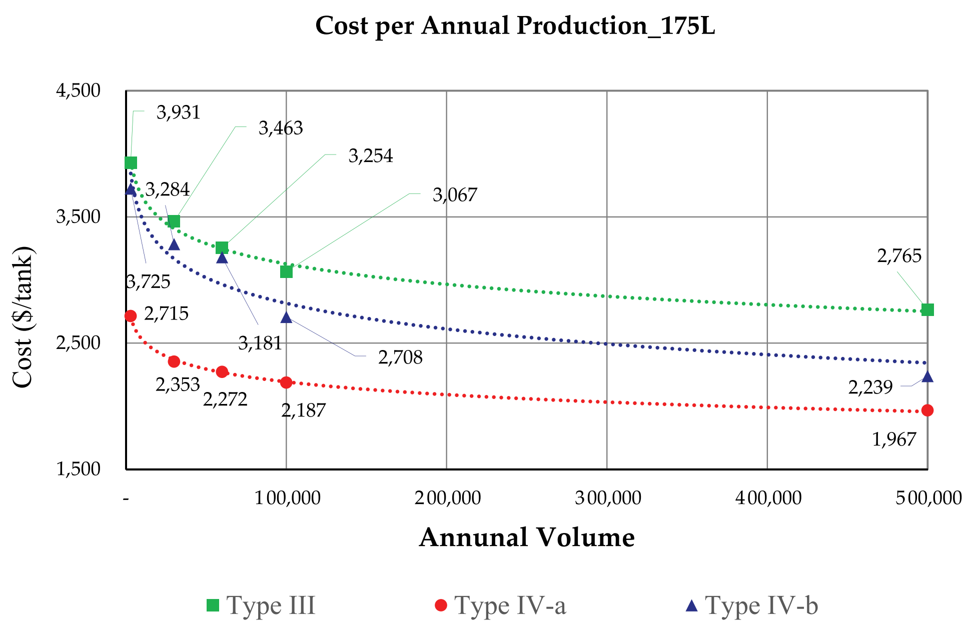
Figure 10 shows the costs according to the annual production volume for the 52 L and 175 L tanks. When the annual production volume was below 10,000 units, the costs for all types of tanks were significantly high. This was attributed to the inefficiency of producing fewer units than the annual capacity of the liner and filament winding equipment. Type III tanks incurred high costs owing to expensive liner equipment, low production rates that affected the overall production, and high labor costs. Consequently, type IV-a and IV-b tanks provided more cost advantages. The learning curve based on an annual production of 30,000 units showed that labor costs and process cycle times gradually decreased. This highlights the importance of efficiently reducing the process time in practical applications.

The cost of the type III tank (52 L 30,000 units, \$1,231.1) was 46% higher than that of the type IV-a tank (52 L 30,000 units, \$844.8). This was because even though both tanks used the same wet filament winding method, the type III tank incurred higher manufacturing costs because of its aluminum liner material. In the case of the 52 L tanks (30,000 units), the cost of the type IV-b tank (\$1,018.2) was 21% higher than that of the type IV-a tank (\$844.8). This was primarily because the material cost of the type IV-b tank was high owing to the towpreg. However, the labor, energy, and capital investment costs of the type IV-b tank were lower than those of the type IV-a tank. As the annual production volume increased from 3,000 units to 500,000 units, the cost of the type IV-a tank decreased from \$1,182.5 to \$844.8, \$795.5, \$753.4, and \$661.9 and that of the type IV-b tank decreased from \$1,384.4 to \$1,018.2, \$966.1, \$827.3, and \$677.8. The important cost-driving factors for the type IV-a and IV-b tanks were the carbon fibers and towpreg. In this study, the towpreg price was assumed to be 1.27 times the price of the carbon fibers at low volumes. The towpreg should be priced lower than the carbon fibers for the cost of the type IV-a tank to be competitive with respect to that of the type IV-b tank, and the optimal level is lower than 0.97. When it was assumed that the price of 1 kg of the towpreg was 97% of the price of the carbon fibers, the costs of the type IV-b tank at different production volumes were \$1,199.8, \$841, \$793.1, \$754.0, and \$662.4, which were equivalent to or slightly lower than those of the type IV-a tank.

The total cost, cost per kilogram of the tank, and cost per kilowatt hour were calculated using the annual production volume. For an annual production volume of



(a)



(b)

Figure 10. Manufacturing cost breakdown for 700 bar hydrogen gas storage tank according to production annual production volumes: (a) 52 L; (b) 175 L.

500,000 units for the type IV-a tanks, the cost per kilogram of the hydrogen storage capacity was calculated as \$9.6/kg H_2 for the 52 L tank and \$9.5/kg H_2 for the 175 L tank. These costs were lower than the DOE and CHSS ultimate and 2030 Target Cost values provided in Table 2, and the costs decreased as the capacity increased. It should be noted that the cost calculation in this study excluded valves, regulators, packaging, and shipping, which imposed limitations on direct comparisons. Assuming that the BOP cost is approximately 30% of the total cost, the cost per kilowatt hour should be less than 7.

Hycost was utilized to perform comprehensive cost calculations and a detailed analysis of the investment requirements, including land, plant facilities, and equipment, for tanks in practical applications. For example, cost analysis was conducted for the 175 L type IV-b tank for an annual production volume of 30,000 units, considering a profit margin that incorporated 3% of the material costs, labor costs, expenses, and general administrative expenses. The tank cost was \$2,353, and the price was \$2,586. The corresponding initial investment was approximately \$10.0 million. The investment included \$6.4 million for equipment (four filament winding machines and three ovens) and \$3.6 million for building investments (area of 5,880 m^2). Hycost allowed for the comparative analyses of costs, prices, and investments for the production of type III and IV-a tanks for the same production volume.

To validate Hycost analysis technique and results, a comparison was made with the results announced by the U.S. Department of Energy (DoE) in 2022 [133]. For an annual production of 500K, a 52 liter type IV-a tank was estimated at \$9.6/kWh, and type IV-b at \$9.6/kWh. For a 175 liter tank, type IV-a was estimated at \$8.4/kWh, and type IV-b at \$9.5/kWh. These figures showed a 3% difference compared to the cost of the 147-liter tank announced by the DoE in 2022, which was \$9.9/kWh. Given the consideration of variables such as exchange rates, this demonstrates the excellence of Hycost analysis technique.

Conclusions

We analyze the key factors the influence the cost of hydrogen gas storage tanks and optimize the cost. Material costs, such as carbon fiber, epoxy resin, towpreg, and liner costs, significantly affect the overall cost. Labor, energy consumption, capital investment, and indirect costs are examined. A detailed understanding of these factors can improve cost efficiency and financial effectiveness in production. In addition, the price of the towpreg should be similar to that of the carbon fibers for the cost of dry winding to be competitive compared to wet winding.

The Hycost program is developed for modeling the costs and investments associated with hydrogen gas storage tanks. This program accurately calculates the costs of hydrogen storage tanks by considering various factors such as the capacity, liner type, manufacturing processes, and production volume. It also incorporates the investment requirements and features that determine customized selling prices. Hycost is a valuable tool for economic analysis, decision making, and efficiency improvements in the development and investment processes of hydrogen storage tank companies. It is important to note that the manufacturing costs for tanks depend on their capacity, design, and type, thereby necessitating substantial investments in factories and manufacturing equipment.

Our study not only predicts costs but also investments and profits. We develop a comprehensive cost – profit model to estimate unit costs and investments for various types of tanks. This model facilitates informed decision making regarding cost estimation and investment planning by providing valuable insights into the economic aspects of tank production.

In the future, the costs, investments, and profitability of tanks of different capacities and types should be analyzed. Additionally, the optimization of design and materials, technological advancements for efficiency improvements, exploration of environmentally friendly production methods, and strategic approaches for cost reduction and profit maximization should be investigated. These efforts will contribute to the development of the hydrogen energy industry and the realization of a sustainable and ecofriendly future.

Acknowledgements

The authors would like to express gratitude to the Department of Mechanical Engineering and the Structural and Composites Lab at Hanyang University, as well as Cevotec GmbH. Additionally, this research was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP)(No. 20223030020160).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study received no external funding.

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Conceptualization, S.K.H.; writing – original draft preparation, H.K.S; review and editing, S.K.H. All authors have read and agreed to the published version of the manuscript.

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