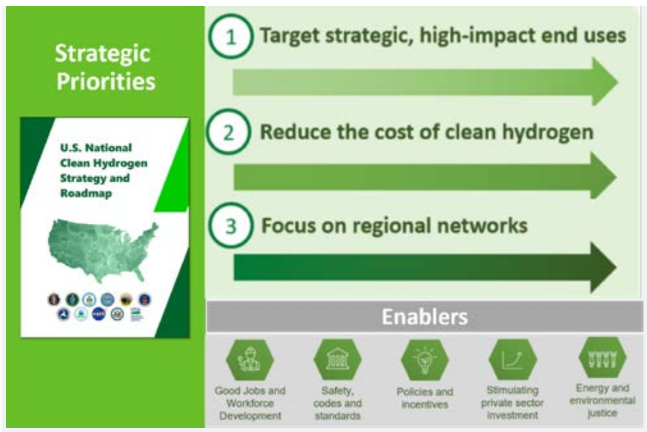
4 Hydrogen Infrastructure

4.1 Overview

Goals and Objectives

The goal of the **Hydrogen Infrastructure** subprogram is to accelerate innovations in R&D to enable commercialization and large-scale adoption of efficient and durable clean hydrogen technologies with a focus on the storage, transmission, distribution, delivery, and dispensing of hydrogen for various delivery pathways and end uses. The Hydrogen Infrastructure subprogram works closely with the Hydrogen Production subprogram to advance the R&D needed to deploy clean hydrogen technologies. *Hydrogen infrastructure* refers to the technologies used for transmission, distribution, storage, and dispensing of hydrogen—from the point of production to the end-use application. The Hydrogen Infrastructure subprogram's RD&D primarily focuses on reducing the cost and improving the reliability of current hydrogen infrastructure options for today's end uses.

The Hydrogen Infrastructure subprogram supports key strategic priorities identified by the **DOE Hydrogen Shot** and the ***U.S. National Clean Hydrogen Strategy and Roadmap***[48] to ensure that clean hydrogen is developed and adopted as an effective decarbonization tool for maximum benefit to the United States. The subprogram directly supports the strategic priority to reduce the cost of clean hydrogen, foundational to all the priorities; and it coordinates closely with the other HFTO subprograms to support priorities targeting strategic high-impact uses for clean hydrogen and focusing on regional networks.



Second to the cost of clean hydrogen to the end user, the need for sufficient infrastructure has been identified as an important priority.

RD&D solutions pursued by the Hydrogen Infrastructure subprogram will take a holistic approach that considers both the hydrogen production method and end use. For example, the left and central parts of Figure 4.1 show the various types of production, delivery, and storage technologies that can be linked together into various pathways that support diverse clean hydrogen end uses. Interdependencies among the technologies and processes create unique challenges that can be addressed through RD&D. As an example, the approach chosen for hydrogen distribution (gaseous, liquid, or hydrogen carrier) affects the storage options and

[48] U.S. Department of Energy. *U.S. National Clean Hydrogen Strategy and Roadmap.* 2023. https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

overall cost and efficiency of the pathway. For each end-use application, an optimized integration of production, delivery, and storage technologies throughout the entire pathway is needed to enable competitive, efficient, and clean hydrogen opportunities.

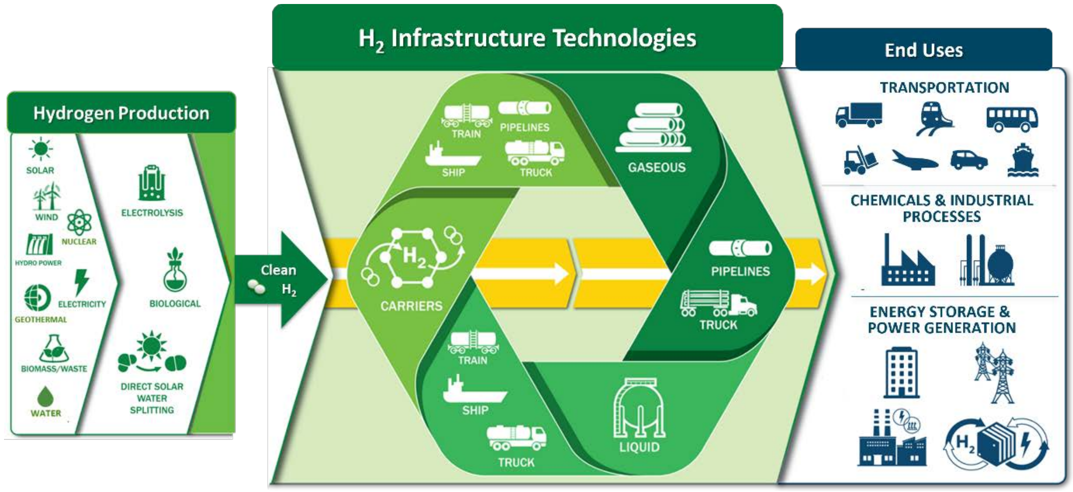


Figure 4.1. Hydrogen Infrastructure Technologies takes a holistic approach that considers the entire pathway from clean hydrogen production through delivery and storage, including storage both during delivery and at the end-use application.

Infrastructure Technologies for Hydrogen Delivery and Storage

RD&D in the Hydrogen Infrastructure subprogram focuses on advancing technologies to lower the cost while enhancing the performance and durability of diverse hydrogen delivery and storage options for different end use applications, specifically addressing market-driven requirements for technology development in each end use.

Hydrogen Delivery

Delivery is an essential component of any future hydrogen infrastructure. It encompasses those processes needed to transport hydrogen from a central or semicentral production facility to the final point of use and those required to feed the energy carrier directly to a given end-use application. Successful commercialization of clean hydrogen systems, including those used in vehicles, backup power sources, distributed power generators, and chemical processing, will likely depend on a hydrogen delivery infrastructure that provides the same level of safety, convenience, and functionality as existing liquid and gaseous fossil fuel-based infrastructures. Because hydrogen can be produced from a variety of domestic resources, its production can take place in large, centralized plants or in a distributed manner, directly at fueling stations, stationary power, and chemical and industrial process sites. As such, the hydrogen delivery infrastructure will need to integrate with these various hydrogen production options.

Hydrogen can be transported and distributed as either a compressed gas or a cryogenic liquid, or it can be bound within a chemical hydrogen-carrier material. Figure 4.1 illustrates the variety of options for delivering hydrogen from the point of production to the intended end use. Each of the transport and distribution methodologies requires a range of technologies, such as compressors, liquefiers, and dispensing technologies (which will need to meet the specific needs for each end-use application). The Hydrogen Infrastructure subprogram's RD&D focuses on developing these technologies to meet targets for dispensed hydrogen to the end user. It's also working to identify materials for hydrogen infrastructure technologies (e.g., pipelines, compressors, pressure vessels) that are compatible with hydrogen or hydrogen blends (e.g. hydrogen blended with natural gas) under various operating conditions.

The type of hydrogen delivery infrastructure installed in a region for a specific end use depends on several key aspects of hydrogen demand, including:

- The **quantity** of hydrogen that the end user requires, including if the demand is constant or intermittent.
- The **purity** or quality of hydrogen that the end user requires.
- The **location** of end users, including their proximity to one another and their proximity to hydrogen production.
- The **outlook** for hydrogen demand and the accuracy with which it can be predicted.
- The **price points** that hydrogen must achieve to be competitive in its end uses.

Hydrogen Storage

Technologies for enabling efficient and affordable hydrogen storage are key for the advancement of hydrogen and fuel cell technologies in an array of applications, including stationary power, portable power, and transportation. As an example, hydrogen can be used as a medium to store clean energy created by intermittent renewable power sources (e.g., wind and solar) during periods of high availability and low demand, increasing the utilization and benefits of the large capital investments in these installations. The stored hydrogen can be used during peak hours; as system backup; or for portable, transportation, or industrial applications.

Because of the low energy density of gaseous hydrogen at room temperature and pressure compared with conventional liquid fuels, hydrogen in current applications is most often *physically* stored as either a compressed gas in pressure vessels or geological formations, or as a cryogenic liquid in double-walled insulated vessels, as illustrated in Figure 4.2. Also shown in the figure are additional advanced *materials-based* approaches to meet storage targets for a growing number of end uses. Hydrogen storage options in the Hydrogen Infrastructure subprogram's RD&D portfolio include physical storage technologies as well as reversible and nonreversible materials-based storage. Approaches for very large-scale bulk storage (such as geological storage) are also under investigation. Infrastructure technologies supporting these different options are needed to accommodate the various scales of hydrogen storage and delivery for different end uses.

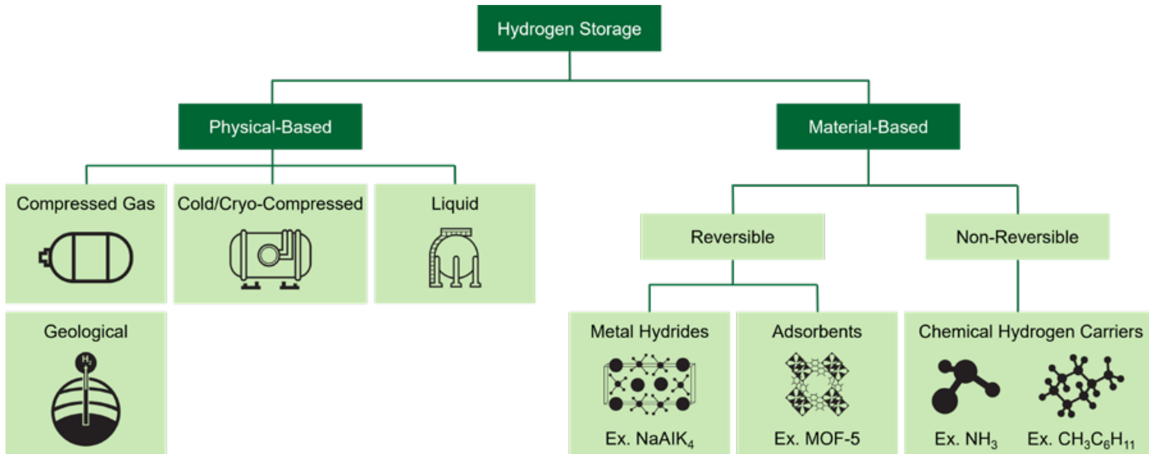


Figure 4.2. Multiple options for hydrogen storage to meet different storage, transport, and end-use requirements, including physical gaseous or liquid storage as well as storage in materials and chemical H_2 carriers

4.2 Strategic RD&D Priorities

The Hydrogen Infrastructure subprogram's overarching strategic framework addressing RD&D for clean hydrogen storage and delivery in the near-, mid-, and longer term is depicted in Figure 4.3. The subprogram works in close coordination with the other HFTO subprograms in support of strategic priorities described in the Introduction.

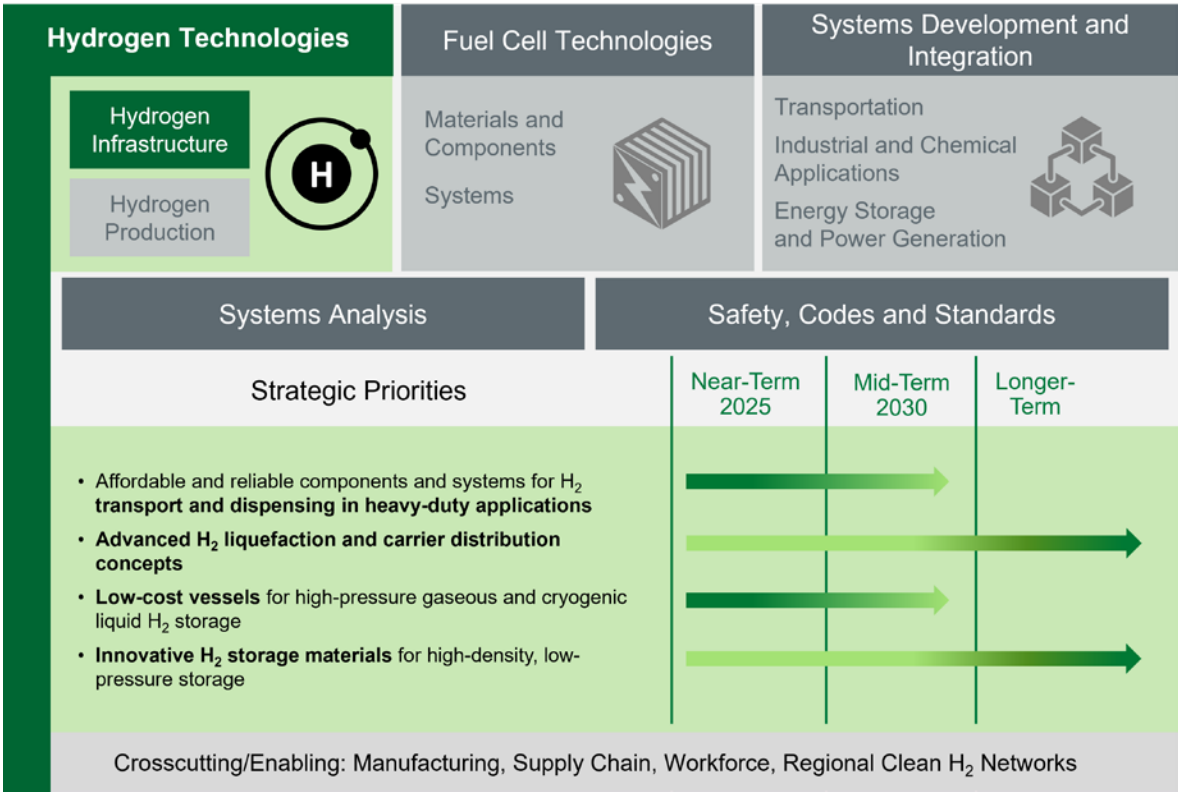


Figure 4.3. Strategic priorities guiding hydrogen storage and delivery infrastructure RD&D

Near- to Mid-Term Priorities

Hydrogen storage technology development for near-term, early market fuel cell applications is focused on developing technologies that can provide an adequate amount of hydrogen to enable efficient operation to meet customer-driven performance metrics in a safe, convenient, and cost-effective package. Targeted metrics are closely related to the operating requirements of the application, such as capacity (i.e., run-time), refill and discharge kinetics, durability, and operability. However, for hydrogen to be competitive with more established incumbent technologies such as batteries and diesel gen-sets, costs must be reduced for all system components, including hydrogen storage. In the near- to mid-term, strategic priorities include affordable and reliable components and systems for H_2 transport and dispensing in heavy-duty vehicle applications as well as materials and components for advanced H_2 liquefaction and carrier distribution concepts.

- **Low-Cost Vessels for High-Pressure Gaseous and Cryogenic Liquid H_2 Storage:** RD&D to improve physical storage methods is primarily focused on reducing cost and minimizing losses from tanks and other technologies in use today for compressed gaseous and liquid hydrogen storage. Compressed gaseous hydrogen can also be contained in bulk in caverns (i.e., underground rock-lined or salt caverns) for long-duration storage applications; however, this approach is limited to specific geographical areas. Novel physical storage technologies that address shortcomings of current technologies are also being investigated, such as compressed storage at subambient temperatures to increase the hydrogen density and subsurface storage options that are more geographically available. For all current and near-term hydrogen storge options, continued research and optimization are needed to reduce cost and ensure safety.

- **Near- to Mid-Term Hydrogen Transport and Dispensing for Heavy-Duty (and Other Near-Term) Applications:** In the near- to mid-term, for heavy-duty vehicle applications, it is expected that most of the hydrogen will be delivered as a compressed gas (either via pipeline or using high-pressure tanks), delivered as a cryogenic liquid, or produced onsite. Most hydrogen supplied via pipeline today is for use in petroleum refining. For other current end uses in the transportation, industrial, and chemical sectors, when large quantities of hydrogen are required, hydrogen production is in close proximity to the demand. Otherwise, hydrogen is commonly transported and stored as either a high-pressure compressed gas (via pipeline or truck) or cryogenic liquid (via tanker). As hydrogen production increases in geographic areas with excess clean renewable energy resources, and demand increases for new and emerging applications such as steel production, it is expected that additional hydrogen pipeline installations will occur. Hydrogen may also be blended with natural gas, thus enabling a partial decarbonization of natural gas use and making use of the extensive existing national pipeline network. To meet the needs of heavy-duty transportation applications, processes and hardware components that can meet the dispensing requirements, including fueling rates, need to be developed. Near- and mid-term RD&D efforts are focused on reducing the cost of these technologies, ensuring the safety of materials used in hydrogen operations and minimizing the losses of hydrogen that occur during transport and dispensing.

Mid- to Longer-Term Priorities

Longer-term RD&D in the Hydrogen Infrastructure subprogram is focused on developing low-cost solutions and new opportunities in affordable hydrogen storage.

- **Innovative Hydrogen Storage Materials for High-Density, Low-Pressure Storage:** Longer-term RD&D is focused on material-based options such as adsorbents, metal hydrides, and chemical hydrogen carriers to open new opportunities in affordable hydrogen storage. These approaches offer the potential to achieve comparable and potentially superior hydrogen storage densities, but at near-ambient operating conditions, without the need for high pressures (as in compressed hydrogen storage) or very low temperatures (as in liquid hydrogen storage), both of which add significant costs and expenditures of energy to the entire pathway. Some of these technologies may also be compatible with existing infrastructure currently in use for other applications, such as oil and gas infrastructure.

- **Advanced H_2 Liquefaction and Carrier Distribution Concepts:** In the longer term, the subprogram seeks to lower the cost of large-scale distribution infrastructure through breakthrough concepts for low-cost, scalable liquefaction and through the development of hydrogen carrier materials to enable bulk hydrogen transport (e.g., coast-to-coast or internationally). Additional RD&D that can support large-scale distribution includes materials research to enable leveraging of natural gas infrastructure in hydrogen use (e.g., hydrogen blending in pipelines) and high-throughput compressors to enable higher volume pipelines.

4.3 RD&D Targets

Target-Setting

The Hydrogen Infrastructure subprogram's RD&D strategy is driven by application-specific targets for the performance, durability, cost, and scale of hydrogen storage and delivery technologies needed to enable cost-competitiveness of clean hydrogen in diverse end uses. Different targets are developed holistically based on the ultimate life cycle cost of storing and delivering clean hydrogen meeting end-use-specific requirements for pressure, temperature, purity, etc. Target-setting is guided by comprehensive modeling and analysis of the different technology options at the materials, components, and systems level. Publicly available and industry-vetted manufacturing cost estimates are incorporated in the analysis to accurately gauge the status and future potential of the technology.

Hydrogen Infrastructure Interim Target Examples

Hydrogen Storage

- Onboard hydrogen storage systems for transportation: $8/kWh stored at 2.2 kWh/kg and 1.7 kWh/L
- High-volume cost of high-strength carbon fiber for tanks: $14/kg

Large-Scale Hydrogen Production, Delivery, and Dispensing

- $7/kg for transportation end uses in early markets (2030)
- $4/kg for ultimate market expansion for high-value products (2030)

Application-Specific Targets

As an example, specifically relevant to its near-term priorities in the transportation sector, the subprogram has developed interim and ultimate cost targets to enable market-competitiveness of onboard storage of pressurized hydrogen in carbon-fiber-wrapped tanks for heavy-duty fuel cell vehicles, as shown in Table 4.1. The technology-agnostic storage system cycle life target in the table represents the minimum number operational cycles required for the entire useful life of a vehicle used in long-haul operation. Pressurized storage systems must meet cycle life requirements in applicable codes and standards (i.e. SAE J2579 and United Nations Global Technical Regulation No. 13), which require significantly more cycles than the storage system cycle life. The hydrogen storage system cost includes the storage tank and all necessary BOP components.

Table 4.1. Hydrogen Storage Targets for Class-8 Vehicles

Characteristic	Units	Interim Target (2030)	Ultimate Target
Hydrogen Fill Rate	kg H_2/min	8	10
Storage System Cycle Life	cycles	5,000	5,000
Pressurized Storage System Cycle Life	cycles	11,000	11,000
Hydrogen Storage System Cost	$/kWh ($/kg H_2 stored)	9 (300)	8 (266)

Recognizing that both technology advancements as well economies of scale are needed for meeting the cost targets, the subprogram has identified key cost drivers related to materials, component, system, manufacturing, scale-up, and supply chain challenges, and it focuses RD&D to address these challenges. The waterfall chart in Figure 4.4 shows how addressing specific challenges can contribute to overall cost reductions aimed at meeting the ultimate cost target of $8/kWh ($266/kg H_2 stored) for a 700-bar onboard hydrogen storage system for long-haul tractor-trailer trucks.

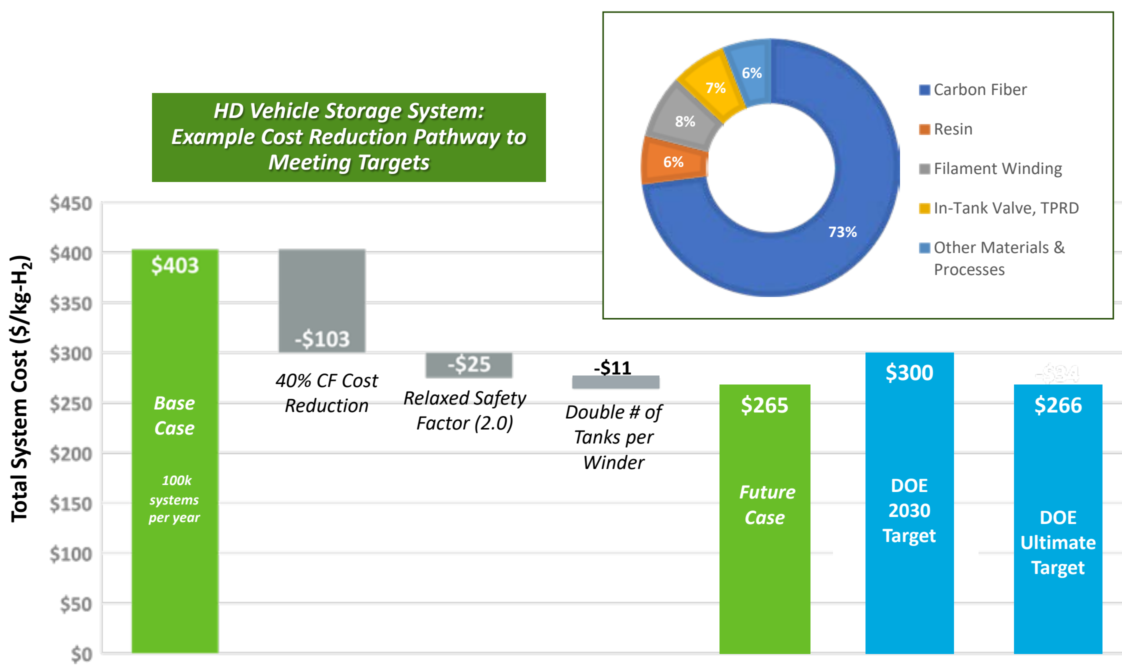


Figure 4.4. Potential pathway to meet ultimate DOE target for 700-bar onboard hydrogen storage system cost through technology advancements along with economies of scale, including cost breakdown for a single representative "behind-the-cab" composite overwrapped pressure vessel with ~12 kg capacity at manufacturing rates of ~100k systems per year

While achieving economies of scale is important, continued technology improvements through RD&D are still needed. For example, a major RD&D focus is needed to reduce the cost of the carbon fiber composite, which accounts for a significant fraction of the total system cost. This focus includes the development of novel, low-cost carbon fiber precursor materials and lower-cost precursor production processes such as melt-spinning, as well as faster and more efficient precursors to carbon fiber conversion processes. In addition, reducing the overall amount of carbon fiber required through improved winding patterns; real-time structural health monitoring; and reduction in carbon fiber manufacturing and winding coefficients of variations all offer potential cost saving strategies. Reducing cost for BOP components through lower-cost manufacturing, improved designs, and integration or elimination of components offers an additional strategy to help meet the ultimate cost target.

For all hydrogen delivery and storage infrastructure technologies, it is important to emphasize that application-specific requirements for performance and durability along with needs based on manufacturing scale and supply chain must be maintained in conjunction with the cost-reduction strategies. Spider charts such as the one illustrated in Figure 4.5 highlight that several subtargets must be addressed simultaneously to achieve a cost-competitiveness for the specific example of onboard hydrogen storage for heavy-duty applications.[49] The spider chart and the waterfall chart indicate the types of related improvements that need to be made simultaneously through comprehensive RD&D to achieve subprogram targets.

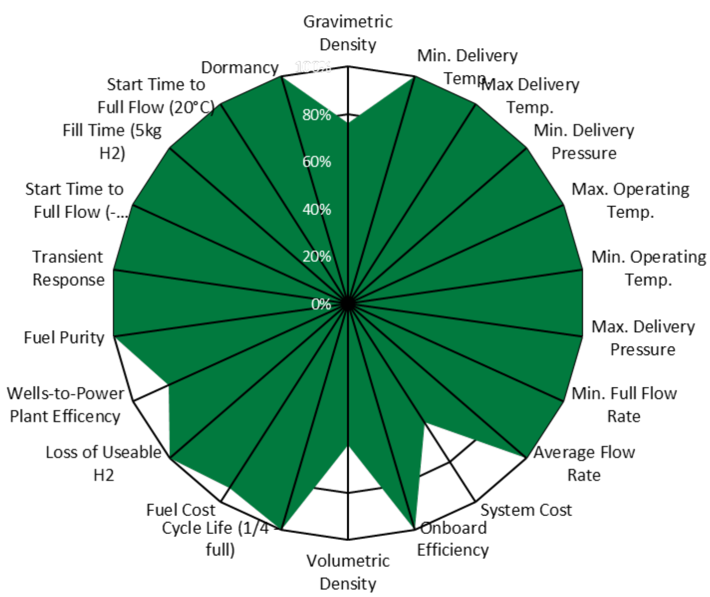


Figure 4.5. Spider chart showing performance of a state-of-the-art Type 4, 700-bar storage system compared against the onboard storage targets

[49] Performance shown is based on prior analysis for light-duty vehicle applications. An updated assessment for heavy-duty vehicle applications is in progress.

In all application areas for hydrogen delivery and storage infrastructure, the subprogram has developed both interim targets for early market adoption and ultimate targets for competitive, widespread commercial viability for specific technology parameters reflecting improvements needed in the current baseline values for achieving cost-competitiveness and commercial liftoff. The technology baselines and targets are periodically assessed and adjusted as needed based on updated information, analysis, and stakeholder feedback.

For the latest, most up-to-date information on technical targets and the status of the technologies covered by HFTO, see:
www.energy.gov/eere/fuelcells/mypp

4.4 Addressing Challenges

Volumetric Density Challenges

The Hydrogen Infrastructure subprogram's RD&D addresses critical challenges and barriers across the various pathways for *delivering* and *storing* hydrogen and the infrastructure technologies needed to support diverse end-use applications. A common delivery and storage challenge relevant to all end uses is the low volumetric density of hydrogen gas under nonextreme temperatures and pressures.

On a mass basis, hydrogen has nearly three times the energy content of gasoline when comparing lower heating values (33 kWh/kg for hydrogen compared to 12 kWh/kg for gasoline). However, on a volume basis, the situation is reversed (approximately 1 kWh/L for 700 bar hydrogen at 15°C compared to 9 kWh/L for gasoline) as shown in Figure 4.6. Improved volumetric densities are achieved through high-pressure compression of gaseous hydrogen, cryogenic hydrogen liquefaction, or incorporation of hydrogen in materials or chemical carriers; but each of these approaches poses different challenges to the delivery and storage infrastructure needed for different end-use applications.

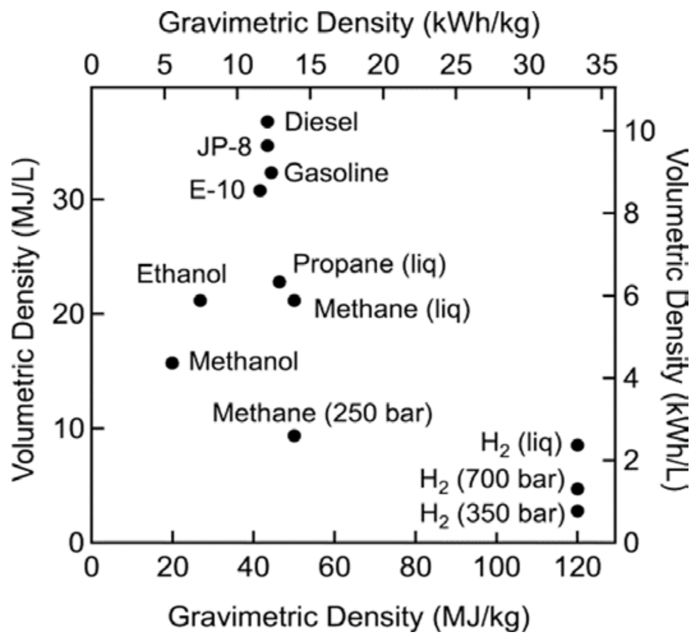


Figure 4.6. Comparison of the volumetric and gravimetric densities of various energy-rich fuels and chemicals

Delivery Challenges

Key challenges include reducing the cost, improving the reliability, and increasing the throughput of hydrogen delivery and dispensing systems and other related systems at the fueling station or point of use. Some specific challenges include: developing high-pressure liquid pumps to enable direct fueling of 350/700 bar; developing novel designs for compressors and other dispensing equipment to ensure sufficient throughput for the medium/heavy-duty market; conducting materials research to increase the life and capacity of high-pressure storage vessels; enhancing the reliability of materials used in dispensing hoses and seals (e.g., in compressors); and improving the life of dispensing hoses through novel designs.

General Hydrogen Delivery Challenges
• Ensuring materials compatibility for hydrogen service under a wide range of conditions • Developing affordable, innovative approaches to hydrogen liquefaction and cryogenic delivery • Improving hydrogen carrier materials and catalysts for hydrogen storage, transport, and release • Developing innovative components for low-cost distribution and dispensing (e.g., compressors, storage vessels, dispensers, nozzles) • Facilitating rights-of-way, permitting, and reduced investment risk of deploying delivery infrastructure

Storage Challenges

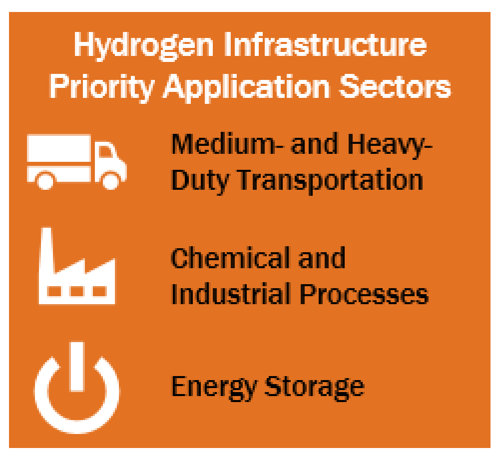
For onboard vehicle storage, hydrogen storage technology development is focused on developing systems that can provide an adequate amount of hydrogen to meet customer driving performance metrics in a safe, convenient, efficient, and cost-effective package. Targeted metrics are closely related to the operating requirements of the end-use application, such as capacity (i.e., run-time), refueling rates, durability, operability, and cost. For offboard or bulk storage, the focus is primarily on reducing cost and footprint while also addressing performance issues such as cycling and material compatibility and developing geographically agnostic technologies.

General Hydrogen Storage Challenges

- Reducing costs for materials, components, and systems
- Developing low-cost, high-strength carbon-fiber for high-pressure tanks
- Ensuring materials compatibility with hydrogen for durability and safety
- Developing innovations for cryogenic hydrogen storage, including liquid and cold/cryo-compressed
- Discovering and optimizing hydrogen storage materials to meet weight, volume, kinetics, and other performance requirements
- Developing sensors and other technologies needed to ensure safe and efficient hydrogen storage
- Optimizing for round-trip efficiency using chemical hydrogen carriers
- Identifying, assessing, and demonstrating geologic storage of hydrogen
- Identifying pathways for the export of hydrogen and hydrogen carriers
- Defining targets for a broad range of storage options and end uses

Comprehensive Approach

HFTO's Hydrogen Infrastructure subprogram's comprehensive RD&D portfolio addresses key techno-economic challenges with respect to hydrogen delivery and storage options in priority application sectors.



The subprogram conducts ongoing and evolving scenario planning to prioritize and identify needs and challenges. This process involves prioritizing high-impact end-use application sectors and then outlining and illustrating appropriate scenarios within sectors. For example, in the medium- to heavy-duty transportation sector, only liquid hydrogen is projected to meet the near-term needs for the large-scale delivery and onsite storage to heavy-duty fueling stations, but gaseous and liquid fueling pathways are both viable onboard storage options being pursued by industry. The process further includes highlighting key components and processes and gathering key metrics through analysis and industry input. Key challenges are identified at the component and process level, leading to an understanding of what can and must be achieved to meet overall cost and performance targets for each of these scenarios.

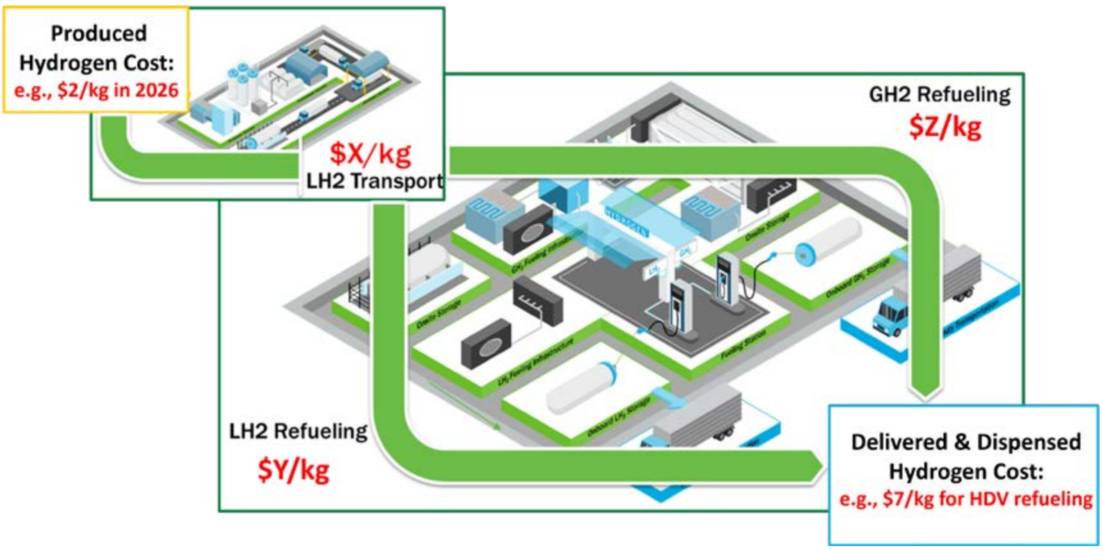


Figure 4.7. Scenario planning as a path to target-setting for infrastructure in the context of production and end-use targets. Figure depicts an example of liquid H_2 delivery to a fueling station, with both gaseous and liquid H_2 pathways for onboard dispensing to the vehicle. Final cost of dispensed H_2 equals the sum of the cost of H_2 production plus cost of delivery to the station, plus the cost of dispensing to the vehicle.

As illustrated in Figure 4.7, this approach to scenario planning is a path for the subprogram to set and revise cost and performance targets at the system and component level, within the bounds defined by targets for hydrogen production and the specific end use.

The three priority sectors—medium- and heavy-duty transportation, chemical and industrial processes, and energy storage—exhibit some overlap in technology needs, while also having distinct needs and opportunities that allow this approach to cover a wide spectrum of technologies and collaborate across the broader DOE Hydrogen Program.

To address hydrogen infrastructure challenges, the Hydrogen Infrastructure subprogram leverages the world-class capabilities of the national laboratories, which includes the formation of several national lab consortia to work with industry and university led projects to address key technology areas. These *c*onsortia that tackle hydrogen infrastructure challenges include HyMARC, H-Mat, and HyBlend.[50]

Consortia Supporting Hydrogen Infrastructure

HyMARC addresses unsolved scientific challenges in the development of viable materials-based storage of H_2 that could lead to more reliable and economic hydrogen use in diverse end uses: HyMARC Consortium

H-Mat focuses on crosscutting R&D on hydrogen materials compatibility to improve the reliability and reduce the costs of materials, and to inform relevant codes and standards: H-Mat Consortium

The HyBlend Pipeline Blending CRADA Project addresses technical barriers to blending H_2 in natural gas pipelines through materials compatibility RD&D and analysis that informs development of publicly accessible assessment tools on blending: HyBlend Consortium

HyMARC focuses on materials for hydrogen transport and storage. The consortium uses a comprehensive approach that incorporates computational modeling to understand the phenomena of hydrogen interactions with materials at the atomistic level, through to bulk materials and system requirements to meet end-use needs, advanced materials synthesis and characterization methods, and performance evaluation. By understanding system-level performance requirements to meet end-use needs, the team is able to "reverse engineer" to determine material level property requirements and identify materials best suited for specific applications. The team is then able to carry out RD&D to improve, characterize and demonstrate materials up through lab-scale demonstration prototypes.

H-Mat focuses on investigating the compatibility of metallic and non-metallic materials for use in hydrogen service. This work includes understanding the impact of hydrogen exposure on the materials' properties under a range of potential use conditions, such as stress-strain, cycle fatigue, and temperatures. The consortium employs computational modeling to understand the phenomena from the atomistic level to bulk properties, and empirical methods to determine the materials' characteristics and performance. Through an iterative approach, the consortium identifies modifications to the materials to improve performance for hydrogen applications. Results from the consortium can be used by industry to produce safe materials and products for

[50] Additional information on HFTO's consortia approach to RD&D can be found in this report's Program Implementation chapter.

use in hydrogen applications and by committees for development of science-based codes and standards.

The HyBlend Pipeline Blending CRADA Project is an industry-focused initiative that includes a multitude of industrial partners working with the national laboratory partners. The consortium addresses key barriers and knowledge gaps related to blending hydrogen into the natural gas network. It includes understanding the potential hydrogen effects on materials used in existing natural gas infrastructure, impact of blended hydrogen on end-use applications, and the techno-economics of blending hydrogen into the natural gas infrastructure. The team also evaluates current regulations and identifies needs for new or revised codes, standards, and regulations regarding blending hydrogen into the natural gas network.

Beyond its consortium collaborations, the Hydrogen Infrastructure subprogram works in close concert with the Hydrogen Production and other HFTO subprograms, as well as across other DOE offices and external agencies to advance commercial liftoff of clean hydrogen technologies across priority application sectors. Leveraging expertise from other HFTO subprograms, DOE offices, and agencies accelerates innovation in clean hydrogen delivery and storage technologies across the spectrum of TRLs.

4.5 RD&D Focus Areas

Technical and economic barriers common to the challenges being addressed in the Hydrogen Infrastructure subprogram include: *Cost, Durability/Reliability, Efficiency/Performance, Life Cycle/Sustainability, Manufacturing/Scale-Up,* and *Safety*. These barriers are summarized in Table 4.2 with some specific examples of associated challenges being addressed for different storage and delivery pathways.

Table 4.2. Hydrogen Infrastructure Barriers and Associated Challenges

Barrier	Associated Challenges
C: Cost *materials, components, systems*	Capital costs of materials and components
	Operations, maintenance, and replacement costs
	Siting and permitting costs
D: Durability/ Reliability	Durability of materials, components, and integrated systems in hydrogen service (including pressure and temperature effects)
	System reliability and lifetime under dynamic operating conditions in hydrogen service (including pressure and temperature effects)
E: Efficiency/ Performance	H_2 losses in handling equipment and infrastructure
	Conversion and round-trip efficiency limits (e.g., in liquefaction and H_2 carriers)

	Mechanical and thermodynamic limits in H_2 processing (e.g., compression)
LC: Life Cycle/ Sustainability	Life cycle costs and environmental impacts
	Cost-effective recycling of materials and components
M: Manufacturing/ Scale-Up and Supply Chain	Materials, components, and systems compatible with processes for affordable scale-up and large-scale manufacturing, and addressing supply chain limitations
S: Safety	Materials, components, and infrastructure with adequate consideration of all hydrogen-related safety issues

The Hydrogen Infrastructure subprogram's comprehensive RD&D portfolio comprises projects and collaborative activities in areas addressing one or more of the barriers described in Table 4.2. The tables below provide a detailed summary of the subprogram's RD&D focus areas that address specific barriers and challenges for the different clean hydrogen storage and pathways, along with examples of key targeted milestones. These RD&D focus areas are aligned with the subprogram's near-, mid-, and longer-term priorities; and based on project results, along with continued analysis and stakeholder engagement, the RD&D portfolio is assessed on a regular basis and is refined to maximize impact.

Near- to Mid-Term Focus Areas

The subprogram's near- to mid-term priorities in hydrogen infrastructure include a focus on transmission and distribution; vehicle refueling (particularly for heavy-duty transportation applications); and near-term opportunities to advance technologies for pressurized gaseous and cryogenic liquid hydrogen storage. Specific RD&D focus areas addressing barriers and challenges are described in Table 4.3. These include areas that overlap both hydrogen delivery and storage and are synergistic with RD&D activities in other HFTO subprograms aimed at advancing hydrogen and fuel cell technologies.

Table 4.3. Infrastructure Focused on Near- to Mid-Term Priority Areas

<table>
<tr><th>Technology</th><th>RD&D Focus Area</th><th>Challenges Addressed</th><th>Key Milestones</th></tr>
<tr><td colspan="4">Near- to Mid-Term Hydrogen Infrastructure for Heavy-Duty Applications</td></tr>
<tr><td rowspan="2">Transmission & Distribution Infrastructure</td><td>Address materials compatibility RD&D to enable hydrogen blending and reductions in hydrogen pipeline and component costs</td><td>D, S</td><td rowspan="2">• Quantify compatibility of natural gas infrastructure with blends of hydrogen and natural gas, at concentrations spanning 0%–100% (2025)
• Demonstrate boil-off rates below 0.1% in all liquid-H_2 systems (2025)</td></tr>
<tr><td>Develop and validate innovative approaches to improve efficiency of liquid tanker-based pathways (e.g., to mitigate boil-off during transfers)</td><td>C, E, LC</td></tr>
<tr><td rowspan="3">Hydrogen Fueling Stations for Transportation</td><td>Increase throughput and expand supply chain for dispensing components (e.g., nozzles, hoses, chillers, and balance of plant)</td><td>C, M</td><td rowspan="3">• Enable H_2 fill rates averaging at least 10 kg/min over the duration of the fill, a 5X increase relative to current methods (2025)
• Enable up to 10X increase in throughput of liquid pumps (2030)
• Enable up to 20X increase in rate of high-pressure (875-bar) hydrogen compression (2030)</td></tr>
<tr><td>Develop high-throughput, low-boil-off cryopumps that vaporize and pressurize liquid hydrogen</td><td>C, E</td></tr>
<tr><td>Develop high-throughput mechanical compressors to meet heavy-duty fueling requirements through novel engineering design</td><td>C, D</td></tr>
<tr><td colspan="4">Near- to Mid-Term Hydrogen Storage Options</td></tr>
<tr><td rowspan="5">Compressed Gaseous Hydrogen Storage</td><td>Develop advanced high-strength, low-cost carbon fiber composites</td><td>C, D ,E</td><td rowspan="5">• Lower the cost of carbon fiber by 50%, with sufficient properties for use in 700-bar H_2 tanks (2026)
• Reduce total cost of compressed-H_2 storage systems to $9/kWh (2030)</td></tr>
<tr><td>Reduce costs of metal tanks and balance of plant through manufacturing innovations</td><td>C, M</td></tr>
<tr><td>Materials RD&D and engineering to enable low-cost, bulk storage and transport</td><td>C, D, E, M</td></tr>
<tr><td>Identify optimized tank configurations and capacities to address volume and weight challenges for various use cases</td><td>C, D, E, M, S</td></tr>
<tr><td>Identify optimized configurations and end-use applications for liquid hydrogen storage</td><td>C, D, E, S, LC</td></tr>
</table>

Overlapping RD&D In Areas Common to Delivery and Storage			
Gaseous Storage	Materials RD&D and innovations employing nondestructive evaluation to address vessel life and cost	C, D	• Lengthen lifespan of 875-bar stationary pressure vessels by 50% compared with current state-of-the-art systems (2025)
	Innovations in tank design to reduce precooling requirements at fueling stations, addressing system cost and lifetime	C, D	
Liquid/ Cryogenic Storage	Address challenges in materials compatibility and durability under cryogenic conditions	C, D	• Assess life of materials used in service at temperatures as low as 20°K, and develop strategies for extending their lifespan (2025)
	Develop strategies to mitigate boil-off losses (e.g., transfer methods, chilling components)	C, D	• Validate strategies that reduce boil-off to below 0.1% in all liquid-H_2 systems (2025)
Fueling Methods	Conduct experiments to inform development of fueling methods for heavy-duty applications, in conjunction with HFTO Codes and Standards activities	C, S	• Inform development of fueling methods that enable cost-competitive fueling averaging at least 10 kg/min over the duration of the fill (2030)

Longer-Term Focus Areas

The subprogram's longer-term priorities in hydrogen infrastructure include a focus on advanced technologies for transmission, distribution, and storage (including innovative liquefaction technologies, as well as materials storage and carriers); and next-generation vehicle refueling technologies. Specific RD&D focus areas addressing barriers and challenges are described in Table 4.4. These include areas that overlap both hydrogen delivery and storage and are synergistic with RD&D activities in other HFTO subprograms aimed at advancing hydrogen and fuel cell technologies.

Table 4.4. Infrastructure Focused on Emerging Opportunities and Longer-Term Priorities

Longer-Term Hydrogen Infrastructure Options			
Transmission & Distribution Infrastructure	Develop innovative methods of liquefaction to improve efficiency and reduce capital cost at smaller scales	C, E, LC	• Enable 50% reduction in the energy used during hydrogen liquefaction (2030)
H_2 Fueling Stations for Transportation	Develop novel approaches to hydrogen fueling (e.g., in liquid form, at low pressure, or at higher temperatures than current approaches)	C, D	• Validate hydrogen delivery and dispensing at $2/kg based on new approaches (2030)
Longer-Term Hydrogen Storage Options			
Materials-Based Storage (Metal Hydrides / Adsorbents)	Develop improved low-cost materials and engineered systems optimizing material capacity and reversibility	C, D, E	• Increase the energy density of current state-of-the-art storage materials by 2X (2030)
	Design materials and engineered systems tailored to application-specific requirements for temperature and pressure for H_2 charge/discharge	E	
	Develop engineered systems addressing application-specific requirements on H_2 discharge/fueling times	C, E	
Longer-Term Overlapping RD&D			
Hydrogen Carriers	Identify and develop carriers with hydrogen capacity, reversibility, and cost optimized for specific end uses (e.g., bulk storage at an industrial facility, bulk hydrogen distribution)	C, D, E, LC, S	• Identify seven carrier materials and associated processes for bulk hydrogen transport and storage (2030) • Develop carriers with capacities and overall efficiencies exceeding conventional compressed-H_2 or liquid-H_2 delivery systems (2030)
	Improve efficiency and cyclability of hydrogenation/dehydrogenation systems to enable commercial viability	E	

Crosscutting

In addition to the focus areas described in Tables 4.3 and 4.4, the subprogram also conducts crosscutting RD&D that is synergistic with activities in other HFTO subprograms and that supports broad strategic priorities relevant to the advancement of clean hydrogen and fuel cell technologies. Examples are included in Table 4.5.

Table 4.5. Hydrogen Infrastructure Crosscutting RD&D activities

Crosscutting RD&D	Barriers Addressed	Key Milestones
Develop standardized testing and validation procedures and protocols	D, E	• Ensure public access to integrated modeling tools to evaluate hydrogen infrastructure across production and end-use scenarios (2024) • Validate achieving hydrogen fuel cost targets for MD/HD transportation of $7/kg (2028) and $4/kg (2031)
Develop low-cost, high-throughput, high-quality manufacturing techniques	M	
Perform application-specific techno-economic analysis and life cycle assessments to inform RD&D priorities	C, LC	
Ensure adherence to rigorous safety standards and protocols	S	
Foster DEIA as well as community engagement across diverse stakeholders to enable energy and environmental justice	LC	• Conduct reviews of Community Benefits Plans and support information-sharing for RD&D projects at least annually