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Techno-economic assessment of large-scale 700-bar Type IV hydrogen storage tank manufacturing: Cost drivers, production-scale effects, and industrial implications

Zuhal Oktay [a,h,*], Can Coskun [b,h], Fedai İnanır [c,h], Muzaffer Erdoğan [d], Şükrü Yildiz [e], Engin Erbayrak [f], Alperen Oktay [g]

[a] Clean Energy Technologies Institute, Yıldız Technical University, Istanbul, Türkiye
[b] Department of Mechanical Engineering, Yıldız Technical University, Istanbul, Türkiye
[c] Department of Physics, Faculty of Arts and Sciences, Yıldız Technical University, Istanbul, Türkiye
[d] Department of Physics, Faculty of Arts and Sciences, Tekirdağ Namık Kemal University, Tekirdağ, Türkiye
[e] Faculty of Engineering and Architecture, Department of Metallurgy and Materials Engineering, Kırşehir Ahi Evran University, Kırşehir, Türkiye
[f] Department of Mechatronic Engineering, Faculty of Engineering and Architecture, Istanbul Gelisim University, Istanbul, Türkiye
[g] Wrocław University of Science and Technology, Poland
[h] Superconducting Cable Industry Inc, Istanbul, Türkiye

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ABSTRACT

The commercialization of hydrogen energy systems requires cost-effective and scalable manufacturing of high-pressure composite storage tanks. This study develops a bottom-up techno-economic framework for industrial-scale 700-bar Type IV hydrogen storage tank manufacturing, integrating manufacturing costs, production capacity, capital investment, operating expenditure, and sensitivity analysis. Six tank configurations with hydrogen storage capacities of 0.9996–6.9203 kg were evaluated. Manufacturing cost per kilogram of stored hydrogen decreased with increasing tank capacity, primarily due to improved material utilization. Carbon fiber composites dominated manufacturing costs, while a ±30% variation in raw material prices caused cost changes of up to ±19.6%. A fixed-configuration analysis using the 103-L tank isolated production-scale from tank-size effects. Increasing production from 25,000 to 100,000 tanks/year reduced unit manufacturing cost by 36.2%, whereas expansion to 113,390 tanks/year provided only an additional 2.2% reduction. These results identify an economic production threshold of 100,000 tanks/year, beyond which further expansion provides limited cost benefits.

1. Introduction

Hydrogen is widely recognized as one of the most promising energy carriers for decarbonizing transportation and other hard-to-abate sectors. However, the large-scale deployment of hydrogen technologies depends not only on low-carbon hydrogen production but also on the availability of safe, lightweight, and cost-effective storage systems. Among the available storage technologies, compressed hydrogen stored in high-pressure composite vessels remains the dominant solution for fuel cell electric vehicles and many stationary applications because of its high gravimetric storage efficiency, operational safety, and technological maturity [1–3].

Type IV hydrogen storage tanks have attracted considerable attention because their lightweight polymer liners are reinforced with carbon fiber composites, significantly reducing vessel weight compared with metallic pressure vessels while maintaining high mechanical performance at operating pressures up to 700 bar [4]. These characteristics have made Type IV tanks a preferred technology for automotive and other mobility applications. Nevertheless, their widespread commercialization remains constrained by high manufacturing costs, particularly those associated with carbon fiber composites and advanced manufacturing processes [5,6].

Numerous studies have investigated the manufacturing economics of composite hydrogen storage tanks using process-based cost estimation, bottom-up manufacturing models, industrial benchmarking, and techno-economic assessment methodologies [7–10]. These studies consistently identify carbon fiber as a dominant cost driver and

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* Corresponding author. Clean Energy Technologies Institute, Yıldız Technical University, Istanbul, Türkiye.
E-mail address: z.oktay@yildiz.edu.tr (Z. Oktay).

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demonstrate that manufacturing cost generally decreases with increasing production volume because of economies of scale. Sensitivity analysis, scenario analysis, and scale-up modelling have also been widely employed to quantify the effects of raw material prices, labor costs, production volume, and manufacturing efficiency on overall tank cost [11–13]. While these studies provide valuable insights into the cost structure of composite pressure vessels, most focus on individual cost components, specific tank configurations, or generalized manufacturing assumptions.

Despite these advances, several important gaps remain. Existing studies rarely integrate bottom-up manufacturing cost modelling, industrial production line design, production capacity estimation, capital investment (CAPEX), working capital, operating expenditure (OPEX), and sensitivity analysis within a single techno-economic framework. Furthermore, relatively few investigations evaluate multiple tank capacities using industrial-scale manufacturing assumptions that reflect realistic production equipment, manufacturing cycle times, and production throughput. As a result, comprehensive economic frameworks capable of supporting industrial investment planning and commercial manufacturing decisions remain limited.

An additional limitation is that the effects of tank capacity and manufacturing scale are often coupled in techno-economic comparisons. When different tank configurations are compared, changes in tank size are generally accompanied by changes in material consumption, manufacturing cycle time, and annual production capacity. Consequently, a reduction in unit manufacturing cost cannot be attributed exclusively to economies of scale because tank geometry, material utilization, and production throughput change simultaneously. Separating these effects is therefore important for determining the extent to which increased manufacturing volume itself contributes to cost reduction [14–16].

To address these gaps, this study develops an integrated bottom-up techno-economic framework for the industrial-scale production of 700-bar Type IV hydrogen storage tanks. The methodology combines detailed manufacturing cost modelling with industrial production line design, production capacity analysis, capital investment estimation, operating expenditure assessment, and sensitivity analysis. The manufacturing system is characterized using representative industrial equipment, including filament winding, curing, machining, inspection, and testing operations, together with realistic production cycle times and plant operating conditions. Six tank configurations with different storage capacities are evaluated under consistent industrial manufacturing assumptions, enabling the effects of tank capacity, material requirements, production capacity, and manufacturing cost to be assessed systematically.

Beyond conventional manufacturing cost estimation, the study introduces a fixed-configuration production-scale analysis to isolate the effect of annual manufacturing volume from tank-size effects. The H103 tank configuration is maintained constant while annual production volume is systematically varied from 25,000 to 113,390 tanks/year. This approach enables the quantitative relationship between production volume and unit manufacturing cost to be determined independently of changes in tank capacity and material requirements. In particular, the analysis identifies the production range over which economies of scale provide substantial cost benefits and the approximate production threshold beyond which additional capacity expansion results in diminishing economic returns.

Accordingly, the contribution of this study is not to establish the general existence of carbon-fiber cost dominance or economies of scale, which have been reported previously, but to quantitatively distinguish manufacturing-scale effects from tank-capacity effects for a 700-bar Type IV storage system under industrially representative conditions. The analysis further identifies the dominant manufacturing cost drivers, evaluates their sensitivity to key economic parameters, and examines the implications of production scale for industrial manufacturing competitiveness. Although the economic inputs are calibrated using conditions representative of Türkiye, the proposed framework is sufficiently generic to be adapted to other geographical regions by modifying local economic parameters.

The outcomes of this study provide a practical techno-economic basis for commercial-scale Type IV hydrogen storage tank manufacturing, supporting industrial investment planning, production-scale selection, and cost optimization. More importantly, the quantitative production-scale analysis distinguishes manufacturing-scale effects from tank-capacity effects and identifies the production range over which economies of scale provide substantial cost benefits, as well as the point beyond which further capacity expansion yields limited reductions in unit manufacturing cost.

2. Manufacturing assumptions and production capacity estimation

The manufacturing assumptions adopted in this study were established using industrial operational data obtained through an on-site technical assessment conducted by the authors at a commercial composite pressure vessel manufacturing facility located outside Türkiye. Owing to confidentiality agreements with the manufacturer, company-specific operational data cannot be disclosed. Therefore, representative engineering parameters are presented in an aggregated form. To ensure the reliability and representativeness of the proposed manufacturing model, the adopted production workflow, equipment configuration, production cycle times, labor allocation, and material consumption were benchmarked against published techno-economic studies, industrial reports, and publicly available information on large-scale Type IV hydrogen storage tank manufacturing. This benchmarking confirmed that the selected assumptions are consistent with current industrial manufacturing practices and are suitable for commercial-scale production.

The manufacturing process considered in this study consists of polymer liner production, metallic boss assembly, filament winding, resin curing, CNC machining, hydrostatic pressure testing, helium leak testing, final inspection, and packaging. The proposed production line was designed assuming a high degree of automation, with automated filament winding, curing, testing, and inspection systems representing the principal manufacturing operations.

Material losses occurring during filament winding, trimming, machining, and quality control were incorporated by assuming an average manufacturing scrap rate of 5%, consistent with industrial composite manufacturing practice. Accordingly, the total carbon fiber requirement was calculated as:

$$m_{CF,Total} = m_{CF,net} \cdot (1 + Srap\ rate) \tag{1}$$

where $m_{CF,Total}$ is the total carbon fiber required for production, including manufacturing losses, and $m_{CF,net}$ is the net carbon fiber required for the composite overwrap.

Among all manufacturing operations, filament winding represents the production bottleneck and therefore determines the overall manufacturing capacity. The total filament winding cycle time was estimated as the sum of a fixed preparation time and a variable winding time:

$$t_{cycle} = t_{fixed} + t_{winding} \tag{2}$$

where t_{cycle} is the total cycle time (min), t_{fixed} is the fixed preparation time (min), and $t_{winding}$ is the winding time (min).

The fixed preparation time was assumed to be 18 min, based on industrial operational observations and published manufacturing data for automated filament winding systems. This period includes liner loading, machine setup, fiber preparation, unloading, and routine cleaning operations and was assumed to be independent of tank size.

The winding time increases with tank size because larger vessels require longer fiber deposition paths and greater carbon fiber consumption. Using the 103 L hydrogen storage tank as the reference configuration, the total cycle time was estimated as:

$$t_{cycle} = 18 + 43.4 \cdot \left(\frac{V}{103}\right) \quad (3)$$

where (V) is the tank water volume (L). The coefficient 43.4 min represents the winding time of the reference 103 L tank, resulting in a total production cycle time of approximately 61.4 min.

The proposed manufacturing facility was assumed to operate 29 automated filament winding machines, 250 operating days per year, and two production shifts per day. Based on these assumptions, the annual production capacity was calculated for each tank configuration. The 103 L reference tank achieves an estimated production capacity of approximately 113,390 tanks per year, which was adopted as the baseline production scenario for the techno-economic assessment. Smaller tanks require shorter winding cycles and consequently achieve higher annual production rates, whereas larger tanks require longer winding times and therefore exhibit lower production capacities under identical manufacturing conditions.

The estimated filament winding cycle times and corresponding annual production capacities are presented in Table 1. These production parameters form the basis for estimating equipment utilization, workforce requirements, capital investment (CAPEX), operating expenditure (OPEX), and unit manufacturing cost throughout the techno-economic analysis.

3. Technical specifications of the Type IV hydrogen storage tank

Type IV hydrogen storage tanks represent the most advanced commercially deployed high-pressure hydrogen storage technology for mobility applications. Unlike conventional Type I (all-metal) and partially composite Type II and Type III pressure vessels, Type IV tanks utilize a non-metallic polymer liner fully reinforced with a carbon fiber–reinforced polymer (CFRP) composite overwrap. The polymer liner serves primarily as a hydrogen gas barrier and provides dimensional stability during manufacturing, whereas the composite overwrap carries nearly all of the mechanical loads generated by high internal pressures. Metallic bosses are integrated into both ends of the liner to accommodate valves, pressure regulators, and other essential fittings required for safe system operation.

The elimination of a metallic structural liner significantly reduces the overall tank weight, resulting in a higher gravimetric hydrogen storage capacity compared with earlier pressure vessel technologies. Consequently, Type IV tanks have become the preferred storage solution for fuel cell electric vehicles (FCEVs), heavy-duty transportation, aerospace applications, and other hydrogen-powered mobility systems where weight reduction directly improves vehicle efficiency and driving range. Despite these advantages, the widespread commercialization of Type IV tanks remains economically challenging because of the high cost of carbon fiber composites, which constitute the largest fraction of the manufacturing cost.

A typical Type IV hydrogen storage system consists of the composite pressure vessel together with several integrated safety and flow-control components. These include check valves, shut-off valves, pressure regulators, and thermally activated pressure relief devices (TPRDs), which ensure safe hydrogen storage under normal and emergency operating conditions. The TPRD is particularly important, as it releases hydrogen in a controlled manner during fire exposure or abnormal temperature increases, thereby preventing catastrophic failure caused by thermal over-pressurization.

For automotive and heavy-duty hydrogen applications, Type IV tanks are generally designed for a Nominal Working Pressure (NWP) of 70 MPa (700 bar), providing high volumetric hydrogen storage density while maintaining long-term structural reliability. Their design and qualification are governed by international standards such as ISO 19881 and SAE J2579, which specify performance requirements including burst pressure, hydrogen permeation limits, pressure cycling durability, environmental resistance, and fire safety. Accordingly, the structural integrity of the proposed Type IV hydrogen storage tank under an internal pressure of 700 bar was evaluated using the finite element method implemented in COMSOL Multiphysics®. The adopted numerical methodology is consistent with previous COMSOL-based finite element studies conducted by the authors on radiation-resistant superconducting dipole magnets operating under cryogenic conditions, demonstrating the capability of the software for accurately analyzing complex engineering systems subjected to extreme operating conditions [17]. For tanks designed for a nominal working pressure of 70 MPa, international standards generally require burst pressures exceeding approximately 157.5 MPa while maintaining structural integrity after thousands of filling and emptying cycles throughout their service lifetime.

Table 1
Estimated filament winding cycle time and annual production capacity.

Model	Volume (L)	Cycle Time (min)	Annual Production (tanks/year)
H026	26	28.95	240,400
H051	51	39.49	176,250
H063	63	44.55	156,300
H103	103	61.40	113,390
H150	150	81.20	85,710
H180	180	93.84	74,170

3.1. Manufacturing workflow

The manufacturing of a Type IV hydrogen storage tank involves a sequence of highly controlled processes designed to achieve excellent mechanical performance, hydrogen tightness, and compliance with international safety standards. As illustrated in Fig. 1, the process begins with the fabrication of the polymer liner, commonly produced from high-density polyethylene (HDPE) or polyamide (PA) using blow molding or injection molding techniques. After the liner is manufactured, metallic bosses are assembled at both ends to provide interfaces for valves and external connections. The assembled liner subsequently undergoes surface preparation and dimensional inspection before being transferred to the composite reinforcement stage. Continuous carbon fibers pre-impregnated with epoxy resin are then applied using an automated filament winding process. Both hoop and helical winding patterns are employed to optimize the stress distribution and enable the vessel to withstand operating pressures ranging from 350 to 700 bar.

Following filament winding, the composite structure is thermally cured in an oven or autoclave to complete resin polymerization and develop the required mechanical properties. After curing, the vessel is machined and finished before undergoing a comprehensive qualification program that includes dimensional inspection, non-destructive evaluation (NDE), hydrostatic pressure testing, leak testing, burst testing, and hydrogen permeation measurements. Tanks that successfully satisfy all qualification requirements are finally equipped with valves and accessories before packaging and deployment. Fig. 1 illustrates the complete manufacturing workflow of a Type IV hydrogen storage tank, beginning with polymer liner fabrication and ending with final inspection and certification.

3.2. Material composition

The structural configuration of a Type IV hydrogen storage tank is primarily composed of four material groups: a thermoplastic liner, an epoxy resin matrix, carbon fiber reinforcement, and metallic end fittings. The thermoplastic liner provides hydrogen impermeability, while the carbon fiber composite overwrap bears nearly all of the internal pressure loads. Owing to its exceptional specific strength and stiffness, carbon fiber enables a high strength-to-weight ratio but also represents the most expensive constituent of the storage vessel.

The material composition, weight distribution, and unit costs of the principal tank components are summarized in Table 2. As shown, carbon fiber accounts for approximately 70% of the tank mass and represents the dominant contributor to the overall manufacturing cost. Consequently, the optimization of carbon fiber utilization has become one of the most important research topics in reducing the production cost of high-pressure hydrogen storage systems.

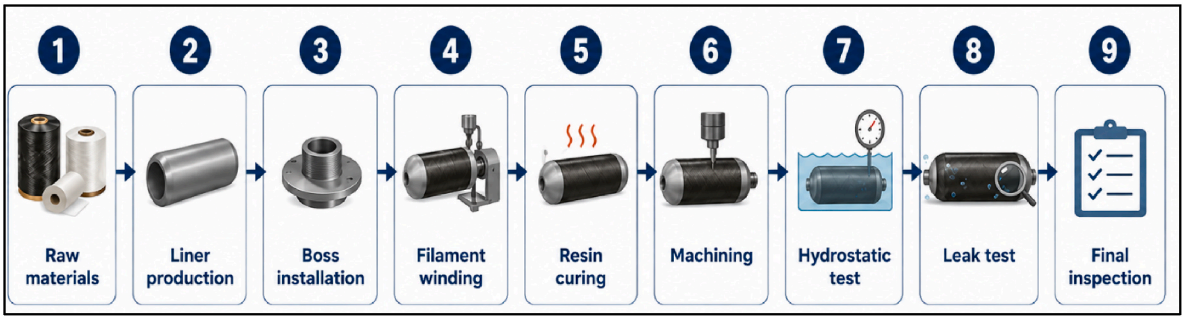

Fig. 1. Manufacturing workflow of a Type IV hydrogen storage tank.

The material distribution presented in Table 2 clearly demonstrates that carbon fiber dominates both the structural mass and manufacturing cost of the vessel. Therefore, improvements in composite design, fiber utilization efficiency, and advanced manufacturing techniques are expected to play a critical role in reducing the overall cost of future Type IV hydrogen storage tanks while maintaining their high mechanical performance and operational safety.

4. Techno-economic methodology for tank production cost estimation

This study employs a comprehensive techno-economic assessment (TEA) framework to estimate the manufacturing cost of high-pressure Type IV hydrogen storage tanks under industrial-scale production conditions. The methodology integrates raw material consumption, component costs, labor requirements, energy consumption, and manufacturing overheads to determine the unit production cost of tanks with capacities ranging from 26 kg to 180 kg at a nominal working pressure (NWP) of 700 bar.

The analysis is based on operational data obtained from an industrial Type IV hydrogen storage tank manufacturing facility located outside Türkiye, which is used as a reference case for the production process and manufacturing parameters. Owing to commercial confidentiality agreements, detailed information regarding the production facility and its operational specifications cannot be disclosed. To improve the applicability of the analysis to potential domestic manufacturing, region-specific economic parameters—including labor costs, electricity prices, and supply chain conditions in Türkiye—were incorporated into the cost model.

The production cost model considers all major cost elements associated with composite hydrogen tank manufacturing. These include raw materials (carbon fiber, polymer liner materials, and epoxy resin), auxiliary components (metallic bosses, valves, and fittings), direct labor, process energy consumption during filament winding and thermal curing, and indirect manufacturing overheads such as equipment maintenance, depreciation, insurance, and facility operation. Accordingly, the total unit production cost is expressed as

$$C_{tank} = C_{materials} + C_{\text{components}} + C_{\text{labor}} + C_{energy} + C_{\text{overhead}} \tag{4}$$

where C_{tank} represents the total manufacturing cost of a single hydrogen storage tank.

Among these cost categories, raw materials constitute the largest share of the total production cost, with carbon fiber reinforcement representing the dominant cost contributor because of both its high unit price and its substantial proportion of the composite structure. Consequently, the overall economic performance of Type IV hydrogen storage tanks is strongly influenced by carbon fiber pricing and material utilization efficiency.

To investigate the influence of storage capacity on manufacturing economics, the model was applied to multiple tank size scenarios. This enables the evaluation of cost scalability, identifies the contribution of each cost category, and provides insight into the economic feasibility of establishing domestic Type IV hydrogen storage tank production in Türkiye. A deterministic cost model was adopted to estimate the base-case manufacturing cost. The financial analysis assumes a 20-year plant lifetime, with capital investments annualized using the straight-line depreciation method. A discount rate of 8% was applied to represent typical industrial investment conditions. Total capital investment includes production equipment, manufacturing facilities, and supporting infrastructure, while working capital covers raw material inventories, labor expenses, and initial operating costs.

To evaluate the robustness of the proposed cost model, a sensitivity analysis was performed by varying the major economic parameters—including raw material prices, labor costs, component costs, and manufacturing overheads—by ±30%. The resulting uncertainty bounds quantify the influence of each parameter on the total production cost and identify the dominant economic factors governing the competitiveness of industrial-scale Type IV hydrogen storage tank manufacturing.

5. Cost analysis of Type IV hydrogen storage tank production

5.1. Raw material cost analysis

The raw material cost of Type IV hydrogen storage tanks is strongly influenced by tank size, material utilization, and structural configuration. As shown in Fig. 2, the raw material cost per kilogram of tank weight decreases significantly as the tank mass increases. For high-pressure (700 bar) Type IV hydrogen storage tanks equipped with a single valve and a top-opening configuration, the material cost decreases from approximately €60/kg for a 26 kg tank to €26.3/kg for a 180 kg tank. This reduction reflects the improved utilization of structural materials and the distribution of fixed components over a larger storage capacity, resulting in enhanced manufacturing economy for larger tanks.

For a representative Type IV hydrogen storage tank with a total mass of 103 kg, the estimated raw material cost is approximately €3143.7 per tank for the single-valve, top-opening configuration. This estimate

Table 2
Material composition and unit cost of Type IV hydrogen storage tank components.

Component	Material	Unit Cost (€)	Weight Share (%)	Function
Inner liner	PE–PA (Polyethylene–Polyamide)	€5.5/kg	9.6	Hydrogen gas barrier
Composite matrix	Epoxy resin	€7.7/kg	20.0	Binds carbon fibers and transfers load
Structural reinforcement	Carbon fiber	€27.5/kg	70.4	Primary load-bearing component
Tank neck and bottom set	Metallic alloy	€24.5/set	–	Structural closure and interface
Tank valve	Stainless steel valve	€998/unit	–	Hydrogen flow control and safety

includes the costs of the polymer liner, carbon fiber reinforcement, epoxy resin, metallic fittings, and valve components, but excludes manufacturing expenses such as labor, energy consumption, equipment depreciation, and factory overhead.

An alternative design employs a dual-valve configuration with both top and bottom openings. Under this configuration, the raw material cost ranges from approximately €99.4/kg for smaller tanks to €32/kg for larger tanks. Although the dual-valve system requires additional metallic fittings and valve components, the overall cost trend similarly decreases with increasing tank size owing to improved material utilization and structural efficiency.

The results indicate that economies of scale play a significant role in reducing the material cost of Type IV hydrogen storage tanks. As tank capacity increases, the contribution of fixed components becomes proportionally smaller, leading to lower specific material costs and improved cost-effectiveness for large-capacity hydrogen storage systems.

5.2. Raw material cost per stored hydrogen mass

The raw material cost normalized to the hydrogen storage capacity provides a more meaningful indicator for evaluating the economic performance of Type IV hydrogen storage tanks than the cost per unit tank mass. As illustrated in Fig. 3, the raw material cost for tanks equipped with a single valve and a top-opening configuration ranges from approximately €1560.5/kg H_2 for small-capacity tanks to €683.2/kg H_2 for large-capacity tanks.

The specific raw material cost decreases progressively with increasing hydrogen storage capacity, indicating that larger tanks achieve more efficient utilization of structural materials. Although the total amount of material increases with tank size, the hydrogen storage capacity increases at a faster rate, leading to a lower material cost per unit of stored hydrogen.

Fig. 3 demonstrates the beneficial effect of economies of scale on material utilization. The reduced specific material cost observed for larger tanks suggests that high-capacity Type IV hydrogen storage systems are economically more attractive for applications requiring large quantities of compressed hydrogen, such as heavy-duty transportation, stationary energy storage, and hydrogen distribution infrastructure.

5.3. Production capacity and manufacturing scale

The proposed manufacturing facility was designed to represent an industrial-scale production system for high-pressure Type IV hydrogen storage tanks. The reference production scenario assumes an annual manufacturing capacity of approximately 113,390 tanks based on the 103 L reference tank configuration, corresponding to approximately 667 standard 40-foot hydrogen container systems per year. The production line operates using an automated filament winding process under a two-shift production schedule, enabling high manufacturing efficiency and production consistency.

Assuming a plant lifetime of 20 years, the facility is capable of producing approximately 2.27 million hydrogen storage tanks, corresponding to a cumulative hydrogen storage capacity of approximately 8980 tonnes of hydrogen. This production scale represents a medium-to-large industrial manufacturing facility intended to support future hydrogen storage and transportation infrastructure.

Although the techno-economic analysis evaluates six different storage capacities, the 103 L tank was selected as the reference production case because it represents the most representative industrial configuration and provides a common basis for estimating annual production capacity, capital utilization, and manufacturing costs. The geometric characteristics of all investigated Type IV hydrogen storage tanks are summarized in Table 3.

The tank geometries adopted in this study were selected to be representative of commercially available 700-bar Type IV composite hydrogen storage vessels. The selected diameter and length combinations are consistent with industrial designs reported for automotive and light-duty hydrogen storage applications while maintaining practical length-to-diameter (L/D) ratios ranging from 2.5 to 4.3. These geometric parameters provide realistic manufacturing dimensions and enable a consistent comparison of production costs across different storage capacities.

The proposed manufacturing facility was designed to achieve a target annual production capacity of 113,390 Type IV hydrogen storage tanks, assuming 250 operating days per year under a two-shift production schedule. The production line is equipped with 29 automated five-axis CNC filament winding machines, which represent the primary manufacturing bottleneck and therefore determine the overall plant capacity.

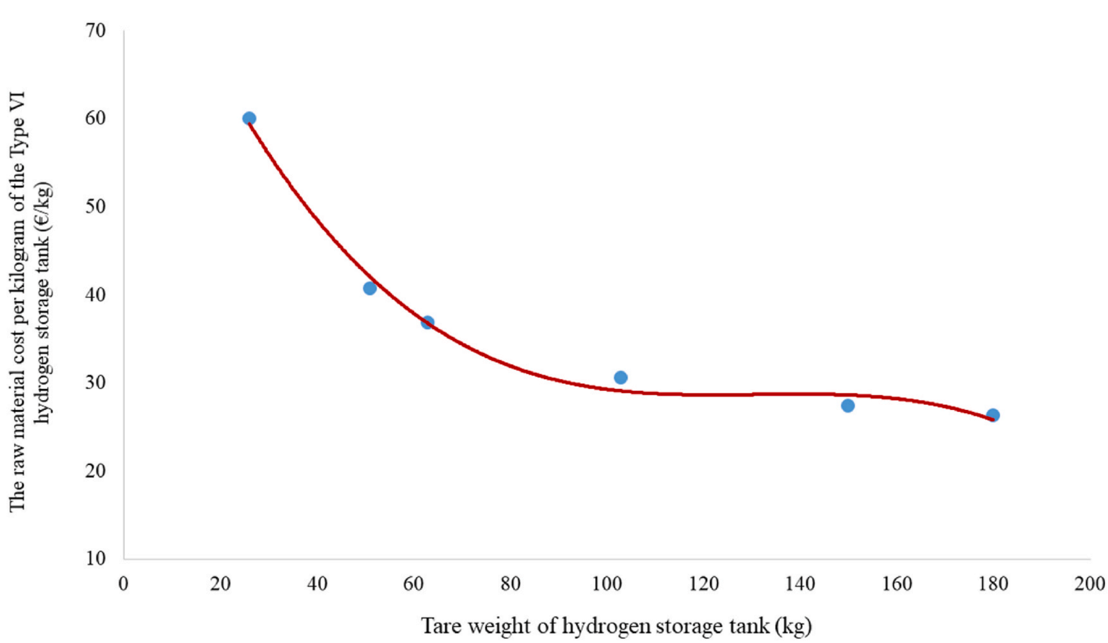

Fig. 2. Raw material cost per kilogram of Type IV hydrogen storage tank mass.

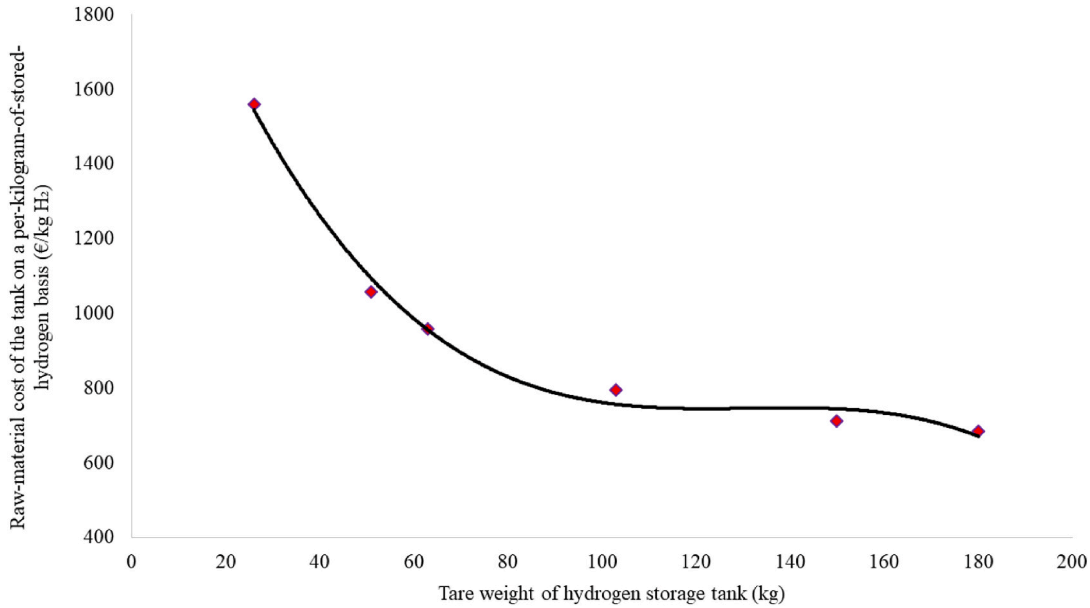

Fig. 3. Raw material cost per kilogram of stored hydrogen for Type IV hydrogen storage tanks.

Table 3
Geometric characteristics of the proposed Type IV hydrogen storage tanks.

Model Number	Water Volume (L)	H_2 Capacity (kg)	Diameter (mm)	Length (mm)	L/D Ratio
H026	26	0.9996	300	750	2.50
H051	51	1.9607	350	950	2.71
H063	63	2.4221	350	1170	3.34
H103	103	3.9599	400	1420	3.55
H150	150	5.7669	430	1750	4.07
H180	180	6.9203	450	1950	4.33

Based on the designed production rate, the average filament winding cycle time is approximately 61.4 min per tank, including winding operations and equipment handling. This cycle time is consistent with industrial manufacturing practices for high-pressure Type IV composite hydrogen storage vessels.

Each filament winding machine is operated by two production operators per shift, resulting in 58 blue-collar employees assigned to the filament winding section. Additional production personnel are allocated to liner manufacturing, metallic boss installation, resin preparation, curing, CNC machining, hydrostatic and helium leak testing, final inspection, material handling, warehouse operations, maintenance, and quality assurance.

The annual production capacity varies depending on the tank configuration because larger tanks require longer filament winding, curing, machining, inspection, and testing times. Consequently, the estimated production capacity ranges from approximately 240,400 tanks per year for the smallest tank configuration to approximately 74,170 tanks per year for the largest configuration, while maintaining the same manufacturing line configuration and operating conditions.

5.4. Labor requirement and production efficiency

5.4.1. Production assumptions

The techno-economic analysis was conducted based on the industrial production assumptions summarized in Table 4. The proposed manufacturing facility is assumed to operate 250 working days per year using a two-shift production schedule. Automated filament winding technology is adopted to ensure high manufacturing efficiency, process consistency, and product quality. A material scrap rate of 5% is considered throughout the production process, corresponding to an overall material utilization efficiency of 95%. Furthermore, the financial analysis assumes a plant lifetime of 20 years and applies a discount rate of 8% to annualize capital investments, representing typical industrial conditions for large-scale Type IV hydrogen storage tank production.

5.4.2. Workforce allocation

The proposed manufacturing facility operates continuously using two production shifts, employing 175 personnel per shift, resulting in a total workforce of 350 employees. The workforce consists of production operators, engineers, quality assurance personnel, maintenance technicians, and administrative staff, enabling continuous industrial-scale production while maintaining high manufacturing efficiency.

Of the total workforce, 140 employees per shift are assigned to blue-collar manufacturing operations, representing approximately 79.7% of the total personnel. These workers are responsible for all major production activities, including filament winding, liner production, boss installation, resin preparation, curing, machining, hydrostatic and leak testing, final inspection, material handling, and maintenance. The remaining 20.3% of employees consist of engineers, supervisors, quality specialists, and management personnel responsible for process optimization, production planning, quality management, and administrative coordination. Among the manufacturing operations, the filament winding department requires the largest workforce, with 58 operators assigned to 29 automated filament winding machines, corresponding to two operators per machine. This workforce distribution ensures balanced production flow, high equipment utilization, and effective quality control throughout the manufacturing process (Table 5).

Table 4
Production assumptions used in the techno-economic analysis.

Parameter	Value
Working days	250 days/year
Production schedule	2 shifts/day
Blue-collar employees	140 employees/shift
Manufacturing process	Automated filament winding
Scrap rate	5%
Material utilization	95%
Plant lifetime	20 years
Discount rate	8%

5.4.3. Labor cost analysis

Based on the proposed workforce structure and salary assumptions, the average monthly labor cost is estimated at €2394 per employee, resulting in a total annual labor expenditure of approximately €10.06 million. Blue-collar workers account for the majority of personnel costs owing to their large share within the workforce, whereas white-collar employees contribute primarily through engineering design, production supervision, quality assurance, and management activities (Table 6).

5.4.4. Energy consumption

Industrial electricity consumption was estimated using an average electricity price of €0.08/kWh, corresponding to the average tariff for industrial consumers in Türkiye in 2023. Electricity costs were calculated for all major manufacturing operations, including filament winding, thermal curing, machining, pressure testing, and auxiliary production systems.

Based on industrial operational data, the electricity consumption required to manufacture a single Type IV hydrogen storage tank ranges from approximately 99 kWh for the smallest tank to 261 kWh for the largest configuration. The curing ovens account for approximately 40% of the total energy demand, followed by filament winding (35%), while machining, testing, and auxiliary systems constitute the remaining energy consumption.

Although the energy consumption per tank increases with tank size, the total annual electricity demand of the facility remains approximately 20 GWh/year. This occurs because larger tanks require longer processing times and consequently reduce annual production volume, whereas smaller tanks can be manufactured at higher production rates. As a result, the overall utilization of manufacturing equipment remains relatively constant throughout the year.

5.4.5. Unit production cost

The detailed manufacturing cost breakdown for Type IV hydrogen storage tanks equipped with a single valve and a top-opening configuration is summarized in Table 7. The total manufacturing cost is divided into five principal components: raw materials, labor, energy, auxiliary components, and manufacturing overhead.

Raw material costs constitute the dominant portion of the manufacturing cost, increasing from €557.13 for the H026 tank to €3857.04 for the H180 configuration. In contrast, labor and energy costs represent only a small fraction of the overall production cost, contributing approximately 2–2.5% and less than 0.5%, respectively. Component and overhead costs exhibit moderate increases with tank size, reflecting the greater structural complexity and manufacturing requirements of larger pressure vessels.

The cost distribution demonstrates that the manufacturing economics of Type IV hydrogen storage tanks are governed primarily by raw material consumption, particularly carbon fiber reinforcement. Since more than 60% of the total production cost originates from carbon fiber, reductions in labor costs alone provide only limited improvements in overall manufacturing economics. Consequently, future cost reduction strategies should focus on improving carbon fiber utilization, optimizing composite lay-up design, increasing material recycling, and developing lower-cost precursor materials rather than solely reducing labor expenses.

Table 5
Workforce allocation for large-scale Type IV hydrogen storage tank manufacturing.

Production Section	Employees/Shift
Filament winding (29 machines × 2 operators)	58
Liner production & preparation	12
Boss installation	8
Resin preparation	8
Curing operation	10
Machining	12
Hydrostatic & leak testing	10
Final inspection & QA/QC	10
Material handling & warehouse	8
Maintenance & utilities	4
Total	140

Table 6
Annual personnel costs by employee category.

Employee Category	Number of Employees	Monthly Compensation (€)	Months	Annual Cost (€)
Blue-Collar	280	2000	12	6,720,000
White-Collar (Level 1)	36	3000	12	1,296,000
White-Collar (Level 2)	34	5000	12	2,040,000
Total	350	–	–	10,056,000

The calculated labor expenditure is incorporated into the techno-economic model as the labor cost component.

5.5. Sensitivity analysis

A sensitivity analysis was performed to evaluate the influence of key cost parameters on the manufacturing cost of Type IV hydrogen storage tanks. Variance-based sensitivity methods are widely employed in energy system modeling to quantify the impact of uncertain input parameters on economic performance [18,19]. In this study, ±30% variations were applied to four major cost categories: raw materials, components, overheads, and labor.

The results indicate that raw material cost is the dominant factor affecting the total manufacturing cost. A ±30% variation in raw material prices results in a total cost variation ranging from approximately ±10.2% to ±19.6%, depending on tank capacity. Larger-capacity tanks exhibit greater sensitivity because material consumption increases almost proportionally with hydrogen storage volume. This observation agrees with previous studies identifying carbon fiber as the principal cost driver in composite pressure vessels.

Component costs represent the second most influential parameter. A ±30% variation produces total cost changes ranging from ±5.2% to ±15.7%, indicating that metallic bosses, liners, valves, and auxiliary components remain important contributors to manufacturing cost, particularly for large-capacity tanks.

In contrast, overhead and labor costs exhibit relatively low sensitivity. A ±30% variation in overhead costs changes the total manufacturing cost by only ±4.4%–±4.9%, while the same variation in labor costs produces changes of only ±0.7%–±0.9%. These results demonstrate that indirect manufacturing expenses and labor constitute a relatively small fraction of the overall production cost.

The corresponding sensitivity trends are illustrated in Fig. 3, which clearly shows that raw material price fluctuations dominate the overall cost uncertainty.

To further evaluate the economic robustness of the proposed manufacturing process, several practical cost-reduction scenarios were investigated. As summarized in Table 8, reducing carbon fiber prices by 10% and 20% decreases the unit manufacturing cost from €3912 to €3690 and €3,470, respectively. By comparison, a 20% reduction in labor cost lowers the unit cost only to €3,890, while a 20% reduction in energy cost results in a marginal decrease to €3904. These findings confirm that carbon fiber cost dominates the overall manufacturing economics, whereas labor and energy costs have comparatively limited influence.

Because raw material prices, energy costs, and industrial production conditions may vary over time, the reported manufacturing costs should be regarded as nominal estimates rather than fixed values. Considering these uncertainties, the expected unit production cost is estimated to range between €4.8×10^3 and €5.4×10^3 per tank, depending primarily on carbon fiber price fluctuations and production scale.

Table 7
Detailed unit production cost breakdown for a single-valve, top-opening Type IV hydrogen storage tank.

	Cost component (€ per tank)					
	Raw Materials	Labor	Energy	Components	Overhead	Tank[a]
	$C_{materials}$	C_{labor}	C_{energy}	$C_{components}$	$C_{overhead}$	C_{tank}
H026	557.13	48.733	7.92	1022.5	318.11	1.954,4
H051	1092.83	62.024	10.08	1022.5	404.86	2.592,3
H063	1349.96	70.956	11.52	1022.5	463.17	2.918,1
H103	2207.08	88.695	14.40	1022.5	578,96	3.911,6
H150	3214.2	115.202	18.72	1022.5	751.98	5.122,6
H180	3857.04	132.383	20.88	1022.5	864.13	5.896,9
Share (%)	28.51–65.41	2.24–2.49	0.35–0.41	17.34-52.32	14.65–16.28	-

[a] Single valve, top opening.

5.6. Capital investment and operating cost assessment

To evaluate the industrial feasibility of large-scale Type IV hydrogen storage tank production, the capital investment requirements for establishing a commercial manufacturing facility were estimated using a bottom-up approach. The assessment considered land acquisition, factory construction, production equipment, utilities and infrastructure, installation and commissioning, engineering activities, and project management requirements.

The estimated total fixed capital investment (CAPEX) of the proposed manufacturing facility is approximately €116.3 million. As summarized in Table 9, land acquisition represents the largest investment component, accounting for approximately 51.6% of the total CAPEX, followed by factory construction (24.1%) and filament winding equipment (7.5%). These three categories constitute the major portion of the initial investment required for establishing a large-scale composite pressure vessel manufacturing plant.

The dominance of land and factory construction costs reflects the assumed industrial-scale production configuration, including a dedicated manufacturing site, production halls, auxiliary facilities, logistics areas, and utility infrastructure. The core manufacturing equipment includes semi-automated five-axis filament winding machines, industrial curing ovens, polymer liner production systems, hydrostatic pressure testing units, helium leak detection systems, CNC machining centers, resin preparation systems, and automated inspection stations.

The CAPEX estimation was developed based on the required production capacity, equipment specifications, plant layout requirements, and industrial manufacturing conditions. In addition to fixed capital investment, initial working capital requirements were estimated separately to account for production start-up needs, including raw material inventories, receivables, and operational cash requirements. Depreciation was not included because the objective of this study is to estimate manufacturing costs under industrial production conditions rather than to perform a complete financial investment appraisal.

In addition to fixed capital investment, the establishment of a commercial manufacturing facility requires significant initial operating resources. Table 10 summarizes the estimated working capital and first-year operating cost requirements.

The total initial operating requirement is estimated at approximately €290.4 million, including working capital, annual operating overheads, and raw material inventory requirements. Working capital was estimated at €22.0 million, covering initial production ramp-up requirements, inventories, receivables, and operational liquidity needs. Annual operating overheads were estimated at €18.1 million, including personnel costs, social security contributions, transportation, workwear, electricity consumption, equipment insurance, maintenance, certification, legal and financial services, and contingency allowances. The relatively high contribution of land cost is associated with the assumed industrial-scale production site, including dedicated manufacturing halls, logistics areas, storage facilities, and future expansion capacity.

The largest operational requirement is associated with raw material inventory, estimated at approximately €250.3 million for one year of production. This cost is primarily associated with carbon fiber, epoxy resin, polymer liner materials, and auxiliary composite materials. A

Table 8
Sensitivity analysis of Type IV hydrogen tank manufacturing cost under different cost reduction scenarios.

Scenario	Tank Cost (€)
Base case	3912
Carbon fiber −10%	3690
Carbon fiber −20%	3470
Labour −20%	3890
Energy −20%	3904

Table 9
Bottom-up estimation of capital investment requirements for an industrial-scale Type IV hydrogen storage tank manufacturing facility.

Investment Item	Cost (M€)	Share (%)	Description
Land	60.00	51.59	Industrial land (15,000 m^2)
Factory Building	28.00	24.08	Production building, offices, utilities, and auxiliary facilities
Filament Winding Machines	8.70	7.48	Twenty-nine semi-automated 5-axis CNC filament winding machines
Curing Ovens	2.50	3.61	Ten automated industrial composite curing ovens
Hydrostatic Testing Systems	1.05	2.75	Three fully automated hydrostatic pressure testing systems (1500–7000 bar), PLC-controlled and CE-certified
CNC Machining Centers	1.50	2.15	Four 5-axis CNC machining centers (±0.005 mm accuracy) for metallic bosses and composite finishing
Polymer Liner Production Lines	1.50	1.81	Two Type IV hydrogen liner extrusion blow molding lines
Utilities and Infrastructure	2.00	1.72	Electrical distribution, compressed air, cooling water, nitrogen supply, HVAC, fire protection, and process utilities
Boss Assembly Stations	0.45	1.29	Three automated metallic boss assembly stations
Resin Preparation Systems	0.24	1.29	Two automated epoxy resin preparation and dispensing systems
Warehouse and Logistics	3.20	0.90	3000 m^2 climate-controlled warehouse with storage racks, forklifts, and material handling systems
Final Inspection Stations	0.20	0.57	Two automated dimensional and visual inspection stations
Leak Test Stations	0.66	0.39	Three automated helium leak detection stations
Installation and Commissioning	4.20	0.21	Mechanical installation, electrical works, commissioning, and operator training
Engineering and Project Management	2.10	0.17	Process engineering, detailed engineering, automation, and project management
Total Capital Investment	**116.3**	**100**	

Table 10
Estimated initial working capital and one-year operating cost requirements for the proposed Type IV hydrogen storage tank manufacturing facility.

Investment Item	Cost (M€)	Share (%)	Description
Working Capital	22.00	7.58	Initial working capital to support production start-up, including inventories, receivables, and operating cash requirements.
Overheads (One-Year Operating Costs)	18.10	6.23	Annual operating overheads including salaries, social security contributions (SSI), withholding tax (€10.06 M), staff meals, transportation and workwear (€4.20 M), electricity (€0.60 M), machine insurance (€1.20 M), machine maintenance and consumables (€0.60 M), legal and financial advisory services (€0.24 M), production certification (€1.00 M), and contingency (€1.20 M).
Production Raw Material Cost	250.30	86.19	One-year raw material inventory for production, including polyethylene/polyamide (PE–PA) liner materials, epoxy resin, carbon fiber, and auxiliary composite materials. A unit raw material cost of €21.43 per kg of composite material was assumed.
Total	290.4	100	

composite material cost of €21.43 kg^{-1} was assumed throughout the analysis. The high contribution of raw material inventory highlights the strong dependence of Type IV hydrogen storage tank manufacturing economics on composite material availability and pricing.

The results indicate that although establishing a commercial-scale Type IV hydrogen storage tank manufacturing facility requires substantial upfront investment, the overall production economics are primarily controlled by raw material costs rather than capital expenditure or labor-related expenses. Therefore, improvements in carbon fiber availability, cost reduction through increased production capacity, recycling technologies, and regional composite material supply chains are expected to provide the greatest impact on manufacturing competitiveness.

At relatively low production volumes, fixed manufacturing costs contribute significantly to the unit production cost. However, as annual production volume increases, these fixed costs are distributed over a larger number of tanks, resulting in improved economic performance due to economies of scale. Under the investigated production scenarios, manufacturing costs gradually stabilize as annual production approaches approximately 100,000 tanks per year. Nevertheless, achieving such production levels requires reliable supply chains, sufficient market demand, and continued technological improvements in composite manufacturing.

For Türkiye, where carbon fiber supply is largely dependent on imports, establishing domestic carbon fiber production capacity and developing recycling infrastructure could significantly enhance the competitiveness and resilience of the hydrogen storage manufacturing sector by reducing exposure to international material price fluctuations.

5.7. *Quantitative production-scale effect and economic production threshold*

The effect of manufacturing scale on the unit production cost of the 700-bar Type IV hydrogen storage tank was further investigated using the H103 configuration as a fixed reference case. This additional analysis was introduced to distinguish the effect of annual production volume from the effect of tank storage capacity. This distinction is important because the six tank configurations investigated in the baseline techno-economic assessment simultaneously differ in tank size, material consumption, manufacturing cycle time, and annual production capacity. Consequently, a direct comparison of their unit costs cannot be interpreted solely as a production-scale effect.

The H103 configuration was therefore selected as the reference tank because it represents the intermediate configuration adopted as the baseline industrial production case in the techno-economic assessment. The H103 tank has a water volume of 103 L and a hydrogen storage capacity of 3.9599 kg, with an estimated filament-winding cycle time of 61.40 min and a nominal annual production capacity of 113,390 tanks/year.

Under the baseline manufacturing configuration, the H103 tank has an estimated unit production cost of €3911.6 per tank. The corresponding cost components are €2207.08 for raw materials, €88.695 for labor, €14.40 for energy, €1022.50 for components, and €578.96 for manufacturing overhead.

To isolate the influence of production scale, the H103 tank geometry, material requirements, component configuration, and manufacturing process were maintained constant, while the annual production volume was systematically varied between 25,000 and 113,390 tanks/year. This approach enables the effect of production-scale utilization and the distribution of fixed manufacturing costs over a larger production volume to be evaluated independently of tank size.

5.7.1. *Production-scale modelling approach*

The unit manufacturing cost was represented using a fixed-plus-variable cost formulation:

$$C_u(Q) = C_{var} + \frac{C_{fix}}{Q} \tag{5}$$

where $C_u(Q)$ is the unit manufacturing cost at an annual production volume Q, C_{var} represents the variable manufacturing cost per tank, and C_{fix} represents the annual fixed manufacturing cost.

For the H103 reference configuration, the variable component was initially represented by the raw-material, energy, and component costs:

$$C_{var} = C_{RM} + C_E + C_{Comp} \tag{6}$$

Using the baseline cost data

$$C_{var} = 2207.08 + 14.40 + 1022.5$$

and therefore:

$$C_{var} = 3243.98 \text{ €/tank}$$

The fixed-cost component was calibrated against the baseline H103 production case of 113,390 tanks/year and its corresponding unit manufacturing cost of €3911.6/tank. Accordingly:

$$C_{fix} = \left(C_{u,0} - C_{var}\right)\cdot Q_0 \tag{7}$$

where $C_{u,0} = 3911.6$ €/tank and $Q_0 = 113,390$ tanks/year. This gives an effective annual fixed-cost component of approximately €75.7 million/year for the scale-effect scenario.

Accordingly, the production-scale relationship used for the additional scenario analysis can be expressed as:

$$C_u(Q) = 3243.98 + \frac{75.7\cdot10^6}{Q}$$

This formulation should be interpreted as a scale-effect scenario model calibrated to the baseline techno-economic case, rather than as an independent accounting estimate of all fixed operating expenses.

5.7.2. *Effect of annual production volume on unit manufacturing cost*

Five production-volume scenarios were evaluated while maintaining the H103 tank configuration unchanged. The investigated production volumes were 25,000, 50,000, 75,000, 100,000, and 113,390 tanks/year. The final value corresponds to the nominal production capacity of the proposed industrial facility.

The corresponding capacity utilization levels were calculated relative to the nominal production capacity of 113,390 tanks/year:

$$U_Q = \frac{Q}{Q_{max}} \cdot 100 \quad (8)$$

where U_Q is the production-capacity utilization and Q_{max} is the nominal annual production capacity. The results are summarized in Table 11.

The results demonstrate a pronounced reduction in unit manufacturing cost as annual production volume increases. Increasing production from 25,000 to 100,000 tanks/year reduces the estimated unit manufacturing cost from approximately €6272 to €4001 per tank, corresponding to a reduction of approximately 36.2%. The corresponding specific storage cost decreases from approximately €1584 to €1010 per kg of stored hydrogen.

In contrast, increasing annual production from 100,000 to the nominal plant capacity of 113,390 tanks/year results in a comparatively small reduction in unit cost, from approximately €4001 to €3912 per tank, corresponding to only about 2.2%. This indicates that the economic benefit obtained from increasing production capacity becomes progressively smaller as the manufacturing line approaches its nominal utilization level.

The analysis therefore identifies an approximate economic production threshold of 100,000 tanks/year for the investigated manufacturing configuration. Beyond this range, additional increases in nominal production capacity provide relatively limited reductions in unit manufacturing cost. This result is consistent with the observation in the baseline techno-economic assessment that manufacturing costs tend to stabilize as annual production approaches approximately 100,000 tanks/year.

5.7.3. *Quantification of economies of scale*

The production-scale analysis provides a quantitative interpretation of the economies-of-scale effect rather than simply confirming its qualitative existence.

At low production volumes, fixed manufacturing costs are distributed over a relatively small number of tanks. Consequently, the fixed-cost contribution to each tank is relatively high. As production volume increases, the same effective fixed-cost burden is distributed over a larger number of units, resulting in a progressively lower unit manufacturing cost.

For example, increasing annual production from 25,000 to 50,000 tanks/year reduces the estimated unit manufacturing cost by approximately 24.1%. A further increase from 50,000 to 75,000 tanks/year results in an additional reduction of approximately 10.6%. However, the reduction decreases to approximately 5.9% when production increases from 75,000 to 100,000 tanks/year, and to only approximately 2.2% when production increases from 100,000 to 113,390 tanks/year.

This progressively diminishing reduction demonstrates that the economic benefit of scale expansion is non-linear. The greatest economic gains are obtained during the transition from low to medium production utilization, whereas further expansion toward full nominal capacity produces substantially smaller unit-cost reductions.

This finding provides a quantitative distinction between production-scale benefit and simple production-volume expansion. The results suggest that once the manufacturing system approaches approximately 88% utilization, corresponding to around 100,000 tanks/year, additional capacity expansion alone is unlikely to provide a proportionally significant reduction in unit manufacturing cost.

Table 11
Quantitative effect of production scale on the manufacturing cost of the H103 Type IV hydrogen storage tank.

Annual production volume	Capacity utilization	Unit manufacturing cost	Specific cost
(tanks/year)	(%)	(€/tank)	(€/kg H_2)
25,000	22.1	6272	1584
50,000	44.1	4758	1202
75,000	66.1	4253	1074
100,000	88.2	4001	1010
113,390	100.0	3912	988

5.7.4. *Distinguishing tank-capacity effects from production-scale effects*

An important contribution of the additional analysis is the separation of two effects that are coupled in the baseline six-tank comparison.

In the original analysis, the annual production capacity decreases from 240,400 tanks/year for H026 to 74,170 tanks/year for H180 because larger tanks require longer filament-winding cycle times. At the same time, larger tanks require substantially greater quantities of composite material, resulting in higher absolute production costs. For example, the unit manufacturing cost increases from €1954.4 for H026 to €5896.9 for H180.

Therefore, the difference between the costs of H026 and H180 cannot be attributed solely to economies of scale. Tank geometry, material consumption, manufacturing cycle time, and production capacity change simultaneously.

The additional H103 analysis overcomes this limitation by maintaining the tank configuration constant while varying only annual production volume. Consequently, the resulting cost trend isolates the effect of manufacturing scale and provides a clearer quantitative interpretation of economies of scale.

This distinction is particularly relevant because the baseline results already demonstrate that raw materials dominate the unit manufacturing cost. For the investigated configurations, raw-material costs increase from €557.13 for H026 to €3857.04 for H180, while labor and energy remain comparatively small contributors. Thus, separating production-scale effects from tank-size effects is necessary to correctly interpret the economic implications of large-scale manufacturing.

5.7.5. *Production Scale and Specific Hydrogen Storage Cost*

For a fixed H103 tank capacity of 3.9599 kg H_2, the unit manufacturing cost can also be normalized by the hydrogen storage capacity:

$$C_{H2} = \frac{C_u}{m_{H2}} \quad (9)$$

where C_{H2} is the manufacturing cost per kilogram of hydrogen storage capacity and m_{H2} is the hydrogen storage capacity of the tank.

The results show that increasing production volume from 25,000 to 113,390 tanks/year reduces the specific manufacturing cost from approximately €1584/kg H_2 to €988/kg H_2.

This reduction demonstrates that production-scale optimization can improve not only the cost per manufactured tank but also the economic cost of providing a unit of hydrogen storage capacity. The result is particularly relevant for large-scale hydrogen infrastructure, where the economic performance of storage systems depends on the cost of delivering storage capacity rather than the cost of an individual pressure vessel alone.

5.7.6. *Industrial implications*

The production-scale results have several implications for industrial deployment of Type IV hydrogen storage manufacturing.

First, establishing a manufacturing facility at a very low utilization rate can result in substantially higher unit costs because fixed manufacturing expenditures are distributed over a limited production volume. The estimated unit cost at 25,000 tanks/year is approximately 60% higher than that obtained at the nominal production capacity.

Second, increasing annual production toward approximately 100,000 tanks/year provides substantial economic benefits. The unit manu facturing cost decreases by approximately 36% between 25,000 and 100,000 tanks/year. This suggests that achieving sufficiently high production throughput may be more economically important than simply increasing the nominal capacity of individual manufacturing machines.

Third, the results indicate a diminishing economic return from additional scale expansion beyond approximately 100,000 tanks/year. At this point, the manufacturing system is already operating at approximately 88% of its nominal capacity, and increasing production to 113,390 tanks/year provides only a further 2.2% reduction in unit manufacturing cost.

Therefore, industrial investment decisions should not be based solely on maximizing nominal production capacity. Instead, the balance among production volume, equipment utilization, market demand, material availability, and unit manufacturing cost should be considered.

This is particularly important for Type IV hydrogen storage manufacturing because raw materials, especially carbon fiber, remain the dominant contributor to production cost. The baseline analysis shows that more than 60% of total production cost originates from carbon fiber, while labor and energy have comparatively limited effects. Consequently, once the production system reaches the identified high-utilization range, further cost reductions are likely to depend increasingly on material-price reduction, material utilization efficiency, recycling, and supply-chain optimization rather than production-volume expansion alone.

5.7.7. *Scientific contribution of the production-scale analysis*

The additional production-scale analysis extends the conventional techno-economic assessment by distinguishing the effects of tank capacity and manufacturing scale. Although economies of scale in composite pressure-vessel manufacturing have been reported previously, the present analysis quantitatively evaluates the scale effect for a fixed 700-bar Type IV tank configuration and identifies the production range over which additional manufacturing volume provides substantial economic benefits.

The results demonstrate that the scale effect is not simply a qualitative decrease in unit cost with increasing production volume. Instead, the economic benefit is strongly dependent on capacity utilization and exhibits a diminishing-return behavior as the production line approaches its nominal throughput. Accordingly, the principal scientific insight of this analysis is the identification of an approximate economic production threshold of 100,000 tanks/year for the investigated industrial configuration. Below this range, increasing production volume provides substantial unit-cost reductions, whereas further expansion toward the nominal capacity of 113,390 tanks/year provides only marginal additional economic benefit. The proposed approach therefore provides a quantitative basis for evaluating the production scale required to achieve economically competitive manufacturing of 700-bar Type IV hydrogen storage tanks.

6. Results and discussion

6.1. *Interpretation of the cost structure*

The present study provides a comprehensive techno-economic assessment of industrial-scale Type IV hydrogen storage tank manufacturing by integrating raw material cost modelling, manufacturing process analysis, production capacity estimation, capital investment evaluation, operating expenditure assessment, and sensitivity analysis. The results demonstrate that manufacturing cost is primarily governed by material consumption, production scale, and tank capacity, highlighting the importance of economies of scale for reducing the cost of hydrogen storage systems.

The analysis indicates that raw material costs represent the dominant contribution to the total manufacturing cost, with carbon fiber being the most influential cost component due to its high unit price and significant contribution to the composite overwrap. This observation is consistent with previous techno-economic studies of composite pressure vessels. However, the present study further demonstrates that the dependence on carbon fiber remains significant under industrial-scale production assumptions and Türkiye-specific economic conditions.

Cost reduction strategies based solely on reductions in labor or operational expenses are unlikely to provide substantial improvements in overall manufacturing economics. Instead, future cost reduction efforts should focus on improving carbon fiber utilization efficiency, reducing composite material waste, developing cost-effective reinforcement materials, and strengthening regional composite material supply chains.

6.2. *Scale effects and engineering interpretation*

The results demonstrate that increasing hydrogen storage capacity increases the absolute manufacturing cost due to higher composite material requirements. However, when normalized by the stored hydrogen mass, the manufacturing cost decreases significantly with increasing tank capacity.

This behavior is primarily associated with economies of scale in composite pressure vessel manufacturing. Although variable costs, particularly composite material consumption, increase with tank size, fixed and semi-fixed manufacturing costs—including tooling, engineering activities, quality assurance, facility operation, and equipment utilization—are distributed over a larger hydrogen storage capacity. As a result, larger tank configurations achieve improved cost efficiency.

From an engineering perspective, this improvement is also related to geometric scaling effects. The reduction in the surface-area-to-volume ratio with increasing vessel dimensions decreases the amount of composite material required per unit of stored hydrogen. Therefore, larger tanks provide improved material utilization efficiency and lower manufacturing costs per kilogram of hydrogen storage capacity.

Nevertheless, increasing tank size introduces practical limitations. Larger composite vessels require longer filament winding and curing cycles, specialized manufacturing equipment, more complex transportation and handling procedures, and additional integration requirements. Therefore, the optimum tank size should be determined by balancing economic advantages with application-specific constraints, including vehicle packaging, installation space, safety requirements, and manufacturing capability.

6.3. *Sensitivity of key cost drivers*

The sensitivity analysis confirms that raw material cost variations have the strongest impact on total manufacturing cost, whereas labor and overhead costs have a comparatively limited influence. This result is mainly attributed to the high contribution of composite materials, particularly carbon fiber, within the overall cost structure of Type IV hydrogen storage tanks.

Carbon fiber prices are strongly influenced by precursor availability, energy prices, and demand from aerospace, automotive, and renewable energy sectors. Therefore, hydrogen storage manufacturing remains highly sensitive to fluctuations in global composite material markets.

The influence of carbon fiber price becomes increasingly significant for larger tanks because composite material consumption increases with storage capacity. In contrast, fixed manufacturing expenses, such as engineering support, tooling, facility operation, and quality control, become less significant when distributed over a larger hydrogen storage capacity.

Unlike conventional cost assessments that primarily evaluate a single tank configuration, the present study quantifies the influence of multiple cost categories across six different storage capacities within a unified industrial manufacturing framework. This approach provides additional insight into the economic robustness and scalability of Type IV hydrogen storage production.

However, the deterministic sensitivity analysis applied in this study evaluates each parameter independently. Interactions between simultaneous variations in carbon fiber price, energy cost, labor expenses, and production volume were not considered. Future studies should therefore employ probabilistic approaches, including Monte Carlo simulation and global sensitivity analysis, to quantify uncertainty propagation under dynamic market conditions.

6.4. Comparison with previous studies

Table 11 compares the manufacturing costs obtained in this study with representative techno-economic analyses and commercial market values reported in the literature.

The estimated costs are generally consistent with previous studies conducted by the U.S. Department of Energy (DOE), the National Renewable Energy Laboratory (NREL), and other researchers when differences in tank capacity, production volume, manufacturing assumptions, and currency basis are considered.

Although variations exist due to differences in carbon fiber price assumptions, regional labor costs, production scale, and manufacturing configurations, all studies consistently identify carbon fiber composite materials as the dominant cost contributor in Type IV hydrogen storage tanks.

The main contribution of the present study is the integration of industrial manufacturing assumptions with region-specific economic parameters representative of Türkiye. Furthermore, evaluating six different tank capacities within a single production framework provides additional insight into manufacturing scalability and cost evolution compared with studies focusing on individual tank configurations.

Table 11 compares the manufacturing costs estimated in the present study with previously reported techno-economic assessments and commercial market values. Although differences exist in production scale, tank capacity, manufacturing assumptions, and cost basis, the reported values show consistent trends regarding the dominant contribution of carbon fiber composite materials. The present results provide additional insight into industrial-scale production costs under Türkiye-specific economic conditions.

6.5. Industrial and policy implications

The findings provide important implications for industrial stakeholders and hydrogen economy development strategies.

From an industrial perspective, improving the competitiveness of Type IV hydrogen storage manufacturing will depend primarily on reducing material-related costs rather than minimizing labor expenses. Investments in domestic carbon fiber production, recycled carbon fiber technologies, automated filament winding systems, and advanced manufacturing processes could significantly improve production economics.

For policymakers, the results highlight the importance of developing integrated hydrogen technology supply chains, including composite material production, storage system manufacturing, and hydrogen infrastructure deployment. Supporting domestic manufacturing capabilities may enhance technological competitiveness and reduce dependence on imported high-value materials.

Furthermore, the proposed techno-economic methodology can support investment decisions by identifying the parameters with the greatest influence on manufacturing cost and by evaluating the economic consequences of different production scenarios.

6.6. Study limitations and research outlook

Although the proposed techno-economic model provides valuable insights into industrial-scale Type IV hydrogen storage manufacturing, several limitations should be considered.

First, the analysis is based on a deterministic bottom-up cost estimation approach using representative industrial manufacturing assumptions. Second, uncertainty evaluation was limited to deterministic sensitivity analysis, and probabilistic uncertainty methods were beyond the scope of this study. Third, detailed operational data from industrial manufacturing facilities could not be disclosed due to confidentiality restrictions, although the modelling assumptions were developed based on industrial production conditions and validated against published literature.

In addition, the present study focuses primarily on manufacturing economics and does not include comprehensive financial investment indicators such as discounted cash flow analysis, net present value (NPV), internal rate of return (IRR), or payback period. Environmental aspects, including lifecycle assessment (LCA), embodied carbon emissions, and circular material utilization, were also not considered.

Future research should extend the proposed methodology by integrating probabilistic techno-economic modelling, lifecycle sustainability assessment, and hydrogen supply chain optimization. Combining manufacturing cost analysis with hydrogen production, transportation, and storage infrastructure models would provide a more comprehensive evaluation of the role of Type IV hydrogen storage systems in future hydrogen energy applications.

7. Conclusions

This study presents a comprehensive techno-economic assessment of the industrial-scale manufacturing of 700-bar Type IV hydrogen storage tanks under Türkiye-specific economic conditions. A bottom-up manufacturing cost model was developed by integrating raw material consumption, labor, energy, component costs, manufacturing overhead, production capacity, and capital investment requirements. The framework was applied to six tank configurations with storage capacities ranging from 26 to 180 L, enabling their economic performance to be evaluated under consistent industrial manufacturing assumptions.

The results demonstrate that raw material costs, particularly carbon fiber composites, are the dominant contributors to manufacturing cost across all investigated configurations. Although larger tanks require greater absolute material consumption and higher cost per tank, their economic performance is influenced by hydrogen storage capacity, material utilization, and production requirements. Sensitivity analysis further shows that raw material price variations have a substantially greater effect on total manufacturing cost than changes in labor, energy, and overhead costs, highlighting the importance of carbon fiber cost and material efficiency.

An important scientific contribution of this study is the quantitative separation of tank-capacity effects from manufacturing-scale effects. In the baseline comparison, tank size, material consumption, manufacturing cycle time, and annual production capacity vary simultaneously, preventing unit-cost differences from being attributed solely to economies of scale. To overcome this limitation, a fixed-configuration production-scale analysis was performed using the H103 tank while maintaining its geometry, storage capacity, material requirements, and manufacturing conditions constant.

The production-scale analysis demonstrates a strongly nonlinear relationship between production volume and unit manufacturing cost. Increasing annual production from 25,000 to 100,000H103 tanks/year reduces the estimated unit manufacturing cost by approximately 36.2%, whereas further expansion to the nominal capacity of 113,390 tanks/year provides only an additional 2.2% reduction. The corresponding specific manufacturing cost decreases from approximately €1584 to €1010/kg H_2 between 25,000 and 100,000 tanks/year and to approximately €988/kg H_2 at nominal capacity. The results identify an approximate economic production threshold of 100,000 tanks/year, beyond which further capacity expansion alone provides limited cost benefits. This quantitative relationship extends conventional techno-economic assessment by identifying the production range over which economies of scale provide substantial benefits for a fixed 700-bar Type IV configuration.

The combined results indicate that production-scale optimization and material-cost reduction should be pursued as complementary strategies. At low production volumes, fixed manufacturing costs are distributed over fewer tanks, increasing unit cost. As production approaches approximately 100,000 tanks/year, the benefit of further scale expansion diminishes. Beyond this level, additional cost reductions are expected to depend increasingly on carbon fiber price reduction, improved composite-material utilization, reduced material waste, and manufacturing-process optimization. Domestic carbon fiber production, recycled carbon fiber utilization, advanced filament-winding technologies, automation, and supply-chain integration may therefore provide significant opportunities for further cost reduction.

From an industrial perspective, investment decisions should not focus solely on maximizing nominal production capacity. Production volume, capacity utilization, tank configuration, material prices, equipment requirements, and market demand should be evaluated simultaneously. The identified 100,000-tank/year threshold provides a quantitative reference for industrial facility planning and for assessing alternative production strategies.

The developed techno-economic framework provides a practical decision-support tool for industrial stakeholders, investors, and policymakers by integrating manufacturing cost modelling, production-capacity assessment, capital investment estimation, operating-cost analysis, sensitivity analysis, and production-scale assessment. Although calibrated to economic conditions representative of Türkiye, the framework can be adapted to other regions by modifying local labor, energy, material, equipment, and capital-investment parameters.

Several limitations should be considered. First, the model uses a deterministic bottom-up approach; probabilistic uncertainty analysis and interactions among multiple economic variables were not evaluated. Second, although capital investment was considered, comprehensive financial indicators such as discounted cash flow, NPV, IRR, and payback period were beyond the scope of this study. Third, environmental indicators, including lifecycle assessment, carbon footprint, and embodied emissions, were not included. In addition, some manufacturing parameters were derived from confidential industrial operational data; although calibrated using published literature and regional economic conditions, detailed facility-level information could not be disclosed.

Future research should extend the framework through probabilistic techno-economic modelling, including Monte Carlo simulation and global sensitivity analysis. Integration of financial investment analysis, lifecycle sustainability assessment, and hydrogen supply-chain optimization would provide a more comprehensive assessment of commercial viability. Further investigation of recycled carbon fiber, alternative composite materials, digital-twin-based manufacturing optimization, advanced automated production technologies, and material-efficient vessel designs could further reduce manufacturing costs and accelerate the deployment of high-pressure hydrogen storage systems.

Study	Application	H_2 Capacity	Production Assumption	Cost Basis	Manufacturing Cost
DOE	Automotive	5.6 kg	500,000 tanks/year	2005 USD (adjusted to 2023 EUR)	~€5200
This study	Industrial storage	1.00–6.92 kg (26–180 L)	26 L: 240,400 tanks/year 180 L: 74,170 tanks/year	2023 EUR	€1954–5897
Commercial Market (2025)	Automotive & Industrial storage	3.85–5.77 kg	Not disclosed	2025 EUR	€2625–6562

Note: The DOE manufacturing cost was originally reported as USD 3490 per tank (constant 2005 dollars). For comparison with the present study, this value was adjusted to 2023 EUR using the U.S. Consumer Price Index (CPI) and the average 2023 USD/EUR exchange rate, resulting in an equivalent manufacturing cost of approximately EUR 5200 per tank.

CRediT authorship contribution statement

Zuhal Oktay: Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Conceptualization. **Can Coskun:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Fedai İnanır:** Investigation, Data curation, Conceptualization, Funding acquisition, Formal analysis, Project administration. **Muzaffer Erdoğan:** Resources, Validation, Visualization, Investigation. **Şükrü Yildiz:** Formal analysis, Data curation, Project administration, Software. **Engin Erbayrak:** Conceptualization, Investigation, Methodology. **Alperen Oktay:** Investigation, Conceptualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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