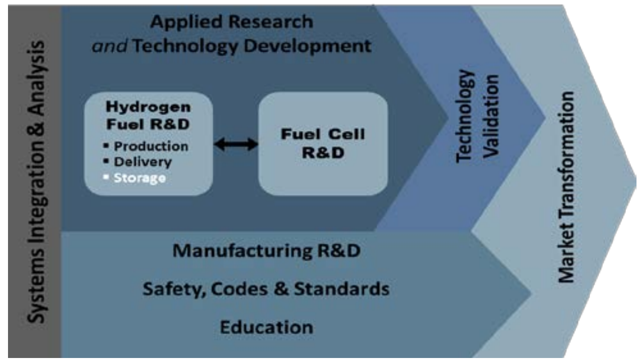
3.3 Hydrogen Storage



Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies that can provide energy for an array of applications, including stationary power, portable power, and transportation. Also, hydrogen can be used as a medium to store 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. The U.S. Department of Energy's (DOE's) efforts through 2011 have primarily been focused on the Research, Development, and Demonstration (RD&D) of onboard vehicular hydrogen storage systems that will allow for a driving range of 300 miles or more, while meeting packaging, cost, safety, and performance requirements to be competitive with conventional vehicles. As of 2011, there were over 180 fuel cell light-duty vehicles and over 20 fuel cell buses utilizing compressed hydrogen storage. In the DOE's Technology Validation sub-program National Fuel Cell Electric Vehicle (FCEV) Learning Demonstration project,[1] automakers have validated vehicles with more than a 250-mile driving range. Additionally, at least one vehicle has been demonstrated capable of 430 miles on a single fill of hydrogen[2]; however the driving range must be achievable across the range of light-duty vehicle platforms and without compromising space, performance or cost.

There is a host of early or near-term power applications in which fuel cell technologies are expected to achieve wide-scale commercialization prior to light-duty vehicles. The early market applications can generally be categorized into three market segments:

- stationary power such as backup power for telecommunications towers, emergency services, and basic infrastructure (e.g., water and sewage pumps).
- portable power such as personal laptop battery rechargers, portable generator sets (gen-sets), or mobile lighting.
- material handling equipment such as forklift trucks, pallet jacks, and airport baggage and pushback tractors.

Currently, these applications are suggested to be the largest markets for fuel cells until fuel cell vehicles are commercialized.[3] Thus, DOE is initiating efforts to establish performance requirements and targets as well as RD&D efforts to address hydrogen storage technology gaps for these applications. Also of interest is to analyze and define the economic feasibility of hydrogen as an energy storage medium to expand the use of renewable energy generation.

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[1] Wipke, K.; Sprik, S.; Kurtz, J.; Ramsden, T.; Ainscough, C.; Saur, G. "National Fuel Cell Electric Vehicle Learning Demonstration Final Report," NREL, July 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/learning_demo_final_report.pdf

[2] Wipke, K.; Anton, D.; Sprik, S. "Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions," NREL and SRNL, August 2009, http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf

[3] 2011 Fuel Cell Technologies Market Report, July 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2011_market_report.pdf

3.3.1 Technical Goal and Objectives

Goal

Develop and demonstrate viable hydrogen storage technologies for transportation, stationary, portable power, and specialty vehicle applications (e.g., material handling equipment (MHE), airport ground support equipment (GSE), etc.).

Objectives

- By 2015, develop and verify a single-use hydrogen storage system for portable power applications achieving 0.7 kWh/kg system (2.0 wt.% hydrogen) and 1.0 kWh/L system (0.030 kg hydrogen/L) at a cost of \$0.09/Wh_{net} (\$3/g $H_{2\ stored}$).

- By 2020, develop and verify onboard automotive hydrogen storage systems achieving 1.8 kWh/kg system (5.5 wt.% hydrogen) and 1.3 kWh/L system (0.040 kg hydrogen/L) at a cost of \$10/kWh (\$333/kg $H_{2\ stored}$).

- By 2020, develop novel precursors and conversion processes capable of reducing the high-volume cost of high-strength carbon fiber by 25% from \$13 per pound to ~\$9 per pound.

- By 2020, develop and verify a rechargeable hydrogen storage system for portable power applications achieving 1.0 kWh/kg system (3.0 wt.% hydrogen) and 1.3 kWh/L system (0.040 kg hydrogen/L) at a cost of \$0.4/Wh_{net} (\$13/g $H_{2\ stored}$).

- By 2020, develop and verify a hydrogen storage system for MHE applications achieving 1.7 kWh/L system (0.050 kg hydrogen/L) at a cost of \$15/kWh_{net} (\$500/kg $H_{2\ stored}$).

- Enable an ultimate full-fleet[4] target of 2.5 kWh/kg system (7.5 wt.% hydrogen) and 2.3 kWh/L system (0.070 kg hydrogen /L) at a cost of \$8/kWh (\$266/kg $H_{2\ stored}$) for onboard automotive hydrogen storage.

3.3.2 Technical Approach

Hydrogen storage research and development (R&D) focuses on advancing technologies to lower the cost and increase the efficiency of both physical storage (e.g., compressed hydrogen) and materials-based storage (e.g., sorbents, metal hydrides) technologies that can enable widespread commercialization of fuel cell systems for diverse applications across stationary, portable, and transportation sectors. Each application—light-duty vehicles, material handling equipment, gen-sets for backup power, and portable power for consumer electronics—has specific market-driven requirements for technology development.

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 of the fuel cell 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 fuel cells 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.

[4] Full-fleet is defined as virtually all light-duty vehicle platforms (e.g., makes and models)

Onboard hydrogen storage to enable a driving range of greater than 300 miles across all light-duty vehicle platforms is a long-term focus of the Hydrogen Storage sub-program. This driving range must be accomplished while meeting the vehicular packaging, cost, and performance requirements necessary to achieve significant market penetration of hydrogen fueled vehicles. R&D activities for vehicle refueling technologies, including the vehicle/forecourt interface, and off-board hydrogen storage will be coordinated with the Hydrogen Delivery sub-program. Hydrogen delivery entails delivering hydrogen from the point of production to the dispenser connection interface onboard the vehicle, including hydrogen storage at the fueling station (see Hydrogen Delivery Multi-Year Research, Development, and Demonstration (MYRD&D) plan section for a complete description of off-board storage).

Physical hydrogen storage (e.g., high-pressure compressed gas cylinders and cryogenic liquid tanks) has thus far been the main hydrogen storage technology used in prototype hydrogen-powered vehicles and is currently the most mature technology for use onboard vehicles. In order to enable widespread use in commercial vehicle platforms, current physical storage efforts focus on reducing the cost of the carbon fiber composite portion of the pressure vessel, which dominates the cost of the compressed gas systems (see Figure 3.3.1). While compressed hydrogen storage is typically at ambient temperatures, cold (i.e., sub-ambient but greater than 150 K) and cryogenic (150 K and below) compressed hydrogen storage is also being investigated due to the higher hydrogen densities achievable. Furthermore, cost-effective pressure vessels and cryogenic tank designs may be required for material-based storage approaches to meet performance requirements. Hence, efforts in advancing physical storage RD&D may also include novel concepts that would benefit material-based hydrogen storage technologies.

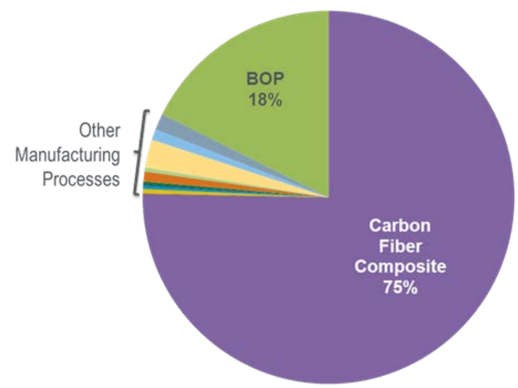


Figure 3.3.1 Systems Analysis sub-program cost analysis of a 700-bar Type IV hydrogen storage system shows >75% of cost is in the filament wound carbon fiber composite layer.

Material-based R&D approaches currently being pursued include reversible metal hydrides, hydrogen sorbents, and regenerable chemical hydrogen storage materials. In addition, for regenerable hydrogen storage materials, it is critical that there are cost effective and energy efficient spent fuel regeneration technologies available to complete the fuel cycle. Therefore, the Hydrogen Storage sub-program will continue to investigate and develop viable spent fuel regeneration technologies for promising regenerable chemical hydrogen storage materials.

The applied materials-based hydrogen storage technology RD&D is focused on developing materials and systems that have the potential to meet the 2015 early market and 2020 light-duty vehicle system targets with the overarching goal of meeting the 2020 early market and ultimate full fleet light-duty vehicle system targets. Specifically:

- Metal hydride materials research focuses on improving the volumetric and gravimetric capacities, hydrogen adsorption/desorption kinetics, and reaction thermodynamics of potential material candidates. Long-term cycling effects will also be investigated.

- Sorbent materials research focuses on increasing the dihydrogen binding energies, optimizing the material's pore size, increasing pore volume and surface area, and investigating effects of material densification.

- Chemical hydrogen storage materials research focuses on improving volumetric and gravimetric capacity, transient performance, other system performance requirements, and the efficient regeneration of the spent storage material.

Additionally, the Hydrogen Storage sub-program's RD&D portfolio includes engineering RD&D to address the engineering challenges posed by various storage technologies. These efforts include comprehensive system modeling and engineering analyses and assessments of material-based storage system technologies for detailed comparisons against the DOE performance targets for light-duty vehicles. Engineering system component RD&D, including bench-scale testing and evaluation, and conceptual design validation, is conducted to address deficiencies and enable progress towards meeting the storage system level targets.

As technologies with potential for onboard storage are down-selected, future activities on vehicle refueling requirements and technology needs will be coordinated with the Delivery sub-program. Vehicle refueling connection devices will need to be compatible with high-pressure and cryogenic storage in the near-term. In the long-term, as progress is made on material-based technologies, vehicle refueling issues such as thermal management or by-product reclamation will need to be addressed.

Beyond vehicle and early market applications, the Hydrogen Storage sub-program will begin addressing the potential of hydrogen storage in grid energy storage applications. For hydrogen use in grid energy storage applications, electrical energy that is generated in excess of the immediate demand can be used to generate hydrogen through use of an electrolyzer or reversible fuel cell. The hydrogen produced by the excess electrical energy is then stored for later consumption—conversion back to electricity when electricity demand exceeds generation capacity or in other applications such as an automotive transportation fuel. Grid energy storage is expected to facilitate the penetration of renewable energy sources, especially intermittent types such as wind and solar, and improve the flexibility, reliability, and efficiency of the grid. Cost, overall efficiency, and durability are all key barriers associated with implementing hydrogen into grid energy storage applications. Further, RD&D and analyses are required to identify the specific grid energy storage applications where hydrogen is a practical option and to determine additional engineering and technology developments required to meet key performance criteria. RD&D activities will be conducted in coordination and collaboration with the DOE Office of Electricity Delivery and Energy Reliability.

Interactions with the DOE Office of Science are ongoing to define and coordinate the basic research activities for hydrogen storage materials. The Hydrogen Storage sub-program will also conduct analyses to examine the system level performance, lifecycle cost, energy efficiency, environmental impact of the technologies, any changes in the system-level requirements that might alter the technical targets, and the progress of each technology development effort toward achieving the technical targets.

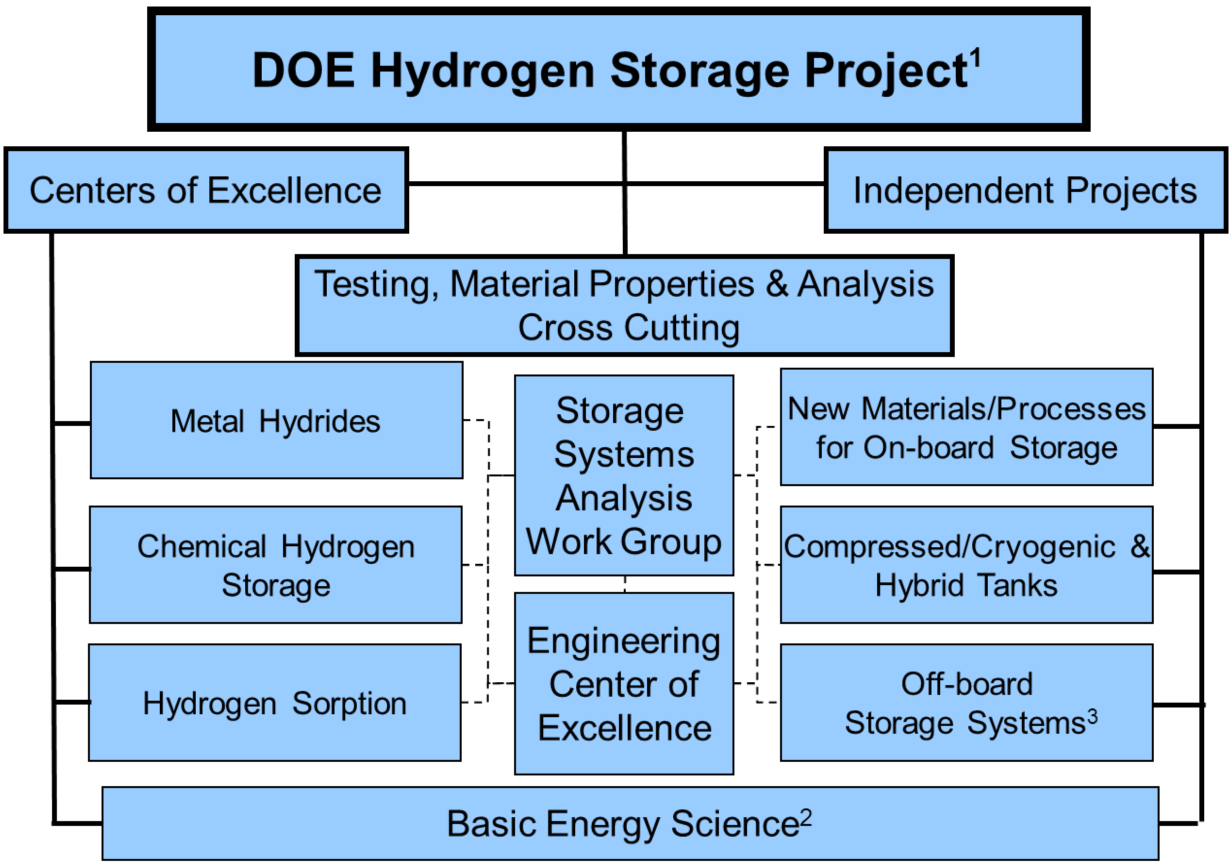
3.3.3 Programmatic Status

Hydrogen storage RD&D efforts were previously conducted under the framework of the National Hydrogen Storage Project. The National Hydrogen Storage Project included independent projects and Centers of Excellence (CoEs) in applied hydrogen storage RD&D funded by the DOE Office of Energy Efficiency and Renewable Energy and basic research projects for hydrogen storage funded by the DOE Office of Science.

During that time, the Hydrogen Storage sub-program established three competitively selected CoEs that operated from 2005 to 2010 for a concerted effort to discover and develop low-pressure hydrogen storage materials. The three CoEs focused on the development of: 1) high-capacity metal hydrides including borohydrides, destabilized metal hydrides, and lightweight multinary alloys; 2) chemical hydrogen storage materials including liquid chemical hydrogen carriers and boron-based materials; and 3) sorbents including novel metal-carbon hybrids, metal-organic framework materials, polymers, and other nanostructured, high surface area materials. The three CoEs made significant progress in discovering and developing new and innovative hydrogen storage materials as well as progress towards meeting the onboard vehicular hydrogen storage targets. However, while this effort led to the discovery of many new types of hydrogen storage materials, no current material can meet all of the onboard targets simultaneously. Therefore, the Hydrogen Storage sub-program will continue to add new material development R&D projects to its portfolio. Final reports from each of the three CoEs are available through the Fuel Cell Technologies website at: http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage.

Current Activities

To address the critical challenge of hydrogen storage for stationary, portable, and transportation applications, as well as energy storage for variable renewables, the Hydrogen Storage sub-program continues with its overarching strategy to conduct RD&D through a comprehensive portfolio of competitively awarded projects that include applied, target-oriented research of advanced concepts, innovative chemistries, and novel materials, as well as engineering RD&D with the potential to meet onboard vehicular, material handling equipment, and/or portable power hydrogen storage targets. The organization of the Hydrogen Storage project portfolio is shown in Figure 3.3.2. The Hydrogen Storage portfolio consists of independent and collaborative efforts led by universities, companies, and Federal and National laboratories. Within the portfolio, activities exist that address both physical and materials-based technologies as well as cross-cutting activities of testing and analysis. The sub-program rigorously assesses emerging technologies based on performance, cost, life-cycle energy efficiencies, and environmental impact through storage systems analysis and engineering activities.



1. Coordinated by DOE Energy Efficiency and Renewable Energy, Fuel Cells Technologies Program
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

Figure 3.3.2 Structure of the DOE Hydrogen Storage activities

Table 3.3.1 summarizes the current activities in the Hydrogen Storage sub-program.

Table 3.3.1 Hydrogen Storage Sub-Program Current (2015) Activities

Challenge	Approach	Current Activities
Materials Storage	Materials Discovery • Develop reversible metal hydrides with improved kinetics while maintaining high gravimetric capacity at relevant release temperatures and pressures • Develop sorbent materials with increased binding energy and volumetric capacity • Develop off-board regenerable materials with improved well-to-power plant efficiency at relevant temperatures and pressures	Materials Discovery • **Ames Laboratory**: High-capacity H_2 storage systems via mechanochemistry • **Ardica:** Low-cost α-alane for H_2 storage • **Boston College:** Novel carbon-boron-nitrogen-containing H_2 storage materials • **The California Institute of Technology:** Design and synthesis of materials with high capacities for H_2 physisorption • **HRL Laboratories:** Boron-based H_2 storage: ternary borides and beyond • **Lawrence Berkeley National Laboratory:** H_2 storage in metal-organic frameworks • **Lawrence Livermore National Laboratory:** Improving the kinetics and thermodynamics of $Mg(BH_4)_2$ for H_2 storage • **National Institute of Standards and Technology:** Neutron characterization and thermodynamic modeling of H_2 storage materials • **National Renewable Energy Laboratory (NREL):** H_2 storage materials measurement qualification and characterization • **Savannah River National Laboratory (SRNL):** Development of electrochemical reversible formation of alane • **Texas A&M University:** High-capacity and low-cost H_2 storage sorbents for automotive applications • **University of Michigan:** H_2 adsorbents with high-volumetric density: New materials and system projections
Materials Storage	Engineering • Develop, test, and validate complete integrated storage system models and designs with appropriate operating parameters necessary to meet fuel cell power plant requirements at acceptable costs	Engineering • **Hydrogen Storage Engineering Center of Excellence**—partners include SRNL (lead), Ford Motor Company, General Motors, Los Alamos National Laboratory, Hexagon Lincoln, NREL, Oregon State University, Pacific Northwest National Laboratory (PNNL), United Technologies Research Center, University of Michigan, University of Quebec at Trois-Rivieres, and BASF: Design and projections for complete, integrated H_2 storage systems that can simultaneously meet or exceed all the DOE targets through the development of system models, advanced engineering concepts, and storage system designs that utilize condensed phase materials as the primary H_2 storage media (i.e., reversible metal hydrides, sorbents, and

Table 3.3.1 Hydrogen Storage Sub-Program Current (2015) Activities		
Challenge	**Approach**	**Current Activities**
		chemical H_2 storage materials). Through use of the models and reverse engineering from the systems, the team has also determined minimum H_2 storage material property requirements needed for systems to meet the onboard storage system targets. • **Hawaii Hydrogen Carriers:** Low-cost, metal hydride based H_2 storage system for forklift applications (SBIR Phase II)
Physical Storage	Ambient • Develop low-cost, high-pressure H_2 storage systems while maintaining/improving performance at reduced cost Cold/Cryo-compressed • Develop and validate operation of pressure-capable cryogenic vessels with improved dormancy and long cycle life at reduced cost	Ambient • **Center for Transportation and the Environment:** Conformable H_2 storage coil reservoir • **Composite Technologies Development:** Optimizing the cost and performance of composite cylinders for H_2 storage using graded construction (SBIR Phase II) • Oak Ridge National Laboratory: Development of melt-processable PAN fibers as carbon fiber precursors • Materia Inc.: Next-generation H_2 storage vessels enabled by carbon fiber infusion with a low viscosity, high toughness resin system • PPG Industries, Inc.: Achieving H_2 storage goals through high-strength fiber glass • Sandia National Laboratories: Innovative materials selection and testing to reduce cost and weight of balance of plant components Cold/Cryo-compressed • **Lawrence Livermore National Laboratory:** Thermomechanical cycling of thin-liner high-fiber fraction cryogenic pressure vessels rapidly refueled to 700 bar from an LH_2 pump • **PNNL:** Synergistically enhanced materials and design parameters for reducing the cost of H_2 storage tanks
Analysis	• Determine and compare cost and performance metrics of the various H_2 storage systems under development, both materials-based and physical storage technologies, to guide research towards achieving the performance metrics and identify gaps where further development efforts are required	• **Argonne National Laboratory:** Systems-level analysis of H_2 storage technologies • **Strategic Analysis, Inc.:** Cost analyses of H_2 storage systems suitable for automotive and near-term applications

3.3.4 Technical Challenges

Cost, packaging and durability are the major challenges facing hydrogen storage systems prior to widespread commercialization of hydrogen fuel cell systems. Automotive system-based hydrogen storage capacities have continuously improved since 2005 as shown in Figure 3.3.3 (a-b); further advancements are needed to meet all automotive performance targets simultaneously. When considering hydrogen storage options, each application must be regarded individually as each has its own distinct set of challenges and performance criteria. For example, one of the most challenging applications, automotive, has very rigorous performance requirements with respect to weight, volume, start-up, rate of refill, transient operation, cost and a number of other performance criteria. In comparison, for material handling equipment applications, such as forklifts, the greatest challenges include system cost and durability; whereas, for man-portable power applications, such as rechargeable battery extenders, the greatest factors to compete with batteries include packaging (i.e., gravimetric and volumetric capacities), cost, and ease of use. Traditional hydrogen storage technologies cannot meet the technical challenges and performance criteria required for all applications.

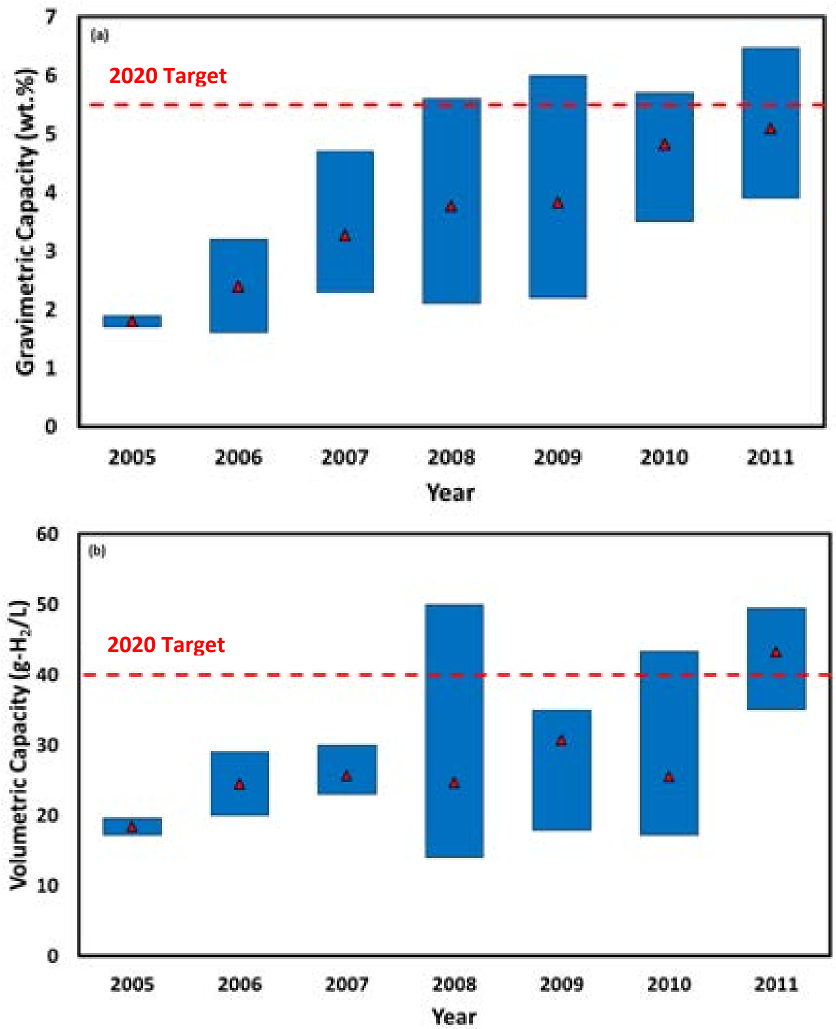


Figure. 3.3.3 (a-b) Estimates of (a) gravimetric and (b) volumetric capacities projected for onboard storage systems that can supply 5.6 kg of usable hydrogen as compared to DOE targets (based upon engineering analyses). Note that the plotted data points are the average value for all systems analyzed during each year while the bars correspond to the range of maximum and minimum values obtained in each year. Also note that systems with predicted capacities exceeding the gravimetric and volumetric targets do not necessarily meet other targets.

Automotive

The overarching technical challenge for hydrogen storage in automotive applications is the ability to store the necessary amount of hydrogen required for a conventional driving range (greater than 300 miles), within the constraints of weight, volume, durability, efficiency, and total cost. The current dominant hydrogen storage technologies for automotive use are 350- and 700-bar (5,000- and 10,000-psi, respectively) compressed hydrogen systems. Vehicles have been demonstrated that are able to achieve 250 miles driving range (U.S. Environmental Protection Agency adjusted combined drive cycle) with 700-bar compressed hydrogen systems.[5] The hydrogen storage capacities for 350- and 700-bar compressed hydrogen systems ranged from about 2.8 to 4.4 wt.% hydrogen[6] and 0.017 to 0.025 kg hydrogen/L system.[7] Table 3.3.2 includes the current projected status for physical and materials-based hydrogen storage systems. Many important technical challenges for hydrogen storage must be resolved to meet the ultimate performance and safety targets. Substantial improvements must be made in the weight, volume, and cost of these systems for automotive applications. Additionally, durability over the performance lifetime of these systems must be validated, and acceptable refueling times must be achieved.

Table 3.3.2 Projected Performance of Hydrogen Storage Systems[a]

Hydrogen Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Cost ($/kWh; projected to 500,000 units/yr)	Year Published
700-bar compressed (Type IV)[b]	1.7	0.9	19	2010
350-bar compressed (Type IV)[b]	1.8	0.6	16	2010
Cryo-compressed (276 bar)[b]	1.9	1.4	12	2009
Metal hydride ($NaAlH_4$)[c]	0.4	0.4	TBD	2012
Sorbent (AX-21 carbon, 200 bar)[c]	1.3	0.8	TBD	2012
Chemical H_2 storage (AB-liquid)[c]	1.3	1.1	TBD	2012

[a] Assumes a storage capacity of 5.6 kg of usable H_2
[b] Based on Argonne National Laboratory performance and TIAX cost projections[8]
[c] Based on Hydrogen Storage Engineering Center of Excellence performance projections[9]

Early Markets

Successful commercialization of hydrogen fuel cell products in early market applications is expected to help increase public awareness and acceptance of hydrogen fuel cell technologies, generate data on the performance of the technologies in real-world use and help build the supply base, all of which can benefit commercialization of hydrogen fuel cell technologies in automotive applications. For early market applications, the major technical challenge for hydrogen storage is the ability to provide an adequate amount of hydrogen to enable operation of the fuel cell to meet customer-driven performance metrics. Hydrogen storage materials have the potential to meet many of the performance demands of the identified applications,

[5] DOE's Technology Validation sub-program Fuel Cell Electric Vehicle (FCEV) Learning Demonstration Project Composite Data Product: http://www.nrel.gov/hydrogen/docs/cdp/cdp_2.jpg

[6] Hydrogen Storage Weight % Hydrogen Composite Data Product: http://www.nrel.gov/hydrogen/docs/cdp/cdp_10.ppt

[7] Hydrogen Storage Volumetric Capacity Composite Data Product: http://www.nrel.gov/hydrogen/docs/cdp/cdp_11.ppt

[8] Bowman, Jr., R.C.; Stetson, N.T. "Onboard hydrogen storage systems: projected performance and cost parameters." DOE Hydrogen and Fuel Cells Program Record; 2010, July 02, Available online: http://hydrogen.energy.gov/pdfs/9017_storage_performance.pdf.

[9] Anton, D.L.; Motyka, T.; Hardy, B.; Tamburello, D. "Hydrogen Storage Engineering Center of Excellence (HSECoE)." DOE Fuel Cell Technologies Program Annual Progress Report. Available: http://www.hydrogen.energy.gov/pdfs/progress12/iv_d_1_anton_2012.pdf.

specifically portable power and material handling equipment; thus, the primary focus of the Hydrogen Storage sub-program will be the development and demonstration of engineered systems that meet the application specific performance metrics and to lower manufacturing costs. Material optimization and development efforts, such as improvements in gravimetric and volumetric capacities of materials, faster charging/discharging rates and reduced operational temperatures, will be pursued as ways to lower system costs by reducing material usage and increasing system efficiency.

Material Handling Equipment

Hydrogen fuel cells are being successfully commercialized in material handling equipment, however, systems to date almost exclusively rely on high-pressure (350 bar or higher) hydrogen storage. The infrastructure required for refueling at high pressures adds substantial costs and therefore limits deployment to operations with large fleets of material handling equipment (e.g., >10 forklifts). Development of advanced hydrogen storage technology that would eliminate the need for a high-cost, high-pressure infrastructure could lead to deployment of hydrogen fuel cells into operations with small fleets and thus, significantly increase the potential market size.

Portable Power

Portable power systems range in power output from a watt or so to a few hundred watts. The energy storage requirements range from a few watt-hours to a kilowatt-hour or so. For portable power applications, safety and ease of use are critical requirements. System weight and volume are also key constraints; however, due to the relatively low amount of hydrogen required, on a specific energy and energy density basis, they tend to be less stringent than for other applications. Conversely, costs for portable power applications can be more stringent than even automotive applications as consumer electronics operate as a low-cost, low-margin business and fuel cell technology must be priced to compete with incumbent primary and secondary batteries. Both single use and rechargeable technologies are expected to be acceptable, analogous to primary and rechargeable batteries.

Technical Targets

Note: Revised onboard vehicle targets were issued May of 2017, please refer to energy.gov/node/1315186 for updated targets.

The technical performance targets for hydrogen storage systems onboard light-duty vehicles are summarized in Table 3.3.3. These targets were established through the U.S. DRIVE Partnership, a partnership between DOE, the U.S. Council for Automotive Research (USCAR), energy companies, and utility companies and organizations. The targets are subject to change as more is learned about system-level requirements and as fuel cell technology progresses. The targets are based upon requirements for the "Ultimate Full Fleet," defined as virtually all light-duty vehicle platforms (e.g., makes and models), to achieve significant market penetration of hydrogen fueled vehicles. The Ultimate Full Fleet targets allow for manageable increases in weight and volume over current internal combustion engine vehicle systems and are intended to make hydrogen-fueled propulsion systems competitive across the majority of vehicle classes and models (from small compact cars to light-duty trucks). A detailed explanation of the targets and the process used in deriving them is provided at: www1.eere.energy.gov/hydrogenandfuelcells/storage/current_technology.html.

Tables 3.3.4 through 3.3.7 list the DOE technical performance targets for material handling equipment and portable power applications. These targets were developed with input to DOE through extensive communications with various stakeholders, industry developers and end-users, including through a 2012 request for information and workshops. Additionally assessments were performed by SNL, NREL, and PNNL.[10, 11, 12] The following useful constants are relative to Tables 3.3.3 through 3.3.7: 0.2778 kWh/MJ; Lower heating value for H_2 is 33.3 kWh/kg H_2; 1 kg H_2 ≈ 1 gal gasoline equivalent (gge).

[10] Hydrogen Storage Needs for Early Motive Fuel Cell Markets, http://www.nrel.gov/docs/fy13osti/52783.pdf

[11] Analysis of H_2 Storage Needs for Early Market Non-Motive Fuel Cell Applications, http://prod.sandia.gov/techlib/access-control.cgi/2012/121739.pdf

Table 3.3.3 Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles[a, i]			
Storage Parameter	**Units**	**2020**	**Ultimate**
System Gravimetric Capacity • Usable, specific-energy from H_2 (net useful energy/max system mass)[b]	kWh/kg (kg H_2/kg system)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity • Usable energy density from H_2 (net useful energy/max system volume)[b]	kWh/L (kg H_2/L system)	1.3 (0.040)	2.3 (0.070)
Storage System Cost	$/kWh net ($/kg $H_{2\,stored}$)	10 333	8 266
• Fuel cost[c]	$/gge at pump	2–4	2–4
Durability/Operability			
• Operating ambient temperature[d]	ºC	-40/60 (sun)	-40/60 (sun)
• Min/max delivery temperature	ºC	-40/85	-40/85
• Operational cycle life (1/4 tank to full)	Cycles	1,500	1,500
• Min delivery pressure from storage system	bar (abs)	5	3
• Max delivery pressure from storage system	bar (abs)	12	12
• Onboard efficiency[e]	%	90	90
• "Well" to power plant efficiency[e]	%	60	60
Charging/Discharging Rates			
• System fill time (5 kg)	min (kg H_2/min)	3.3 (1.5)	2.5 (2.0)
• Minimum full flow rate	(g/s)/kW	0.02	0.02
• Start time to full flow (20 °C)	s	5	5
• Start time to full flow (-20 °C)	s	15	15
• Transient response at operating temperature 10%–90% and 90%–0%	s	0.75	0.75
Fuel Quality (H_2 from storage)f	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety			
• Permeation & leakage[g]	-	Meets or exceeds applicable standards, for example SAE J2579	
• Toxicity	-		
• Safety	-		
• Loss of usable H_2[h]	(g/h)/kg $H_{2\ stored}$	0.05	0.05

[a] Targets are based on the lower heating value of hydrogen, 33.3 kWh/kg H_2. Targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant. All targets must be met at the end of service life (approximately 1,500 cycles or 5,000 operation hours, equivalent of 150,000 miles).

[b] Capacities are defined as the usable quantity of hydrogen deliverable to the power plant divided by the total mass/volume of the complete storage system, including all stored hydrogen, media, reactants (e.g., water for hydrolysis-based systems), and system components. Tank designs that are conformable and have the ability to be efficiently package onboard vehicles may be beneficial even if they do not meet the full volumetric capacity targets. Capacities must be met at end of service life.

[c] Hydrogen cost is independent of pathway and is defined as the untaxed cost of hydrogen produced, delivered and dispensed to the vehicle.[http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf]For material-based storage technologies, the impact of

[12] Technology and Manufacturing Readiness of Early Market Motive and Non-Motive Hydrogen Storage Technologies for Fuel Cell Applications, http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-21473.pdf

the technology on the hydrogen cost, e.g., off-board cooling, off-board regeneration of chemical hydrogen storage materials, etc., must be taken into account.

[d] Stated ambient temperature plus full solar load (i.e., full exposure to direct sunlight). No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Onboard efficiency is the energy efficiency for delivering hydrogen from the storage system to the fuel cell power plant, i.e., accounting for any energy required for operating pumps, blowers, compressors, heating, etc. required for hydrogen release. Well-to-power plant efficiency includes onboard efficiency plus off-board efficiency, i.e., accounting for the energy efficiency of hydrogen production, delivery, liquefaction, compression, dispensing, regeneration of chemical hydrogen storage materials, etc. as appropriate. H2A and HDSAM analyses should be used for projecting off-board efficiencies.

[f] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards for fuel cell vehicles (see SAE J2719 and ISO/PDTS 14687-2). Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case-by-case basis as more information becomes available.

[g] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with applicable standards for vehicular tanks including but not limited to SAE J2579 and the United Nations Global Technical Regulation. This includes any coating or enclosure that incorporates the envelope of the storage system.

[h] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

[i] Details in this table are being revised to match changes in the high level cost target.

Table 3.3.4 Technical System Targets[a]: Material Handling Equipment			
Storage Parameter	**Units**	**2015**	**2020**
Hydrogen Capacity	kg	2	2
System Volumetric Capacity • Usable energy density from H_2 (net useful energy/max system volume)[b]	kWh/L (kg H_2/L system)	1.0 (0.03)	1.7 (0.05)
Storage System Cost	$/kWh net ($/kg $H_{2\ stored}$)	20 (667)	15 (500)
Durability/Operability • External operating temperature rangec • Min/max delivery temperatured • Operational cycle life (1/10 tank to full) • Min delivery pressure from storage system • Max delivery pressure from storage system	 ºC ºC Cycles bar (abs) bar (abs)	 -40/60 -40/85 5,000(5 yr) 3 12	 -40/60 -40/85 10,000(10 yr) 3 12
Shock & Vibration • Shock • Vibration	 g g	 40 5@10Hz – 0.75@200Hz	 40 10@10Hz – 1@200Hz
Charging/Discharging Rates • System fill time (2 kg) • Minimum full flow rate • Start time to full flow (20 °C) • Start time to full flow (-20 °C) • Transient response 10%–90% and 90%–0%	 min (kg H_2/min) (g/s)/kW s s s	 4.0 (0.5) 0.02 5 15 0.75	 2.8 (0.7) 0.02 5 15 0.75
Fuel Purity (H_2 from storage)[e]	% H_2	SAE J2719 & ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety • Permeation & Leakage[f] • Toxicity • Safety	 - - -	Meets or exceeds applicable standards, for example CSA HPIT 1	
• Loss of useable H_2[g]	(g/h)/kg $H_{2\ stored}$	0.1	0.05

[a] The targets are based on the lower heating value of hydrogen, without consideration of the conversion efficiency of the fuel cell power plant. Targets are for the complete hydrogen storage and delivery system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling or heating capacity, and/or other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant during normal use. All targets must be met at the end of service life. Since most applications of material handling equipment (MHE) require extra mass as a counterbalance, the system gravimetric capacity is not specified as it can vary widely among types of MHE. However, system gravimetric capacity should be considered when developing hydrogen storage systems for MHE applications. All targets must be met at the end of service life.

[b] "Net useful energy" or "net" excludes unusable energy (i.e., hydrogen left in a tank below minimum fuel cell power plant pressure, flow, and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g., fuel used to heat a material to initiate or sustain hydrogen release).

[c] Stated ambient temperature. No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[d] Delivery temperature refers to the inlet temperature of the hydrogen to the fuel cell.

[e] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards, such as CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components. Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[f] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with appropriate standards, for example CSA HPIT 1: Compressed Hydrogen Powered Industrial Trucks (forklifts) On- Board Fuel Storage and Handling Components. This includes any coating or enclosure that incorporates the envelope of the storage system.

[g] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of operational time.

Table 3.3.5 Technical Performance Targets[a]: Hydrogen Storage Systems for Low Power (≤2.5 W) Portable Equipment					
Storage Parameter	Units	2015		2020	
		Single-Use	Rechargeable	Single-Use	Rechargeable
Hydrogen Capacity	g H_2	≤1			
System Gravimetric Capacityb • Usable, specific-energy from H_2 (net useful energy/max system mass)[c]	kWh/kg ($kg\ H_2/kg$ system)	0.7 (0.02)	0.5 (0.015)	1.3 (0.04)	1.0 (0.03)
System Volumetric Capacity • Usable energy density from H_2 (net useful energy/max system volume)	kWh/L ($kg\ H_2/L$ system)	1.0 (0.03)	0.7 (0.02)	1.7 (0.05)	1.3 (0.04)
Storage System Cost	$/Wh net ($\$/g\ H_{2\ stored}$)	0.09 (3.0)	0.75 (25)	0.03 (1.0)	0.4 (13)

Table 3.3.6 Technical Performance Targets[a]: Hydrogen Storage Systems for Medium Power (>2.5 W–150 W) Portable Equipment					
Storage Parameter	Units	2015		2020	
		Single-Use	Rechargeable	Single-Use	Rechargeable
Hydrogen Capacity	g H_2	>1 – 50			
System Gravimetric Capacity[b] • Usable, specific-energy from H_2 (net useful energy/max system mass)[c]	kWh/kg ($kg\ H_2/kg$ system)	0.7 (0.02)	0.5 (0.015)	1.3 (0.04)	1.0 (0.03)
System Volumetric Capacity • Usable energy density from H_2 (net useful energy/max system volume)[c]	kWh/L ($kg\ H_2/L$ system)	1.0 (0.03)	0.7 (0.02)	1.7 (0.05)	1.3 (0.04)
Storage System Cost	$/Wh net ($\$/g\ H_{2\ stored}$)	0.2 (6.7)	1.0 (33)	0.1 (3.3)	0.5 (17)

Table 3.3.7 Portable Power Durability & Operational Targets[a]			
Storage Parameter	Units	2015	2020
		Single-Use & Rechargeable	Single-Use & Rechargeable
Durability/Operability			
• External operating temperature range[d]	ºC	-40/60	-40/60
• Min/max delivery temperature[e]	ºC	10/85	10/85
• Min delivery pressure from storage system	bar (abs)	1.5	1.5
• Max delivery pressure from storage system	bar (abs)	3	3
• External temperature[f]	ºC	≤40	≤40
Discharging Rates			
• Minimum full flow rate	(g/s)/kW	0.02	0.02
• Start time to full flow (20 °C)	s	5	5
• Start time to full flow (-20 °C)	s	10	10
• Transient response 10%–90% and 90%–0%	s	5	2
Fuel Purity (H_2 from storage)[g]	% H_2	Meets applicable standards	
Environmental Health & Safety • Toxicity • Safety • Loss of usable H_2[h]		Meets ISO-16111:2008; IEC 62282 Part 6; or other applicable standards as appropriate or required for the application and targeted usage	

Footnotes to Tables 3.3.5 – 3.3.7:

[a] The targets are based on the lower heating value of hydrogen, without consideration of the conversion efficiency of the fuel cell power plant. Targets are for the complete hydrogen storage and delivery system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling or heating capacity, and/or other balance-of-plant components. All capacities are defined as usable capacities that could be delivered to the fuel cell power plant during normal use. All targets must be met at the end of service life.

[b] Generally the 'full' mass (including hydrogen) is used; for systems that gain weight on hydrogen release, the highest mass during discharge is used (e.g., hydrogen release through hydrolysis reaction resulting in the formation of oxides/hydroxides). All capacities are net usable capacity able to be delivered to the fuel cell power plant. Capacities must be met at end of service life.

[c] "Net useful energy" or "net" excludes unusable energy (i.e., hydrogen left in a tank below minimum fuel cell power plant pressure, flow, and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g., fuel used to heat a material to initiate or sustain hydrogen release).

[d] Stated ambient temperature plus full solar load (i.e., if exposed to direct sunlight or stored within a container exposed to direct sunlight for extended periods of time). No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Delivery temperature refers to the inlet temperature of the hydrogen to the fuel cell.

[f] The external device temperature is the maximum temperature generated at the external surface of the hydrogen storage container during operation.

[g] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards, such as ISO-16111:2008 and IEC 62282 Part 6. Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[h] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with appropriate standards, such as ISO-16111:2008 and IEC 62282 Part 6. This includes any coating or enclosure that incorporates the envelope of the storage system.

3.3.5 Technical Barriers

The following technical barriers are relevant to all hydrogen storage applications.

A. System Weight and Volume

The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate operation on a single fill compared to incumbent technologies. Storage media, materials of construction, and balance-of-plant components are needed that allow compact, lightweight, hydrogen storage systems while enabling an adequate operating range to meet the user needs (e.g., range greater than 300-miles for light-duty vehicle applications). Reducing weight and volume of thermal management components is also required.

B. System Cost

The cost of hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost media, materials of construction, and balance-of-plant components are needed, as well as low-cost, high-volume manufacturing methods.

C. Efficiency

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to transfer hydrogen into and out of the storage media or material is an issue for all material options. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent media and by-products are typically regenerated off-board. In addition, the energy associated with the compression, cooling, and liquefaction of hydrogen must be considered for compressed, cryogenic, and liquid hydrogen technologies. Thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency for all approaches.

D. Durability/Operability

Durability of hydrogen storage systems is inadequate. Storage media, materials of construction, and balance-of-plant components are needed that allow hydrogen storage systems with acceptable lifetimes and with tolerance to hydrogen fuel contaminants. An additional durability issue for material-based approaches is the delivery of sufficient quality hydrogen for the application power plant.

E. Charging/Discharging Rates

In general and especially for material-based approaches, hydrogen refueling times are too long. For automotive applications, there is a need to develop hydrogen storage systems with refueling times of less than three minutes for a 5-kg hydrogen charge, over the lifetime of the system. Thermal management that enables quicker refueling is a critical issue that must be addressed. Also, all storage system approaches must be able to supply a sufficient flow of hydrogen to the power plant (e.g., fuel cell or internal combustion engine) to meet the required power demand.

F. Codes and Standards

Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, are being established for automotive applications and need to be established for early market applications. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. Materials of Construction

High-pressure containment for compressed gas and other high-pressure approaches limits the choice of construction materials and fabrication techniques, within weight, volume, performance, and cost constraints. For all approaches of hydrogen storage, vessel containment that is resistant to hydrogen permeation and corrosion is required. Research into new materials of construction, such as metal ceramic composites, improved resins, and engineered fibers, is needed to meet cost targets without compromising performance. Materials to meet performance and cost requirements for hydrogen delivery and off-board storage are also needed (see Hydrogen Delivery MYRD&D section).

H. Balance-of-Plant (BOP) Components

Lightweight, cost-effective BOP components are needed for all approaches of hydrogen storage, especially those requiring high-pressure or extensive thermal management. These components include tubing, fittings, check valves, regulators, filters, relief and shut-off valves, heat exchangers, and sensors. System design and optimal packaging of components to meet overall volumetric targets are also required.

I. Dispensing Technology

Requirements for dispensing hydrogen to and from the storage system have not been fully defined for all storage platforms. These include meeting heat rejection requirements during fueling especially for onboard reversible material-based approaches. For chemical hydrogen approaches, methods and technology to recover spent material from the fuel tank for regeneration during "refueling" are needed. Activities will be coordinated with the Delivery sub-program.

J. Thermal Management

For all approaches of hydrogen storage—compressed gas, cryogenic, and materials-based—thermal management is a key issue. In general, the main technical challenge is heat removal during hydrogen fueling of hydrogen for compressed gas and onboard reversible materials within fueling time requirements. Onboard reversible materials typically require heat to release hydrogen. Heat must be provided to the storage media at reasonable temperatures to meet the flow rates needed by the power plant, preferably using the waste heat of the power plant. Depending upon the chemistry, chemical hydrogen approaches often are exothermic upon release of hydrogen to the power plant, or optimally thermal neutral; exothermic systems will require heat rejection during operation.

K. System Life-Cycle Assessments

Assessments of the full life-cycle, cost, efficiency, and environmental impact for hydrogen storage systems are lacking. An understanding of infrastructure implications, particularly for chemical hydrogen storage and approaches to reduce primary energy inputs, is lacking.

Compressed Gas Systems

L. Lack of Tank Performance Data and Understanding of Failure Mechanisms

An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failure due to accident or to neglect is lacking. Research on tank performance and failure is needed to optimize tank structure for performance and cost. In addition, sensors and associated prediction correlations are needed to predict lifetime and catastrophic tank failure.

Cryogenic Liquid and Cryo-compressed Systems

M. Liquefaction Energy Penalty

The energy penalty associated with hydrogen liquefaction, typically about 30% of the lower heating value of hydrogen, is an issue. Methods to reduce the energy requirements for liquefaction are needed.

N. Hydrogen Venting

The boil-off and subsequent pressure rise of liquid and cold hydrogen requires venting, reduces operation range, and presents a potential safety/environmental hazard, particularly when in an enclosed environment. Materials and methods to reduce boil-off and venting from cryogenic systems are needed.

Reversible Materials-Based Storage Systems (Reversible Onboard)

O. Lack of Understanding of Hydrogen Physisorption and Chemisorption

Improved understanding and optimization of adsorption/absorption and desorption kinetics is needed to optimize hydrogen uptake and release capacity rates. An understanding of chemical reactivity and material properties, particularly with respect to exposure under different conditions (air, moisture, etc.) is also lacking.

P. Reproducibility of Performance

Standard test protocols for evaluation of hydrogen storage materials are lacking. Reproducibility of performance both in synthesis of the material/media and measurement of key hydrogen storage performance metrics is an issue. Standard test protocols related to performance over time such as accelerated aging tests as well as protocols evaluating materials safety properties and reactivity over time are also lacking.

Chemical Hydrogen Storage Systems (Typically Regenerated Off-board)

Q. Regeneration Processes

Low-cost, energy-efficient regeneration processes have not been established. Full life-cycle analyses need to be performed to understand cost, efficiency, and environmental impacts.

R. By-Product/Spent Material Removal

The refueling process is potentially complicated by removal of the by-product and/or spent material. System designs must be developed to address this issue and also the infrastructure requirements for off-board regeneration.

3.3.6 Technical Task Descriptions

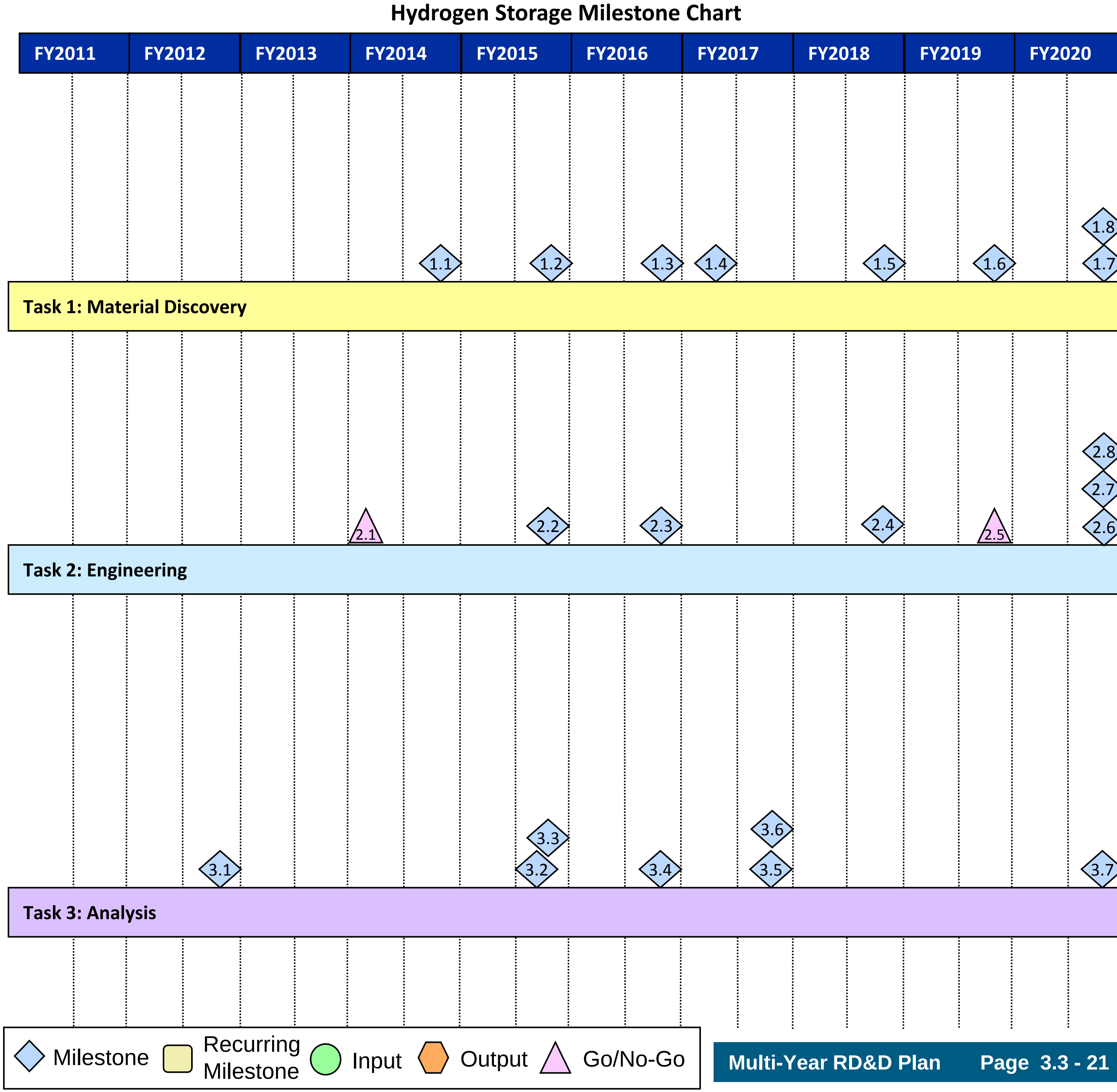
The technical task descriptions are presented in Table 3.3.8. Issues regarding safety will be addressed within each of the tasks. The barriers associated with each task appear after the task title.

Table 3.3.8 Technical Task Descriptions

Task	Description	Barriers
1	Material Discovery • Perform theoretical modeling to provide guidance for materials development. • Determine the decomposition pathways and products of materials to better understand their mechanisms and kinetics. • Determine the H_2 storage capacity of potential storage materials and demonstrate reproducibility of their synthesis and capacity measurements. • Develop sorbent materials with increased binding energy and volumetric density. • Develop reversible metal hydrides with improved kinetics while maintaining high gravimetric capacity at relevant release temperatures and pressures. • Develop off-board regenerable materials with improved overall efficiency at relevant temperatures and pressures. • Develop cost-effective synthesis processes for promising materials.	A-K, O-R
2	Engineering • Develop complete integrated storage systems with appropriate operating parameters necessary to meet fuel cell power plant requirements at acceptable cost. • Develop low-cost, advanced compressed and cryogenic storage systems to meet performance targets. • Develop and optimize lower-cost and improved carbon fiber composites. • Develop lightweight, low-cost, balance-of-plant components for advanced compressed/cryogenic systems. • Coordinate with Delivery and Systems Analysis sub-programs to understand the interrelationship between onboard storage and delivery options (e.g., efficiency, cost, etc.). • Develop cryo-tanks with reduced cost, improved dormancy, and validated system operation and cycle-life at cryogenic temperatures.	A-N, R
3	Analysis • Perform analyses to assess cost effectiveness of materials-based H_2 storage systems including scale-up to high-volume production. • Conduct analyses of high-volume production cost and performance metrics (e.g., well-to-wheels efficiency, greenhouse-gas emissions as well as volumetric/gravimetric capacities and other operating metrics) of competing H_2 storage materials-based systems to guide research toward the most viable systems. • Evaluate the safety performance of the complete systems. • Ensure compatibility with applicable codes and standards for on-vehicle storage and fueling interface.	A-R

3.3.7 Milestones

The following chart shows the interrelationship of milestones and tasks for the Hydrogen Storage sub-program from FY 2012 through FY 2020. The Hydrogen Storage sub-program inputs/outputs are summarized in Appendix B.


Hydrogen Storage Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
1.8
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Task 1: Material Discovery
2.8
2.7
2.1
2.2
2.3
2.4
2.5
2.6
Task 2: Engineering
3.3
3.6
3.1
3.2
3.4
3.5
3.7
Task 3: Analysis
Milestone
Recurring Milestone
Input
Output
Go/No-Go

Task 1: Material Discovery	
1.1	Material Handling: Determine applicability of H_2 storage materials for material handling applications. (4Q, 2014)
1.2	Portable Power: Determine applicability of H_2 storage materials for portable power applications. (4Q, 2015)
1.3	Material Handling: Down-select H_2 storage materials for material handling applications. (4Q, 2016)
1.4	Portable Power: Down-select H_2 storage materials for portable power applications. (2Q, 2017)
1.5	Transportation: Evaluate status and down-select endothermic chemical H_2 storage materials based on technical and economic viability. (4Q, 2018)
1.6	Transportation: Evaluate status and down-select metal hydrides based on their potential to meet a system gravimetric capacity of 6 wt.% H_2 and an energy density of 0.05 kg H_2/L with 90% onboard efficiency. (4Q, 2019)
1.7	Transportation: Evaluate status and down-select adsorbents based on their potential to meet a system gravimetric capacity of 5.5 wt.% H_2 and an energy density of 0.04 kg H_2/L at ambient temperatures. (4Q, 2020)
1.8	Transportation: Evaluate status and down-select chemical hydrides based on their potential to meet a system gravimetric capacity of 6 wt.% H_2 and an energy density of 0.05 kg H_2/L with a well-to-power plant efficiency of 60%. (4Q, 2020)
Task 2: Engineering	
2.1	Transportation: Go/No Go decision on construction of subscale sorbent and chemical hydride prototypes. (1Q, 2014)
2.2	Transportation: Determine material specific properties required for 2020 onboard storage system targets. (4Q, 2015)
2.3	Transportation: Complete subscale prototype and evaluate against 2020 targets. (4Q, 2016)
2.4	Material Handling: Complete prototype of an onboard sorbent and/or chemical H_2 system and evaluate against 2015 targets. (4Q, 2018)
2.5	Transportation: Go/No Go decision on materials-based system strategies to meet ultimate onboard system storage targets. (4Q, 2019)
2.6	Transportation: Develop and verify onboard storage systems achieving capacity of 5.5% by weight and an energy density of 0.04 kg H_2/L. (4Q, 2020)
2.7	Crosscutting: Reduce the high-volume cost of high-strength carbon fiber by 25% from $13 per pound to ~$9 per pound. (4Q, 2020)
2.8	Portable Power: Evaluate a complete prototype against DOE targets. (4Q, 2020)

Task 3: Analysis	
3.1	Quantify performance targets for H_2 storage for key early market, stationary, and portable fuel cell applications. (4Q, 2012)
3.2	Crosscutting: Evaluate status of carbon fiber cost reduction efforts against the 2010 baseline cost of $32/kg. (3Q, 2015)
3.3	Transportation: Complete economic evaluation of cold H_2 storage against targets. (4Q, 2015)
3.4	Transportation: Complete well-to-wheels analysis for cost, efficiency, and greenhouse gas emissions of most promising sorbent and chemical H_2 materials pathways. (4Q, 2016)
3.5	Crosscutting: Evaluate status of composite tank cost compared to 2013 baseline projected cost of $17/kWh. (4Q, 2017)
3.6	Update early market storage targets. (4Q, 2017)
3.7	Transportation: Complete analysis of onboard storage options compared to ultimate targets. (4Q, 2020)