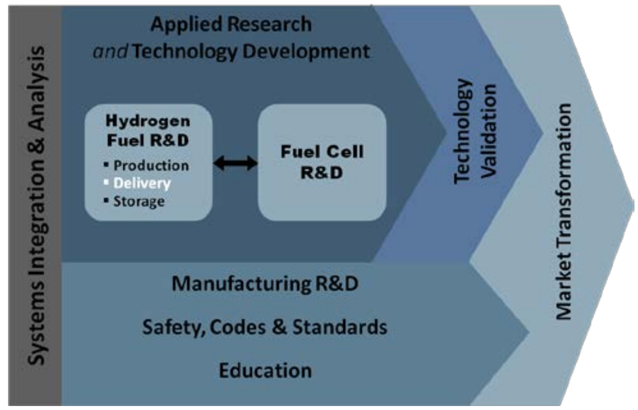
## 3.2 Hydrogen Delivery




Delivery is an essential component of any future hydrogen infrastructure. It encompasses those processes needed to transport hydrogen from a central or semi-central production facility to the final point of use and those required to load the energy carrier directly onto a given fuel cell system. Successful commercialization of hydrogen-fueled fuel cell systems, including those used in vehicles, back-up power sources, and distributed power generators, 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 and stationary power sites. As such, the hydrogen delivery infrastructure will need to integrate with these various hydrogen production options. It is estimated that for hydrogen to become an economically viable energy carrier for light duty vehicles, the combined cost of its production and delivery must achieve the threshold of $2.00 - $4.00/gallon of gasoline equivalent (gge) (untaxed).[1] Currently, the levelized cost of dispensed hydrogen lies well above this limit.

### 3.2.1 Technical Goal and Objectives

#### Goal

Develop technologies that reduce the costs of delivering hydrogen to a level at which its use as an energy carrier in fuel cell applications is competitive with alternative transportation and power generation technologies.

#### Objectives

- By 2012, identify optimized delivery pathways that meet an as-dispensed hydrogen cost of <$4/gge (~$1.00/100 standard cubic feet [scf], including the average cost of hydrogen at current production facilities) for the emerging fuel cell powered material handling equipment (MHE) market.
- By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$3/gge (~$0.75/100 scf).
- By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge.[2]

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[1] DOE-FCTP Record #11007, "Hydrogen Threshold Cost Calculation." http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf. All costs in this plan are in 2007 dollars to be consistent with EERE planning which uses the energy costs from the 2009 Annual Energy Outlook.

[2] Note that first generation consumer vehicles will likely require gaseous hydrogen compressed to 70 MPa, twice as high as that needed for gas storage onboard MHE. The higher level of compression will incur higher delivery cost.

- By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <\$2/gge.[3]

## 3.2.2 Technical Approach

The Hydrogen Delivery sub-program is focused on meeting its objectives through research, development and demonstration (RD&D) investments made in: (1) innovative technologies and processes to address the challenges of low cost, reliable hydrogen delivery and (2) infrastructure modeling, including delivery pathway analysis and optimization. Toward this end, the Delivery sub-program's efforts will be coordinated with other sub-program endeavors in the Fuel Cell Technologies Program (FCT Program), other DOE programs that have similar objectives, and related activities conducted by the U.S. Departments of Transportation and Commerce. Individual projects will address the barriers outlined in Section 3.2.5 and progress toward meeting sub-program objectives will be measured against the technical targets outlined in Tables 3.2.3 and 3.2.4.

### Hydrogen Transport and Fueling Options

The production of hydrogen is a relatively large and growing industry. In the United States alone, over twenty million metric tons of gaseous hydrogen is produced annually,[4] mostly for use as an industrial feedstock. The majority is produced at or near petroleum refineries and ammonia plants – the primary users of industrial hydrogen. More than 1200 miles of existing hydrogen pipelines serve regions with high concentrations of industrial hydrogen users, along the Gulf coast, near Los Angeles, and near Chicago along the lower portion of Lake Michigan.[5] The comparatively smaller merchant hydrogen market is serviced by cryogenic liquid hydrogen trucks or gaseous hydrogen tube trailers.

With respect to fuel cell use, processes associated with the delivery of hydrogen can be categorized either as transport operations, involving the transmission and distribution of hydrogen from one point to another, or as fueling operations involving the transfer of hydrogen into the final receiving device (e.g., to an onboard storage tank). Hydrogen delivery from a centralized or semi-centralized production facility requires both transport and fueling operations, while delivery operations associated with distributed production (i.e., on-site production directly at the point of use) typically involve only fueling operations. There are three means by which hydrogen is commonly transported, shown schematically in Figures 3.2.1 (a) – (c), as a liquid by cryogenic tank truck or as a compressed gas by tube trailer or by pipeline. Also shown in Figure 3.2.1 (d) is a fourth option, transport in solid or liquid carrier form – an approach that is still in the research and development phase. While the

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[3] This target is for a well-established hydrogen market demand for transportation (e.g., 15% market penetration in an urban population with a population of approximately 1M). The specific scenario examined assumes central production of $H_2$ that serves a city of moderately large size (population: ~1.2M), that the distance between the plant and city is 100 km (or 62 mi), and that the average fueling station capacity is 1000kg/day.

[4] M.D. Garvey, "The Hydrogen Report," CryoGas International, February 2011.

[5] By comparison, over 320,000 miles of natural gas transmission pipeline exists in the United States, Ref: "PHMSA Calendar Year 2009 Annual Reports for Gas Transmission and Gathering, Gas Distribution and Hazardous Liquid," PHMSA Calendar Year 2009 NPMS submissions for LNG Plants; http://primis.phmsa.dot.gov/comm/PipelineBasics.htm.

first three pathways involve the transport of molecular hydrogen, the latter approach employs a material that chemically binds or physisorbs hydrogen.

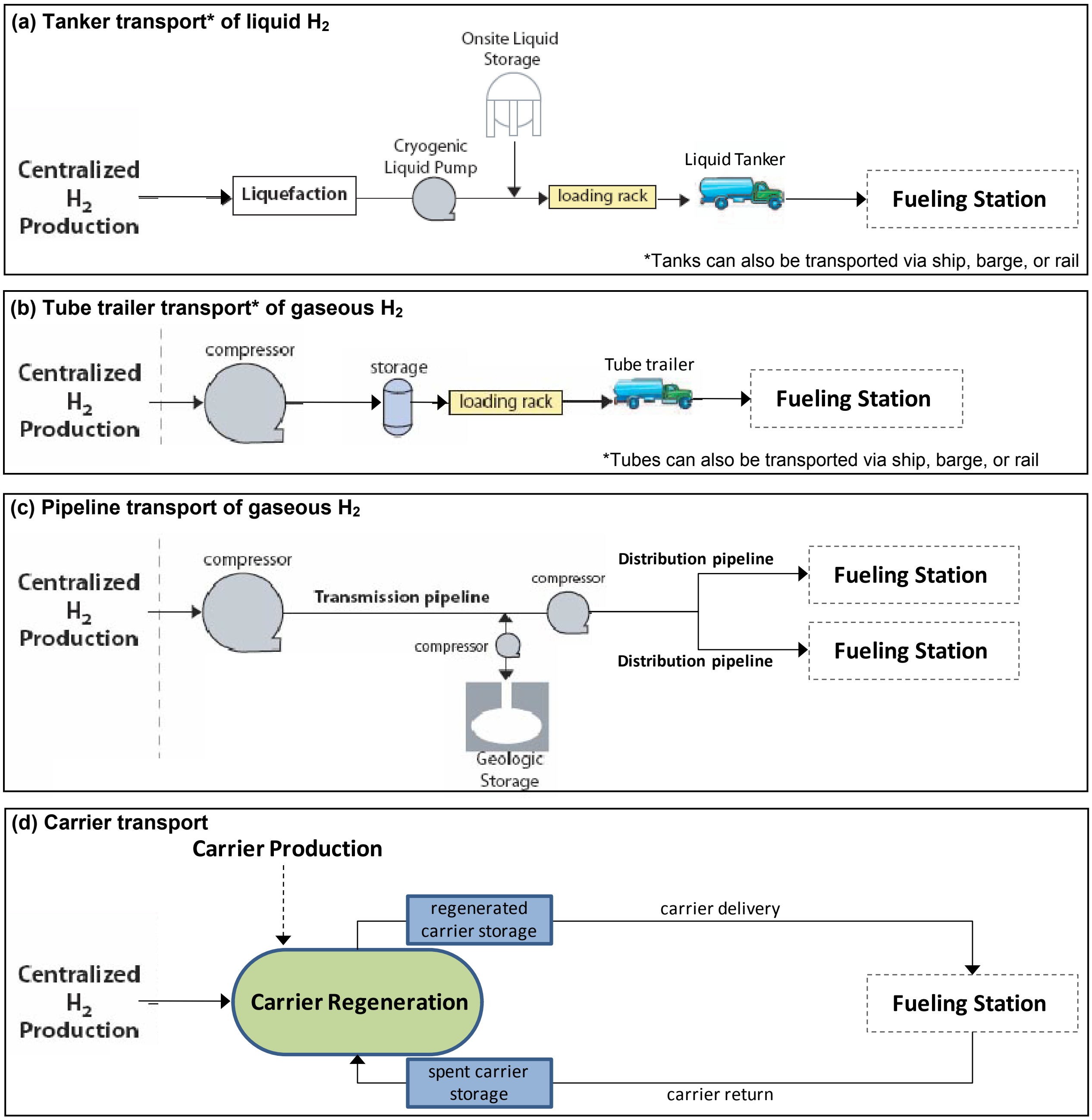


**Figure 3.2.1 Basic hydrogen transport pathway options.**

Each transport option consists of a series of process operations that in turn are comprised of a set of individual process components. Conceivably, alternative pathways could be chosen that combine elements from two or more of these basic approaches. For example, gaseous hydrogen can be transported by pipeline to a terminal where it is liquefied for distribution by cryogenic tank truck (a practice currently employed at several North American facilities) or it could be transformed at the terminal into a carrier for subsequent distribution. To minimize delivery costs, transport logistics are optimized by geographic location, availability of operational resources (e.g., transmission and distribution pipelines, trucks, compressors, etc.), market size and type (urban, interstate, or rural), and customer needs. These pathways have evolved over time with the growth of the industrial gas market and will continue to do so as various fuel cell markets emerge and expand and as new delivery technologies are developed and implemented.

The final point in the delivery chain for fuel cell applications are the fueling sites. At present, there are approximately 60 fueling stations in the U.S. that cumulatively have been supplying more than 1,500 kg/day of hydrogen to over 200 light-duty fuel cell electric vehicles (FCEVs) and 20 fuel cell buses. While the majority of these stations reside in Southern California, approximately a dozen each are located in the Midwest and Mid-Atlantic states. Most were constructed as demonstration projects, designed to provide data on the installation and operation of hydrogen fueling equipment, including cost. They generally do not include other retail features, such as a convenience store, fast food outlet, or car wash. The cost of dispensed hydrogen at these facilities can vary significantly depending on a number of factors, one of which is station capacity, or the maximum amount of hydrogen that can be dispensed daily at a given site. This quantity impacts the upstream method of hydrogen transport. For example, stations with capacities at or above 100 gge/day often rely on

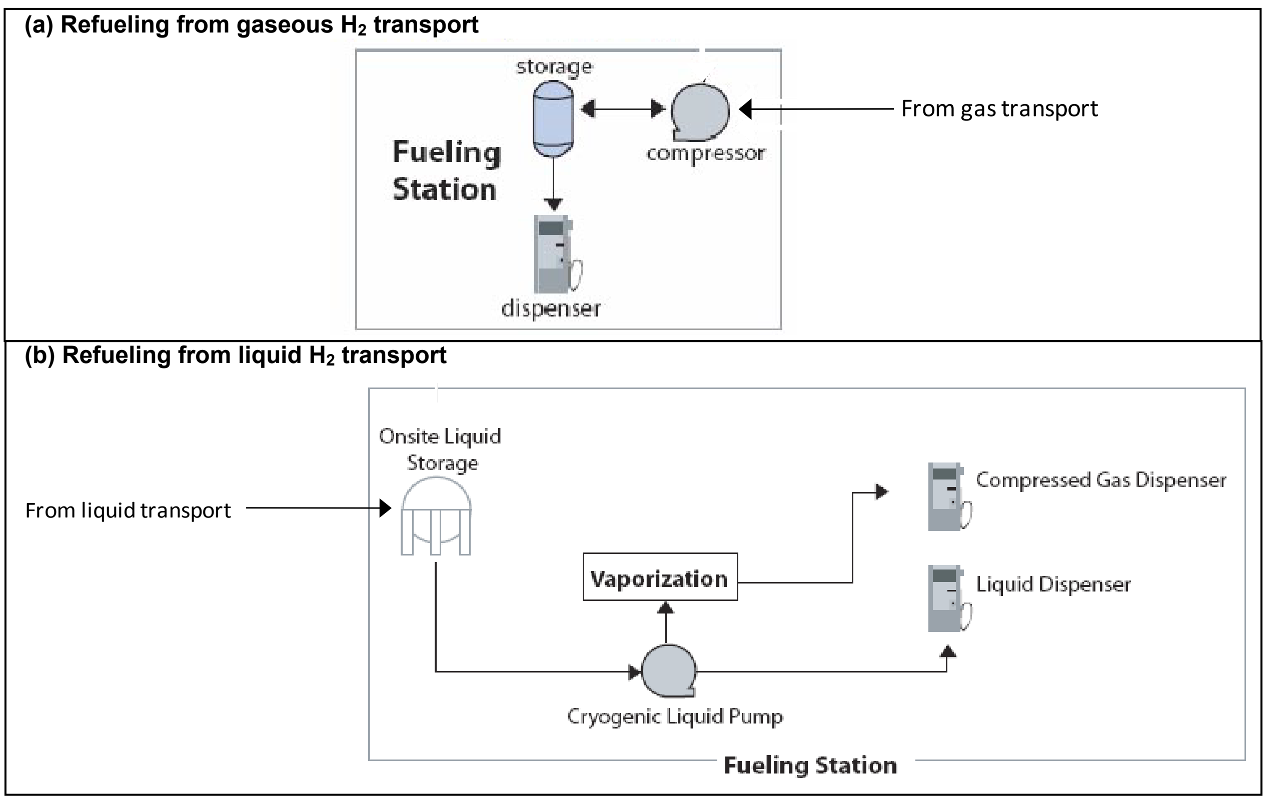


**Figure 3.2.2 Typical hydrogen fueling options.**

liquid transport, with the resulting dispensed gas ranging in price from \$5.70 to \$8.00/gge.[6] In comparison, smaller stations (capacities on the order of 10 – 20 gge/day) depend on direct gas transport via tube trailer, with an as-dispensed cost that can be approximately three times higher. In addition, a growing number of manufacturing facilities and distribution centers in the U.S. employ fuel cell powered MHE, such as forklifts,[7] and are equipped with on-site fueling operations. For nearly all current MHE and light-duty FCEVs, as well as back-up power generators, hydrogen is stored onboard at room temperature as a high-pressure compressed gas inside a steel or composite vessel. Shown in Figure 3.2.2 are the key process operations employed at present-day liquid- and gas-based hydrogen fueling stations. Note that delivery of a hydrogen-bearing carrier would require a different series of fueling operations. In all cases, the costs associated with the fueling station are significant, representing as much as half of the overall delivery cost.

### Hydrogen Transport and Fueling Operations and Components

Along many product delivery pathways are regional terminals that receive large volumes of the product and further process, apportion, and/or package it for final distribution to small retail outlets. In the case of hydrogen, the terminal might receive hydrogen (for example in gaseous form from a pipeline) and further purify, compress, and load it onto tube trailers for distribution to various fueling sites. As seen from the schematic for this in Figure 3.2.3, there are a number of commonalities between process operations at each stage. As a result, improved technology developed for one stage of hydrogen delivery might also be applied at other points of the infrastructure. For example, improved storage technology could be used at both terminals and fueling stations. There is also the potential for pathway optimization through technology advances to reduce overall delivery cost. An example of this would be the development of high-pressure tube trailers that could deliver hydrogen gas to fueling stations at the desired dispensing pressure, thereby partially offsetting the need for multiple-stage, small-scale compressors at each of these sites using a single set of large-scale compression units at the terminal. Listed in Table 3.2.1 are the individual process components employed for both transport and fueling, along with a brief description of the commercial status of each. As outlined in Section 3.2.5, many of these will require improvement in order to establish a cost-effective hydrogen delivery infrastructure that meets the objectives defined above.

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[6] California Fuel Cell Partnership, "Hydrogen Fuel Cell Vehicle and Station Deployment Plan: A Strategy for Meeting the Challenge Ahead," Feb. 2009.

[7] As of 7/2011, fuel cell powered forklifts were deployed at 36 U.S. facilities; http://www.fuelcells.org/resources/charts/

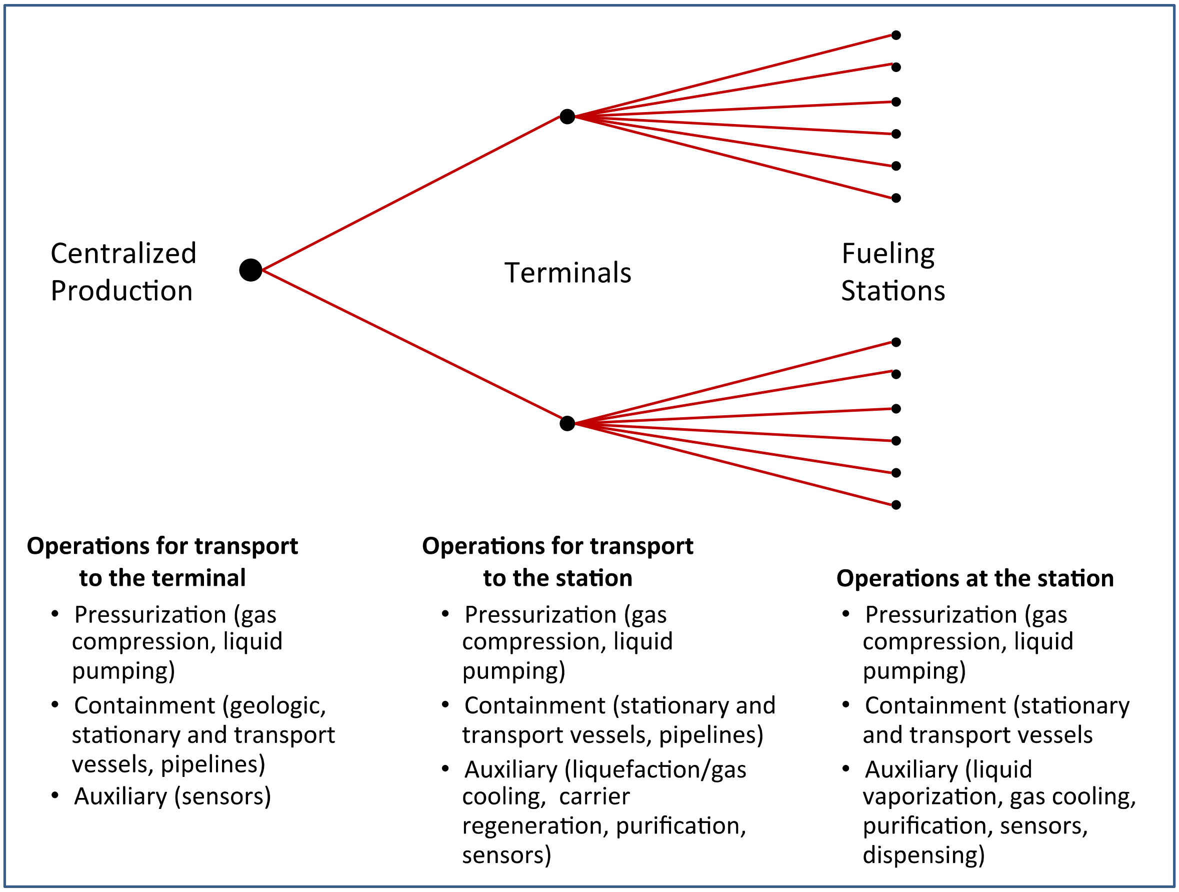



**Figure 3.2.3 Commonality of process operations along a generic hydrogen delivery pathway.**

| Table 3.2.1 Hydrogen Delivery Infrastructure Components | | |
|---|---|---|
| | **Delivery Component** | **Current Status** |
| Pressurization | Gas compressors | Compression operations can be differentiated based on capacity and pressurization needs. For pipeline transport, high flow rates (thousands of kg/hr) and relatively low pressures (<10MPa) and compression ratios (10:1) are required. The opposite is true at fueling stations, where compressor flow rates may be 5 - 100kg/hr and compression pressures as high as 90 MPa (900 bar). Loading operations at terminals generally have intermediate needs.<br>High flow rate reciprocating piston compressors are typically employed for pipeline transport and terminal pressure vessel loading operations and high-pressure diaphragm compressors are used at hydrogen fueling stations (although small reciprocating and intensifier compressors are also used). Ionic liquid compressors are beginning to be commercialized for use in low-to-moderate flow rate and high-pressure gas compression operations. |
| | Liquid pumps | Liquid $H_2$ is typically pressurized with specially designed centrifugal pumps. Cryogenic reciprocating pumps have also been employed. |
| Containment | Pipelines | This is the perceived lowest cost option for large volume $H_2$ transport. However, because the capital investment for pipelines is high, there must be a steady, high volume gas demand to justify the investment cost.<br>Transmission line pressures are typically 3 – 15 MPa (30 – 150 bar), while distribution line pressures range from 1 – 5 MPa (10 – 50 bar).[a]<br>Materials of construction are mild, low carbon steels. Embrittlement concerns for these materials are far less than for higher strength steels and are further mitigated by proper pipeline design (there are some concerns with combined fatigue effects due to pressure surging in the lines and with poor welds at pipe joints).<br>Long pipelines for liquid hydrogen are currently cost prohibitive. |
| | Gas storage | The most common pressure vessel construction is the Type 1 steel tube. These are capable of storing gaseous $H_2$ at pressures of 13.5 – 41 MPa (135 – 410 bar) and can be interconnected to increase overall storage capacity.<br>Storage pressure is limited for over the road transport based on DOT regulations, which depend on vessel construction, vessel size, and transport container design. Current carrying capacity for steel tube trailers is only about 300 kg (at ~18 MPa, or 180 bar).<br>Because of the limited amount of $H_2$ that can be transported by steel tube trailer, this transport approach is economically constrained to a radius of ~ 300 km from the point of production. Compressed hydrogen gas can also be delivered by rail, ship, and barge.<br>Composite pressure vessels are also available. Typically these cost more than steel vessels of equivalent size, but generally will store $H_2$ at higher pressures (and therefore higher capacity) and storage costs on a “per kg of $H_2$ stored” basis are often lower. The use of composite vessels for tube trailer transport and for onsite storage is being developed. |
| | Geologic storage | Geologic storage is commonly used in the natural gas delivery infrastructure to store large quantities of gas at modest pressures (~15 – 20MPa, or ~150 – 200 bar). Caverns are typically formed in impermeable salt domes to minimize gas loss.<br>There is one $H_2$ storage salt cavern site in the U.S. at Lake Jackson, TX that has been in operation for several decades and two others that have been built recently (also in Texas). |

| Table 3.2.1 Hydrogen Delivery Infrastructure Components | | |
|---|---|---|
| | **Delivery Component** | **Current Status** |
| Auxiliary Processing | Liquefaction systems | Over 90% of merchant hydrogen is transported in liquid form, which is currently the most economical means of truck transport for large market demands (> 100 kg/day) and for distances greater than ~300 km.[b]<br>There are ten liquefaction plants in North America, each varying in capacity from 5,400 – 32,000 kg/day.[c]<br>These plants employ multiple cooling cycles (including pre-cooling with liquid $N_2$, a Brayton cycle, and a Joule-Thompson cycle) and are energy intensive, consuming electricity ~⅓ of the energy in the hydrogen. |
| Auxiliary Processing | Gas cooling systems | 70 MPa (700 bar) dispensing of gaseous $H_2$ into Type IV tanks at a fill rate of 1.6 kg/min currently requires pre-cooling of the gas to overcome the heat of compression and the consequent effects on pressure vessel strength.[c] Several early-design 70 MPa (700 bar) dispensing systems employ liquid $N_2$ cooling to about -40°C. |
| Auxiliary Processing | Separators/ purifiers | Common practice is to use pressure swing adsorption to remove impurities from gaseous hydrogen for use in fuel cells. This is done at the point of production. Other technologies include membrane and cryogenic separation. Compressor lubricants are removed by filtration. |
| Auxiliary Processing | Dispensers | Commercial vehicle station gas dispensers often consist of a locking nozzle equipped for communication with the tank to ensure proper pre-programmed fill rates, safety breakaway hoses, electronically controlled delivery valving, and temperature/pressure compensated metering in packaging that resembles a standard gasoline dispenser. Dispenser systems exist that handle either 35 or 70 MPa (350 or 700 bar) gas pressure. |
| Auxiliary Processing | Sensors | Hydrogen is colorless and odorless and its flames are virtually invisible in daylight. Commercial hydrogen sensor technology currently can be categorized as one of six basic types: electrochemical, palladium and palladium alloy film, metal oxide, pellistor, thermal conductivity, and optical/acoustic devices. |
| Auxiliary Processing | Evaporators | Used to generate gas from liquid $H_2$ at a given pressure, these units are usually composed of a series of finned heat exchangers that can be heated indirectly by air, water, or steam. |
| Carrier | Carrier systems | Currently not employed for $H_2$ transport. Preliminary assessments of ammonia, liquid hydrocarbons, metal hydrides, adsorbents, and chemical hydrides indicate that these materials may not offer a significant economic advantage relative to molecular hydrogen solely for delivery needs. However, results from the Storage sub-program may yet show a benefit for the combination of $H_2$ delivery and onboard storage. In addition, methane is currently being considered as a potentially viable carrier of hydrogen. |

[a] Nexant, Inc., "Hydrogen Delivery Infrastructure Options Analysis, Final Report." DE-FG36-05GO15032, Dec. 2008.

[b] http://hydrogen.pnl.gov/cocoon/morf/hydrogen.

[c] DOE-FCTP Record #9013, "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs."

## Research Strategy

Hydrogen can become a key energy carrier in the U.S. only after critical economic and technical barriers to the development of a more expanded infrastructure are overcome. The needs for RD&D range from incremental improvements to major advances in technology. Research activities can be staged; i.e., it is anticipated that certain needs must be satisfied in the near term to solidify early fuel cell markets, while others do not need to be fully met until there are appropriate signs for more widespread consumer demand. In addition, there are several factors that will impact the strategic choices made for Delivery sub-program RD&D investment, including:

- Emergence of potentially sustainable fuel cell markets – Sub-program support for emerging market applications will be critical in developing commercial acceptance and demand for fuel cell technology, as well as establishing low cost delivery technologies that can serve future markets. Nascent markets, such as the use of fuel cells in back-up power sources and material handling equipment, will likely continue to take advantage of the present merchant hydrogen infrastructure. However for these markets to grow and become sustainable, the levelized, as-dispensed cost of hydrogen must be reduced, including the delivery portion of that cost. Advances in delivery technology and process optimization that commercially entrench these early markets will also make the next set of market applications in the evolutionary chain (e.g., delivery vehicles and larger-scale distributed power generation) more economically attractive and therefore more viable.

- Hydrogen production strategy – The Fuel Cell Technologies Program's threshold for the untaxed, as-dispensed cost of hydrogen includes the costs of both production and delivery. Under several scenarios, there may be inherent trade-offs between the cost of production and the cost of delivery. Distributed hydrogen production, for example at the fueling site, eliminates costs associated with transporting hydrogen from a centralized or semi-centralized production facility. However, economies of scale associated with the latter two would result in lower production costs than experienced with a smaller size, on-site production system. In addition, it is possible to produce hydrogen at pressures higher than that delivered in current steam methane reformation practice. Again, there is a trade-off in the higher costs incurred with high-pressure production equipment versus the reduction in compression cost downstream at the fueling site.

- Required form of hydrogen for application storage – Fuel cell powered forklifts currently utilize 350 bar compressed hydrogen gas (CHG), while light-duty FCEVs will initially require 700 bar CHG for full range. The latter requires higher compression capability at FCEV fueling stations and a means of cooling the gas prior to dispensing (to avoid issues associated with hydrogen heating as it is compressed into the vehicle's tank), both of which represent higher fueling cost. In addition, the Storage sub-program is developing next generation storage strategies that may require the delivery of cryogenic liquid hydrogen to FCEV fueling stations, a different level of gas cooling, or liquid delivery of chemical hydrides that require off-board regeneration, each of which would require a different set of process operations than those currently used to serve MHE.

- Safety, codes, and standards considerations – The implementation of codes and standards by regulating authorities govern safe equipment/facility design, construction, and operation for every aspect of the hydrogen delivery infrastructure – including truck, rail, and pipeline transport; tank and geologic storage; handling at the terminal; and handling and dispensing at the fueling site. By nature, they also affect the costs for all of these operations, as well as for other factors such as insurance. Possible elimination or mitigation of processes constrained by regulation in favor of those less constrained can potentially reduce overall delivery cost. The development of safety equipment that facilitates approved use of a lower cost operation, less land use, lower cost facility design (e.g. fueling station), or reduced insurance costs can have the same effect.

With the above in mind, the Delivery sub-program will be aligned along the following RD&D thrusts:

**1) Innovative Technologies and Processes to Address the Challenges of Low Cost, Reliable Hydrogen Delivery**

The largest RD&D activity will concentrate on developing innovative process technologies that can reduce hydrogen transport and fueling costs. Investment decisions for these technologies will be guided by results from process and pathway optimization studies, as outlined for the analysis activity below. Stakeholder input and results from recent analyses indicate for long-term, high market penetration of light-duty fuel cell vehicles that advancements in the following delivery components would offer the greatest opportunity toward meeting the Program's threshold cost for as-dispensed hydrogen:

- Low cost, high efficiency pressurization equipment – including gas compressors and cryo-compression liquid pumps.
- Advanced containment technology – including low-cost pipelines and high pressure gas transport and stationary storage vessels.
- Auxiliary process units and enabling technologies – including novel hydrogen liquefaction or gas cooling systems; low-cost, high reliability dispensers; and advanced materials and sensors that promote more economic delivery processes.

**2) Infrastructure Modeling**

*a. Delivery Pathway Analysis*

The publicly available Hydrogen Delivery Scenario Analysis Model (HDSAM)[8] links together various hydrogen delivery component functions and costs to develop capacity/flow parameters for a variety of different potential hydrogen delivery infrastructure options. The model can be used to calculate the full cost of a given hydrogen delivery pathway, define underlying individual cost contributions, and examine the economic effects of new delivery technologies as a function of hydrogen demand, transport distance, underlying finance

[8] HDSAM V2.3; http://www.hydrogen.energy.gov/h2a_delivery.html

factors (e.g., internal rate of return, insurance, land costs, etc.). In addition to stakeholder feedback, this modeling tool provides a means of identifying those processes or factors likely to have the greatest impact on delivery cost for future sub-program technology development. Future efforts will include: (i) refining the cost inputs and assumptions made to the model as new data become available, (ii) assessing the potential impact of current technology development projects on hydrogen delivery cost as a means of measuring individual project progress towards the targets listed in Tables 3.2.3 and 3.2.4, and (iii) evaluating the impact of hydrogen production and onboard storage technologies on delivery pathway options, operations, and costs. Of particular strategic importance to the Program is an investigation of delivery pathway options for emerging markets such as MHE to identify key near-term technical and cost barriers for these.

*b. Delivery Pathway Optimization*

HDSAM also allows one to examine trade-offs between components and process operations along any potential delivery pathway and determine the effects of individual process or equipment optimization in minimizing overall cost; in essence carrying out a "deep-dive" to frame the engineering limits for competing process technologies. While the infrastructure analysis activity described above will identify key cost contributors, this research thrust will investigate how these contributors can be mitigated or eliminated through hypothetical, but practical changes in technology. This will afford a more deliberate basis for making investments in new delivery technology. The example of advanced high-pressure tube trailers discussed previously is one possible technology topic for consideration. Another includes understanding hydrogen temperature effects. For example, a recent preliminary analysis suggests that cooling hydrogen to 70 – 90 K at a production site or terminal, transporting it in insulated tube trailers, and charging cold gas to the vehicle may offer significant delivery cost advantages, as well as achieve a higher volumetric FCEV storage efficiency due to the higher density of the cold hydrogen gas relative to ambient gas. Again, initial efforts will focus on emerging markets to provide immediate value to the FCT Program.

## 3.2.3 Programmatic Status

Projects currently funded by the Delivery sub-program are shown in Table 3.2.2. Activities focused on pressurization technology development include the design of centrifugal compressors for high hydrogen flow rates, an electrochemical means of achieving high compression ratios for fueling applications, and the evaluation of ionic liquid compression of hydrogen gas and reciprocating pumping of hydrogen liquid. Advanced pressurized containment technology being developed includes the design of high-pressure gas vessels for transport and stationary storage, the characterization of hydrogen embrittlement enhanced fatigue in base and weld metal sections of common pipeline steels, and the evaluation of fiber reinforced polymers as alternative pipeline materials. In addition, magnetic refrigeration is being explored for hydrogen liquefaction. Analysis efforts include the use of HDSAM and other models to benchmark the projected costs of technologies in development against those of technologies currently employed by industry, to evaluate various delivery pathway costs for the MHE market, and to carry out a detailed optimization analysis of gas compression.

| Table 3.2.2 Current Hydrogen Delivery Projects | | |
|---|---|---|
| **Challenge** | **Approach** | **Activities** |
| Analysis | | |
| Identify the cost effective options for hydrogen delivery | Evaluate pathways and process for delivering gaseous or liquid H2 and novel carriers under various technology market, and financial assumptions | Argonne National Laboratory and Pacific Northwest National Laboratory: Evaluate delivery options for MHE and carry out a detailed engineering evaluation of compression technology and evaluate the trade-offs between compression and storage pressure/temperature at various points along competing delivery pathway options. |
| Pressurization | | |
| Compression: Increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compressors. | Develop improved compression technologies for gaseous hydrogen. | Concepts NREC and Mohawk Innovative Technologies Independently develop high flow rate centrifugal compression technology suitable for hydrogen.<br><br>Fuel Cell Energy: Develop electrochemical hydrogen compression technology.<br><br>National Renewable Energy Laboratory: Evaluate the operation and maintenance requirements for ionic liquid compression at a fueling site. |
| Pumps: Increase the reliability, reduce the cost, and improve the energy efficiency of liquid hydrogen pumps. | Develop improved compression technologies for liquid hydrogen. | Lawrence Livermore National Laboratory (LLNL): Evaluate the operation of a new reciprocating cryo-pump design. |
| Containment | | |
| Pipelines: reduce installed costs and ensure safety, reliability, and durability. | Resolve hydrogen embrittlement of steel concerns and evaluate new materials for pipeline delivery of hydrogen. | Sandia National Laboratories: Pipeline and weld materials testing and modeling.<br><br>Oak Ridge National Laboratory (ORNL) and Savannah River National Laboratory: Evaluate low-cost fiber reinforced polymer (FRP) composite pipelines. |
| Tube trailer and storage vessels reduce capital cost on a $/kg $H_2$ stored basis while ensuring safety, reliability, and durability | Develop vessels that can store gas under higher pressure and/or reduced temperature. | Lincoln Composites: Develop a high-pressure, composite tube trailer vessels.<br><br>LLNL: Evaluate composite materials and structures for high-pressure/reduced temperature stationary and transport storage.<br><br>ORNL: Develop an in-ground reinforced concrete based vessel. |
| Auxiliary | | |
| Liquefaction – reduce the capital cost and improve the energy efficiency of hydrogen liquefaction. | Explore new approaches to hydrogen liquefaction. | Prometheus, Inc.: Develop an alternative method of cryogenically cooling $H_2$ to <20 K via magnetic refrigeration. |

## 3.2.4 Technical Challenges

### Cost and Energy Efficiency

The overarching techno-economic challenge for this sub-program is to reduce the cost of hydrogen delivery so that stakeholders can achieve the return on the investment required for infrastructure build out. Without cost competitive hydrogen sourcing, fuel cell technology will not be economically viable for broad market application. To meet the long-term target of <$2.00/gge (i.e. the delivery half of the upper threshold cost) [9] significant improvements in delivery technology are required. For example, if pipeline transport is to be employed at greater scale, the capital cost for pipeline procurement and installation needs to be reduced, while maintaining the same level of safety and reliability that has been achieved for the last 50+ years in the industrial gas market experience. If cryogenic liquid transport is to be used in higher volume, the capital cost and energy efficiency associated with liquefaction must be improved dramatically and losses due to vaporization need to be minimized. The use of gaseous tube trailers could be very attractive if their carrying capacities can continue to be increased, perhaps through the use of higher pressure and/or cooled gas or the use of a novel carrier in the tubes. The gas compression technology used at terminals and fueling sites must be more reliable (i.e., reducing the need for back up units), require less/easier maintenance, and be lower cost. In general, the costs at fueling sites need to be brought down to a level that ensures a positive return on investment can be realized far more quickly than is currently projected.

### Hydrogen Purity Requirements

Polymer Electrolyte Membrane (PEM) fuel cell stacks requires very high quality hydrogen (see Appendix C). If the hydrogen is produced at the required specifications, then design of the delivery infrastructure must either guard against contamination or provide for a final purification step just prior to dispensing. Alternatively, hydrogen could be produced at lower purity levels and purified to specification further downstream along the delivery pathway prior to dispensing. The optimum purification strategy that will minimize overall costs will depend on the nature of the potential contamination issues and thus the technologies employed across production and delivery. The delivery research plan includes inputs and outputs across Hydrogen Production, Delivery, Storage, Fuel Cells, and Systems Analysis to coordinate this strategy.

### Hydrogen Leakage

Diatomic hydrogen is a very light molecule and can diffuse at much higher rates than other fuel or energy carrier gases, such as natural gas. This property introduces unique challenges in designing process equipment and selecting suitable materials of construction that mitigate hydrogen leakage. Currently, significant leakage issues are avoided in the handling and use of large quantities of hydrogen in industrial settings because process operations are highly monitored and equipment is maintained and operated by trained, skilled operators. The establishment of hydrogen as a major energy carrier, where it will be handled in more open settings at times by the general public (e.g.,

[9] DOE-FCTP Record 12001, "$H_2$ Production and Delivery Cost Apportionment." http://www.hydrogen.energy.gov/program_records.html

vehicle fueling), will require robust system design and engineering and appropriate safety measures for many of the processes discussed above.

## Analysis of Infrastructure Trade-Offs

The development of HDSAM offers a means of identifying key cost contributors for various delivery scenarios. To date, its use for this purpose has specifically focused on long-term fuel cell applications, notably a light-duty FCEV market. However, it is recognized that the infrastructure for long-term markets will likely grow out of that which initially develops around smaller near-term fuel cell applications markets. Analysis of the delivery options and challenges for these early markets is needed. In addition, a subsequent analysis must be undertaken that focuses on how potentially interdependent process operations (e.g., high-pressure storage and gas compression) can be optimized to reduce overall pathway costs. Other trade-off studies that should be conducted include: (1) evaluation of the effects of production strategy (e.g., distributed and high-pressure production) on the as-dispensed cost of hydrogen, (2) further investigation of a cold (~80K) delivery pathway, and (3) an initial delivery operations analysis of the chemical hydrides being developed for onboard FCEV storage in the Storage sub-program.

## Technical and Threshold Cost Targets

The key to achieving the sub-program's goal and objectives is to reduce capital and operating costs and improve performance reliability for major delivery process technologies: pressurized containment (for stationary and transport operations), pressurization (compression and pumping), and liquefaction. The sub-program targets listed in Tables 3.2.3 and 3.2.4 are designed to meet the Program's threshold cost target for as-dispensed hydrogen. They are based on an analysis of current technology and costs and estimates of what might be possible with technology advances and on the projected market-driven requirements for the total delivery system costs. The current technology costs are derived from a recently updated version of HDSAM [10] that includes the latest information from stakeholders. Delivery system costs are a complex function of the technology, delivery distances, system architecture, and hydrogen demand. The 2020 cost targets in the table are the estimated costs needed for these technologies to meet an overall delivery system cost contribution of <$2.00/gge[11] of hydrogen. Initial targets are also given for cold hydrogen gas delivery and liquid-carrier technologies that could prove useful for hydrogen delivery and vehicle storage.

[10] HDSAM V2.3; http://www.hydrogen.energy.gov/h2a_delivery.html.
[11] DOE-FCTP Record 12001, "$H_2$ Production and Delivery Cost Apportionment." http://www.hydrogen.energy.gov/program_records.html

| Table 3.2.3 Threshold Cost Targets for Hydrogen Delivery[a] | | | | |
|---|---|---|---|---|
| **Category** | **2005 Status[y]** | **FY 2011 Status** | **FY 2015 Target** | **FY 2020[z] Target** |
| **Hydrogen Delivery Sub-Program Threshold Cost Targets** | | | | |
| ***Delivery costs associated with distributed $H_2$ production[aa]*** | | | | |
| Aggregate fueling station cost ($/gge) | 1.90 | 2.50 | 2.15 | <1.70 |
| ***Delivery costs associated with centralized $H_2$ production[aa]*** | | | | |
| Cost of transport and distribution ($/gge) | 2.10 – 2.30 | 1.90 – 2.20 | 1.40 | <1.30 |
| Aggregate fueling station cost ($/gge) | 1.30 – 1.60 | 1.70 - 2.20 | 1.60 | <0.70 |

| Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a] | | | | |
|---|---|---|---|---|
| **Category** | **2005 Status[y]** | **FY 2011 Status** | **FY 2015 Target** | **FY 2020[z] Target** |
| **Gaseous Hydrogen Delivery** | | | | |
| ***Pipelines: Transmission*** | | | | |
| Total Capital Investment ($/mile for an 8-in. equivalent pipeline) [excluding right-of-way][b] | 765,000 | 765,000 | 735,000 | 710,000 |
| ***Pipelines: Distribution: Trunk and Service Lines*** | | | | |
| Total Capital Investment ($/mile for a 1-in. pipeline) [excluding right-of-way][b] | 440,000 | 440,000 | 375,000 | 250,000 |
| ***Pipelines: Transmission and Distribution*** | | | | |
| Reliability/Integrity (including 3rd-party damage issues)[c] | Acceptable for current service | Acceptable for current service | Acceptable for current service | Acceptable for current service |
| $H_2$ Leakage (kg-$H_2$/mile-yr)[d] | Unknown | Undefined | Undefined | <780 (Transmission) <160 (Distribution) |

| Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a] (continued) | | | | |
|---|---|---|---|---|
| **Category** | **2005 Status[y]** | **FY 2011 Status** | **FY 2015 Target** | **FY 2020[z] Target** |
| ***Large Compressors: Transmission Pipelines, Terminals, Geological Storage*** | | | | |
| Reliability[e] | Low | Low | Improved | Improved |
| Compressor Efficiency (Isentropic)[f] | 88% | 88% | >88% | >88% |
| Losses (% of $H_2$ throughput) | 0.5% | 0.5% | 0.5% | <0.5% |
| Uninstalled Capital Cost ($) (based on 3,000 kW motor rating)[g] | 2.7M | 2.7M | 2.3M | 1.9M |
| Maintenance (% of Installed Capital Cost) | 4% | 4% | 3% | 2% |
| Contamination[h] | Varies by design | Varies by design | Varies by design | None |
| ***Small Compressors: Fueling Sites*** | | | | |
| Reliability[i] | Low | Improved | Improved | High |
| Compressor Efficiency (Isentropic)[j] | 65% | 65% | 73% | 80% |
| Losses (% of $H_2$ throughput) | 0.5% | 0.5% | 0.5% | <0.5% |
| Uninstalled Capital Cost ($) (based on 1000 kg/day station, [~100 kg $H_2$/hr peak compressor flow][k] | 530,000 (Three compressors at $176,666 each. Two at 50% throughput each, and one backup) | 675,000 (Three compressors at $225,000 each. Two at 50% through-put each, and one backup) | 400,000 (Two compressors at $200,000 each. Both at 50% through-put each, no backup) or $360,000 (one compressor, no backup) | 240,000 (one compressor, no backup) |
| Maintenance (% of Installed Capital Cost) | 4% | 4% | 2.5% | 2% |
| Outlet Pressure Capability (bar)[l] | 430 | 860 | 860 | 860 |

| Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a] (continued) | | | | |
|---|---|---|---|---|
| Category | 2005 Status[y] | FY 2011 Status | FY 2015 Target | FY 2020[z] Target |
| Compression Power (kW) | 200 (20 bar at inlet) | 300 (20 bar at inlet) | 260 (20 bar at inlet) | 240 (20 bar at inlet) |
| Contamination[m] | Varies by design | Varies by design | Varies by design | None |
| **Stationary Gaseous Hydrogen Storage Tanks (for fueling sites, terminals, or other non-transport storage needs)[n]** | | | | |
| Low Pressure (160 bar) Purchased Capital Cost ($/kg of $H_2$ stored) | 1000 | 1000 | 850 | 700 |
| Moderate Pressure (430 bar) Purchased Capital Cost ($/kg of $H_2$ stored) | 1100 | 1100 | 900 | 750 |
| High Pressure (860 bar) Purchased Capital Cost ($/kg of $H_2$ stored) | N/A | 1,450 | 1,200 | 1000 |
| ***Tube Trailers[o]*** | | | | |
| Delivery Capacity (kg of $H_2$) | 280 | 560 | 700 | 940 |
| Operating Pressure Capability (bar) | 180 | 250 | 400 | 520 |
| Purchased Capital Cost ($) | 260,000 | 470,000 | 510,000 | 540,000 |
| ***Geologic Storage[p]*** | | | | |
| Installed Capital Cost[q] | Assumed equal to natural gas caverns | Assumed equal to natural gas caverns | Assumed equal to natural gas caverns | Assumed equal to natural gas caverns |
| **Liquid Hydrogen Delivery** | | | | |
| ***Small-Scale Liquefaction (30,000 kg $H_2$/day)*** | | | | |
| Installed Capital Cost ($)[r] | 54M | 54M | 42M | 29M |
| Energy Required (kWh/kg of $H_2$)[s] | 10 | 10 | 8.0 | 6.5 |

| Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a] (continued) | | | | |
|---|---|---|---|---|
| **Category** | **2005 Status[y]** | **FY 2011 Status** | **FY 2015 Target** | **FY 2020[z] Target** |
| ***Large-Scale Liquefaction (300,000 kg $H_2$/day)*** | | | | |
| Installed Capital Cost ($)[r] | 186M | 186M | 150M | 110M |
| Energy Required (kWh/kg of $H_2$)[s] | 8 | 8 | 7.0 | 5.4 |
| ***Liquid $H_2$ Pumps (Fueling)[t]*** | | | | |
| Uninstalled Capital Cost ($) (430 bar pressure capability, 100 kg/h) | 100,000 | 100,000 | 85,000 | 70,000 |
| Uninstalled Capital Cost ($) (870 bar pressure capability, 100 kg/h) | N/A | N/A | 150,000 | 150,000 |
| **Cold Gas Delivery[u]** | | | | |
| ***Cold Gas Fueling Compressors (same requirements as fueling compressors above except the following)[v]*** | | | | |
| Uninstalled Capital Cost ($K) (based on a 1000 kg/day refueling station, 75 kW [50 kg $H_2$/hr peak compressor flow] | Undefined | 97,000 | 85,000 | 75,000 |
| Outlet Pressure Capability (bar) | Undefined | 350 | 350 | 350 |
| Temperature Capability (K) | Undefined | 90 | 90 | 70 - 90 |
| **Cold Gas Delivery (Off-Board Storage)[w]** | | | | |
| Low Pressure Storage Vessel Cost (160 bar; $/kg-$H_2$) | Undefined | Undefined | Undefined | 750 |
| High Pressure Storage Vessel Cost (430 bar; $/kg-$H_2$) | Undefined | Undefined | Undefined | 800 |
| Temperature Capability | Undefined | Undefined | Undefined | 40 K - ambient |
| **Cold Gas Delivery (Tube Trailer Transport)[w]** | | | | |
| Temperature Capability ( K) | Undefined | Undefined | Undefined | 60 K to ambient |
| Delivery Capacity at 90K (kg of $H_2$) | Undefined | Undefined | Undefined | 1,500 |
| Operating Pressure Capability (bar) | Undefined | Undefined | Undefined | 340 |
| Purchased Capital Cost ($) | Undefined | Undefined | Undefined | <600,000 |

| Table 3.2.4 Technical Targets for Hydrogen Delivery Components[a] (continued) | | | | |
|---|---|---|---|---|
| **Category** | **2005 Status[y]** | **FY 2011 Status** | **FY 2015 Target** | **FY 2020[z] Target** |
| **Liquid Carrier Based Hydrogen Delivery[x]** | | | | |
| Carrier $H_2$ Content (kg of $H_2/m^3$) | Undefined | Undefined | Undefined | >70 |
| Cost to regenerate | Undefined | Undefined | Undefined | <$1.00/kg of $H_2$ |
| Carrier System Energy Efficiency (from the point of $H_2$ production through dispensing at the fueling station) (%) | Undefined | Undefined | Undefined | ≥70 |
| **Gas Dispenser** | | | | |
| Uninstalled cost/dispenser ($ at the design pressure specified, two hoses per dispenser) | 30,000 (430bar) | 50,000 (860bar) | 40,000 (860bar) | 35,000 (860bar) |

a All costs in Table are in 2007 dollars to be consistent with EERE planning which uses the energy costs from the 2009 Annual Energy Outlook.

b Pipeline Capital Costs: The 2005 and 2011 costs are from HDSAM, V2.3. (For more details on the HDSAM, see www.hydrogen.energy.gov.) The model uses historical costs published by Brown et al (Brown, D., J. Cabe, and T. Stout, *National Lab Uses OGJ Data to Develop Cost Equations*, Oil & Gas Journal, Jan. 3, 2011 for natural gas steel pipelines as a function of pipeline diameter. It is assumed that hydrogen steel pipelines costs are 10% higher than natural gas pipelines based on discussions with industrial gas companies who build and operate the current system of hydrogen pipelines in the U.S. The costs are broken down into materials, labor, and miscellaneous costs in HDSAM. Because they vary widely based on the location of pipeline installation, right-of-way costs have been excluded in the analysis. However they can account for a significant fraction of installation cost, particularly in urban areas. The 2020 target costs are based on projected potential costs for spoolable FRP pipelines of less than 6" diameter similar to those used for natural gas gathering lines. (Note: An 8" transmission line service could use two 6" FRP pipelines for equivalent service.) Transmission line pressures are assumed to be as high as 150 bar, trunk lines as high as 50 bar, and service lines as high as 30 bar.

c Pipeline reliability refers to maintaining integrity of the pipeline relative to potential hydrogen embrittlement, third party damage, or other issues causing cracks or failures. The 2020 target is intended to be at least equivalent to that of today's natural gas pipeline infrastructure.

d Hydrogen leakage is hydrogen that permeates or leaks from fittings, etc., from the pipeline as a percent of the amount of hydrogen put through the pipeline. The 2020 target is based on being equivalent to today's natural gas pipeline infrastructure based on the article: David A. Kirchgessner, et al, "Estimate of Methane Emissions from the U.S. Natural Gas Industry," Chemososphere, Vol.35, No 6, pp. 1365-1390, 1997.

e Large Compressor Reliability: Currently the only hydrogen compressor technology available for pipeline transmission service and other high throughput, modest pressure boost service (e.g., a compression ratio of 1.5 to 10) is reciprocating compression. Due to the large number of moving parts and other challenges with hydrogen purity, this technology has low reliability. This translates to installing multiple compressors to ensure high availability. The status (2005, 2011) of "Low" is modeled in HDSAM, V2.3 as installing three compressors, each rated at 50% of the system peak flow. The 2020 target of "Improved" reliability assumes two compressors each rated at 50% of the peak flow for pipeline transmission and truck loading service and one compressor for hydrogen storage service. Reciprocating compression technology will need significant improvement or new technology (e.g., centrifugal compression applicable to hydrogen) may be needed to achieve these levels of reliability.

f Large Compressor Efficiency: The current status (2011) of 88% isentropic energy efficiency for the compressor itself is typical for large reciprocating compressors used for hydrogen. Isentropic efficiency of compressors is defined as "the increase in the enthalpy of hydrogen due to compression" divided by "the total mechanical energy used by the compressor" under isentropic conditions of compression. The difference between these two is dissipated as waste heat in the compression operation. The 2020 target is set to at least maintain this efficiency.

g Large Compressor Capital Cost: These 2005 and 2011 status cost is based on HDSAM, V2.3. The model uses capital cost estimates for large two- and three-stage reciprocating compressors based on data supplied by various vendors. (For more details on the large compressor capital cost data see "Hydrogen Delivery Infrastructure Options Analysis, Final Report." Nexant Inc., DE-FG36-05GO15032, Dec. 2008). The 2020 target cost is set at 70% of the 2011 cost to achieve overall delivery cost objectives.

h Large Compressor Contamination: Some reciprocating gas compressor designs require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen quality specifications for PEM fuel cells, the 2020 target is to ensure no possibility of lubricant contamination of the hydrogen from compression. As an alternative, it may be possible to remove such contamination at refueling sites just prior to charging the hydrogen to vehicles if this is not cost prohibitive.

i Fueling Compressor Reliability: Currently several compressor technologies are being demonstrated for refueling station service. The main employed technology is the diaphragm technology, but piston technology and intensifiers are also being used. There are concerns about reliability for this service. This translates to potentially installing multiple compressors to ensure high availability. The 2005 status of "Low" is modeled in the HDSAM V2.3 as installing three compressors each rated at 50% of the station peak hourly flow. The 2011 status of "improved" represents some improvement in this area and is modeled as two compressors each rated at 50% of peak station flow. The 2020 Target of "High" assumes only one compressor is needed at the station and can handle 100% of the peak station flow. This is deemed necessary to achieve the overall hydrogen delivery cost targets.

j Fueling Compression Efficiency: The 2005 and 2011 status of 65% isentropic energy efficiency for the compressor itself, is typical for the size of hydrogen refueling station compressors. Isentropic efficiency of compressors is defined as "the percentage of mechanical energy that ends up utilized as compression energy" divided by "the total energy used by the compressor" under isentropic conditions of compression. The difference between these two is dissipated as waste heat in the compression operation. The 2020 target represents new or improved technology to increase the compressor isentropic energy efficiency to 80%.

k Fueling Compressor Capital Cost: the 2005 cost is based on compression for 350 bar hydrogen dispensing. The 2011 cost is based on compression to 860 bar for 700 bar dispensing. Both costs are modeled using HDSAM, V2.3. The model uses a cost correlation as a function of motor kW required based on information obtained from a number of hydrogen compressor vendors. The 2020 target cost is set at 35% of the 2011 cost to achieve the overall delivery cost objectives.

l Fueling Hydrogen Fill Pressure: Light-duty fuel cell vehicles planned to be rolled out by OEMs in the 2015 timeframe will require 700 bar fills for full vehicle range, which in turn requires station compression capability of 860 bar. This is already being demonstrated at some fueling sites. The long term goal of the DOE is to develop solid or liquid carrier or other systems for vehicle storage tanks that allow for at least 300 miles of driving between refueling with more modest pressure storage (<500 bar psi). The DOE has set targets that include 700 bar fills in 2020 to allow for the introduction of hydrogen fuel cell vehicles with high pressure vehicle gas storage technology prior to achieving commercialization of the ultimate goal of lower pressure vehicle storage technology.

m Fueling Compressor Contamination: Some gas compressor designs with dynamic seals require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen quality specifications for PEM fuel cells, the 2020 target is to ensure no possibility of lubricant contamination of the hydrogen from fueling station compression.

n Stationary Gaseous Storage Tank Capital Costs: Several different pressures are likely for stationary storage purposes in a hydrogen delivery infrastructure. Low pressure storage at terminals and fueling stations where storage is needed but cost dictates lower pressures; moderate pressures for 350 bar refueling and high pressures for 700 bar refueling. The 2005 and 2011 status represents the cost of standard steel and composite tanks. The 2020 target is set at 65% of the 2011 cost to achieve the overall delivery cost objectives.

[o] Tube Trailers: The 2005 and 2011status tube trailer characteristics and costs are based on the HDSAM, V2.3, which uses available information on tube trailers from vendors. The 2020 cost targets are set to achieve the overall delivery cost objectives. There are several possible technology approaches to achieve these 2020 targets. It may be possible to develop more cost effective composite structures to increase the working pressure of gaseous tube trailers. The pressures in the Target Table are based on the pressure required to achieve the targeted hydrogen capacity. Another approach would be to utilize solid carrier technology and/or to employ low temperature hydrogen gas. It may also be possible to utilize some combination of these approaches. The key targets are hydrogen capacity and tube trailer capital cost.

[p] Geologic Cavern Capacity Availability: Transportation vehicle fuel demand is significantly higher in the summer than in the winter. To handle this demand surge in the summer without building prohibitively expensive excess production capacity, there will need to be significant hydrogen storage capacity within the hydrogen delivery system. Geologic storage is a very cost effective storage method for these types of demand swings and is used very effectively for similar demand swings for natural gas. There are only a few currently operating geologic storage sites for hydrogen in the world (in Texas and one in Teeside, England). Greater knowledge needs to be developed on the availability and suitability of hydrogen geologic storage sites. Technology development may also be required to ensure suitability for hydrogen.

[q] Geologic Cavern Capital Cost: This is based on HDSAM V2.3 which uses information from a U.S. hydrogen geologic storage site in Texas and assumes that hydrogen geologic caverns have the same capital cost as natural gas caverns. However, this is very limited information and is for a salt dome cavern only. This capital cost target is simply stating that hydrogen geologic storage capital costs need to be about the same as current natural gas geologic storage to make geologic storage of hydrogen cost effective and to enable achieving the overall delivery cost objectives. For more details, see: A.S. Lord, P.H. Kobos, G.T. Klise, and D.J. Borns, "A Lifecycle Cost Analysis Framework for Geologic Storage of Hydrogen: A User's Tool," Sandia Report: SAND2011-6221, Sept. 2011.

[r] Liquefaction Installed Capital: The 2005 and 2011 status costs are based on HDSAM, V2.3 which uses a correlation as a function of capacity derived from information obtained from industrial gas companies and other sources. The 2020 target cost is set to achieve the overall delivery cost objectives.

[s] Liquefaction Energy Use: The 2005 and 2011status energy requirements are based on HDSAM, V2.3 which uses a correlation as a function of capacity derived from information obtained from industrial gas companies and other sources. The 2020 target is set to achieve the overall energy efficiency objectives as well as information based on magnetic liquefaction technology that is being developed.

[t] Liquid Hydrogen Pumps: The 2005 status is based on delivery of liquid hydrogen to refueling stations where it is stored in a cryogenic tank, pumped to an evaporator and then charged to vehicles as a gas for 350 bar refueling with the aid of a cascade charging vessel system. The pump cost correlation is based on information from vendors on hydrogen liquid pumps available in 2005. The 2011 status is based on a technology similar to that available in 2005, except that the pump that charges liquid hydrogen to700 bar prior to passing the evaporator. The pump costs are based on information from developers who are currently beginning to demonstrate this technology with low hydrogen leakage rates and a maximum pumping capacity of 100kg/h is assumed. This is all modeled in HDSAM V2.3. The 2020 target is set to achieve the overall delivery cost objectives

[u] Cold Gas Delivery is a concept now being considered to reduce the cost of delivery and improve vehicle storage volumetric efficiency. The status and Targets are derived based on one promising scenario. At the terminal, hydrogen is cooled to about 90 K using liquid nitrogen. The hydrogen is transported to the refueling station in super insulated tube trailers capable of a 340 bar operating pressure. The tube trailer is dropped off at the station where it is used for storage. A compressor and insulated cascade storage vessel system is used to charge the cold hydrogen to a vehicle at 350 bar. The final temperature of the hydrogen on the vehicle would be about 200K assuming the vehicle came to the station with a tank one quarter full at about 50K which might be typical. The targets for the Cold Gas Delivery scenario are very preliminary and can only be refined when a more detailed analysis of this delivery pathway is completed. Preliminary status and Targets are provided for key components based on this scenario.

[v] Cold Gas Fueling Compressor: The 2011 capital costs are based on information from vendors who are starting to offer compressors for cold hydrogen gas. The 2020 target is based on achieving overall hydrogen delivery cost objectives. The pressure and temperature capability targets are based on the Cold Gas scenario used (see note [u]).

[w] Cold Gas Storage Vessels and Tube Trailers: These targets are based the Cold Gas scenario (see note [u]) and achieving the overall delivery cost objectives. The values include consideration of their ambient temperature component counterpart targets and inclusion of expected costs for insulation.

[x] Liquid Carrier Based Hydrogen Delivery: Hydrogen liquid carriers are being researched for onboard vehicle storage. In this case, the hydrogen is chemically bound and is released on the vehicle for use by the fuel cell. Liquid carriers might meet the volumetric storage efficiency targeted for vehicle storage. However, the spent liquid carrier must be returned to fairly large, semi-central facilities to be chemically processed and "recharged" with hydrogen (carrier regeneration). If the liquid carrier has a high enough hydrogen content, as indicated in the Target Table, its delivery costs could be quite low based on preliminary analysis. This might leave sufficient cost for regeneration and still meet the overall cost objectives for hydrogen delivery. The targets in the Target Table are very preliminary and can only be refined when the cost of regeneration is known and a more detailed analysis of this delivery pathway is completed. The target for carrier hydrogen content is based on achieving delivery capacity of about 1,500 kg of hydrogen in a standard 8,800 gallon gasoline type tanker. These tankers are DOT weight limited when delivering gasoline. Delivery modeling of truck delivery shows a very low cost for this delivery pathway if the truck has sufficient hydrogen delivery capacity.

[y] "2005 Status" numbers retained in the 2011 update to this MYRD&D section to show the differences between 2005 and 2011.

[z] 2020 targets are based on a well-established hydrogen market demand for transportation (15% market penetration). The specific scenario examined assumes central production of $H_2$ that serves a city of moderately large size (population: ~1M) and that the fueling station average dispensing rate is 1000kg/day.

[aa] Costs associated with distributed production refers to an apportionment of the costs required to capitalize, build, and operate a fueling station that are directly attributable to non-production operations, namely gas compression, on-site gas storage (to account for daily and weekly variations in demand), and gas dispensing. Costs associated with centralized production account for the above station costs as well as those required in transmitting the hydrogen from the production facility to the fueling station. Note that station costs associated with distributed production are somewhat higher than those for centralized production. This is because the former requires a higher level of on-site storage to account for seasonal variations in fueling demand. Seasonal variations for the latter are accounted for via geologic and/or terminal storage. The apportionment between the fuelling station cost and the transport and delivery cost is presented in program records 12022 and 12022d .

## 3.2.5 Technical Barriers

**A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis**

While options and trade-offs for hydrogen/carrier delivery from central and semi-central production to the point of use are generally well described for long-term market scenarios, this is not true for early markets. Possible means of *optimizing* delivery for either long-term or short-term market scenario are not well established. The distributed production of hydrogen is another option to be considered in greater detail. Additional analysis is needed to better understand the advantages and disadvantages of the various possible approaches and technology advancements, as well as potential site-specific and regional issues. In all cases, upstream delivery pathway inputs are tied to production outputs and downstream delivery outputs must meet the needs of the onboard storage system. This interdependency between hydrogen production, delivery, and onboard storage needs to be evaluated in order to understand the possible scenarios for minimizing overall life cycle cost, energy use, and environmental impact.

**B. Reliability and Costs of Gaseous Hydrogen Compression**

Current compression technology used for hydrogen requires frequent maintenance, which results in the need for redundant compressors to minimize downtime and leads to high cost. Centrifugal compression is the lowest cost approach for pipeline compression needs (for example in natural gas transmission) but the current technology does not work with hydrogen and new concepts have yet to be demonstrated. Lubricants used in normal compression applications can result in unacceptable levels of contamination for PEM fuel cell use. Refueling station compression currently have a high capital cost per unit throughput. The need for high-pressure (70 MPa), onboard storage in first generation light-duty fuel cell vehicles adds to the challenge. More reliable, lower-cost, and higher efficiency gas compression technologies are needed for pipelines, terminals, and fueling sites.

**C. Reliability and Costs of Liquid Hydrogen Pumping**

Cryogenic liquid pumps currently have lower capital cost per unit pumping capacity compared to gaseous compressors. However, the hydrogen entering the pump must be in the liquid state at all times. Any vaporization will cause cavitation that in turn can damage the pump. Boiloff associated with frequent cooling and heating of the pump requires the installation of recovery compression/storage system which adds to the overall fueling cost. In addition, periodic recharging of the pump is required to purge any frozen or trapped gases, which results in expensive downtime for the pumping process. Technologies that overcome these challenges are needed to ensure a reliable liquid hydrogen transport option.

**D. High As-Installed Cost of Pipelines**

Existing hydrogen pipelines are very limited in extent and location and are not adequate to broadly distribute hydrogen. Labor, materials, and other associated costs result in a large capital investment for new pipelines. Land acquisition or Right of Way can also be very costly. Hydrogen embrittlement of steel is not completely understood, in particular the effects on low cycle fatigue. Current joining technology for steel pipes is a major part of the labor costs and impacts the steel microstructure in a manner that can exacerbate hydrogen embrittlement issues. The use of fiber reinforced polymer (FRP) composite pipelines recently introduced for natural gas for gathering at well heads has the potential to reduce capital cost and is being investigated. However additional effort is needed to understand the reliability, durability, and safety considerations (e.g. third party damage) of this alternative transport option. Also needed is the development of innovative materials and technologies, such as seals, components, sensors, and safety and control systems.

**E. Gaseous Hydrogen Storage and Tube Trailer Delivery Costs**

Gaseous hydrogen storage at various points of use (such as production facilities, fueling stations, and terminals) and for tube trailer transport and pipeline system surge capacity adds cost to the delivery infrastructure. Understanding and optimizing for these storage needs, while adjusting for daily and seasonal hydrogen demand cycles, will be important in minimizing cost. Technologies that satisfy these storage requirements at a lower capital cost per kg of hydrogen stored will also reduce overall delivery costs. Possible approaches to technology improvement include maximizing storage pressure per unit of dollar of capital cost, utilizing cold hydrogen gas, and/or utilizing a solid carrier material in the storage vessel. Advancements of this type for transport via tube trailer will likely require additional considerations to ensure DOT approval. In addition, there are specific materials issues associated with gaseous storage. Like pipelines, steel tanks can be impacted by hydrogen embrittlement exacerbated by material fatigue due to pressure cycling, as discussed in Barrier D. Research into new materials, coatings, and fiber or other composite structures is needed. Costs might also be reduced through the use of Design for Manufacture and Assembly (DFMA) and improved manufacturing technology for high volume production of identical storage units.

**F. Geologic Storage**

The feasibility of extensive geologic hydrogen storage needs to be addressed. There are currently only a few hydrogen geologic storage sites in the world. Identification of geologic structures with particularly promising permeability characteristics may be needed. Potential hydrogen contamination and environmental impacts need to be further investigated.

**G. Low Cost, High Capacity Solid and Liquid Hydrogen Carrier Systems**

Novel solid or liquid carriers that can release hydrogen without significant processing operations are possible options for hydrogen transport or for use in stationary bulk storage. Current solid and liquid hydrogen carrier technologies have high costs, insufficient energy density, and/or poor hydrogen release and regeneration characteristics. Substantial improvements in current technologies or new technologies are needed. Materials-based storage approaches are currently the focus of significant R&D activity supported through the Hydrogen Storage sub-program; refer to the Hydrogen Storage MYRD&D section.

**H. High Cost and Low Energy Efficiency of Hydrogen Liquefaction**

Cryogenic liquid hydrogen has a much higher energy density than gaseous hydrogen. As a result, in the absence of an extensive hydrogen pipeline infrastructure, transporting liquid hydrogen by cryogenic tank truck is significantly less costly than transporting compressed hydrogen by gaseous tube trailer. However, liquefaction is very energy intensive and inefficient (see Table 3.2.3, Liquid Hydrogen Delivery – Liquefaction) and the cost of this process step represents nearly half of the overall liquid hydrogen delivery cost. Improvements in liquefaction technology are needed to reduce the cost of this delivery pathway. Possibilities include increasing the scale of these operations and improving efficiencies of compressors and expanders; integrating these operations with hydrogen production, power production, or other operations that improve energy efficiency; and developing completely new liquefaction technologies such as magnetic or acoustic liquefaction or other approaches. In addition, hydrogen boil-off from cryogenic liquid storage tanks needs to be addressed and minimized for improved cost and energy efficiency.

**I. Other Fueling Site/Terminal Operations**

Other potential operations at refueling sites and terminals need to be low cost (capital and operating). Rugged, reliable dispensers are needed to transfer hydrogen in required form to the onboard fuel cell storage system. Hydrogen cooling may be required for cold stationary or onboard vehicle storage, for high-pressure vehicle fills (70 MPa, or 700 bar), or for thermal management during the charging of material-based onboard storage systems. Final purification may be required at refueling sites. Other systems may be needed for handling particular two-way carrier technologies being explored for onboard vehicle storage (refer to the Storage section of the Multi Year Research, Development, and Demonstration Plan).

**J. Hydrogen Leakage and Sensors**

The hydrogen molecule is light and diffuses more rapidly than other gases. This makes it more challenging to design equipment, seals, valves, and fittings to avoid hydrogen leakage. Current industrial hydrogen processes are monitored and maintained by trained, skilled operators. A delivery infrastructure designed specifically for hydrogen's use as a major energy carrier will need to rely heavily on sensors and robust designs and engineering. Low cost hydrogen leak detector sensors are needed. Suitable odorant technology for hydrogen leak detection may also be needed for hydrogen distribution pipelines. The odorant would need to be completely miscible with hydrogen gas and be easily removed or non-damaging to onboard storage systems and fuel cells. The development and use of mechanical integrity sensors that can be built into pipelines and vessels could provide additional protection against mechanical failures that might be caused by third-party damage or other potential mechanical failures. Additionally, purity sensors will be required to verify fuel quality prior to or during dispensing for fuel cell applications.

**K. Safety, Codes and Standards, Permitting**

Appropriate codes and standards are needed to ensure a reliable and safe hydrogen delivery infrastructure. Some of the hydrogen delivery elements such as tube trailers and cryogenic liquid hydrogen trucks are in commerce today, while others are not. Applicable codes and standards are needed for stationary storage at fueling sites and upstream in the hydrogen supply chain. Siting and permitting hurdles need to be overcome. The plan to address these issues is in the Safety, Codes and Standards section of the Multi-Year Research, Development and Demonstration Plan.

## 3.2.6 Technical Task Descriptions

The technical task descriptions are presented in Table 3.2.5. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate sub-program.

**Table 3.2.5 Technical Task Descriptions**

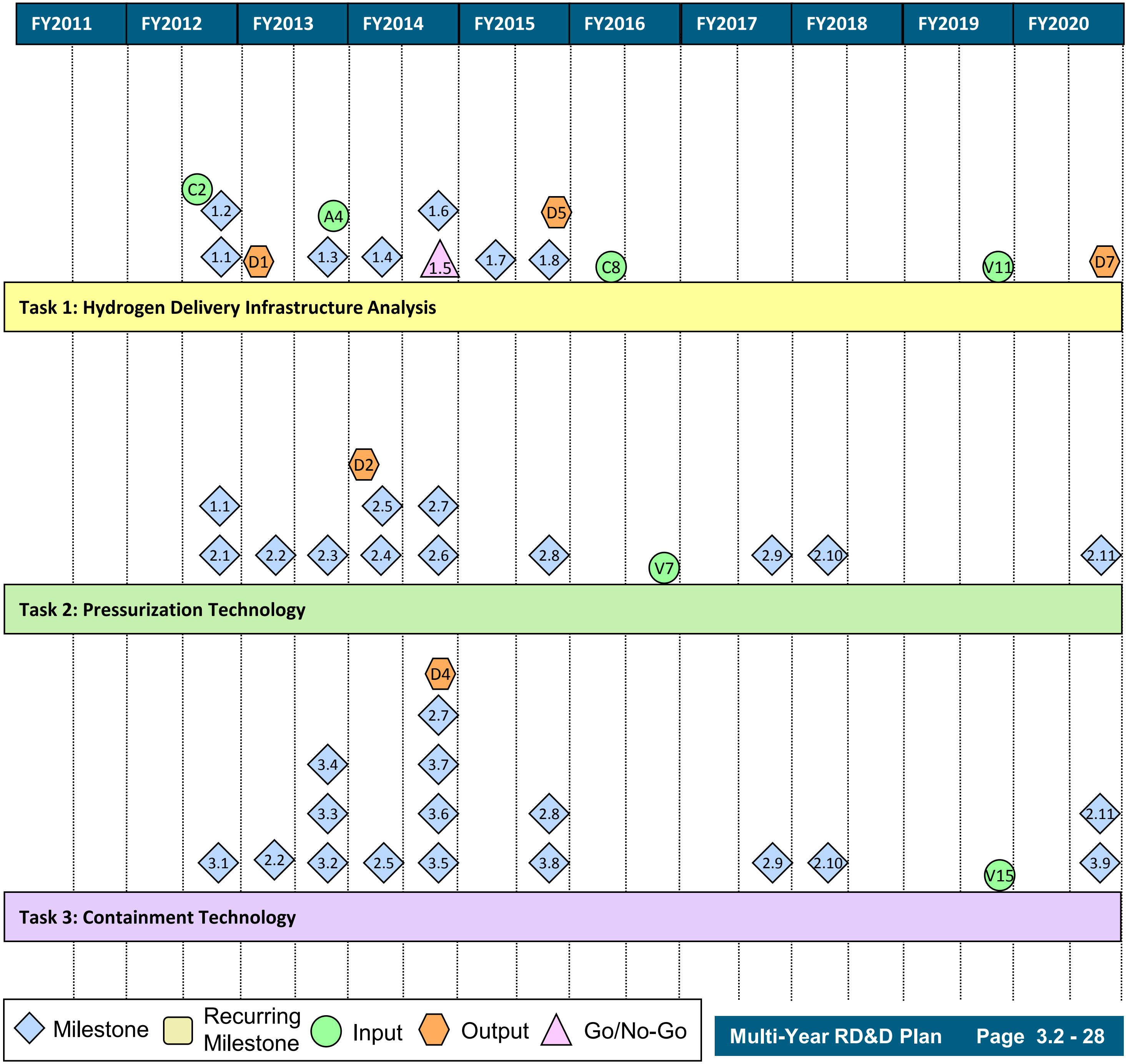
| Task | Description | Barriers |
|---|---|---|
| 1 | **Delivery Infrastructure Analysis**<br>• Characterize the cost and energy efficiency of current and possible future delivery components and pathways and identify the key improvements needed.<br>• Characterize the delivery costs for candidate liquid hydrogen carriers.<br>• Examine the effects of centralized and distributed production output conditions and onboard storage needs (for various markets) on delivery pathway options and cost.<br>• Perform optimization analyses to evaluate the trade-offs between various process operations that can minimize overall delivery cost for near-term markets.<br>• Perform optimization analyses to evaluate the trade-offs between various process operations that can minimize overall delivery cost for mid-and long-term markets. | A, B, C, D, E, F, G, H, I, J |
| 2 | **Reliable, Energy-Efficient, and Lower Cost Pressurization Technology**<br>• Research gas compression and liquid pumping technologies that can improve reliability, eliminate contamination, and reduce cost.<br>• Develop reliable, low cost, energy-efficient gas compression technology for hydrogen pipeline transport service and terminal needs.<br>• Develop reliable, low cost, energy-efficient gas compression technology for hydrogen fueling needs.<br>• Develop reliable, low cost, energy-efficient cryogenic liquid pumping technology for transport and fueling needs | B, C, I, K |
| 3 | **Safe, Lower Cost Containment Technologies**<br>• Research and develop technologies for steel pipeline materials that resolve potential embrittlement concerns.<br>• Research and develop alternative materials for $H_2$ pipelines that could reduce installed cost, while providing safe and reliable operation.<br>• Research and develop more cost effective gaseous $H_2$ bulk storage and tube trailer technology, including: higher pressure and/or cryogenic vessels, novel solid carriers, vessel materials and architecture, and the use of DFMA and high throughput production methods.<br>• Develop improved and lower cost valves, fittings, and seals to reduce hydrogen leakage.<br>• Develop mechanical integrity monitoring and leak detection technology.<br>• Research the feasibility of geologic and pipeline storage as a low cost high volume storage option. | D, E, F, G, I, J, K |

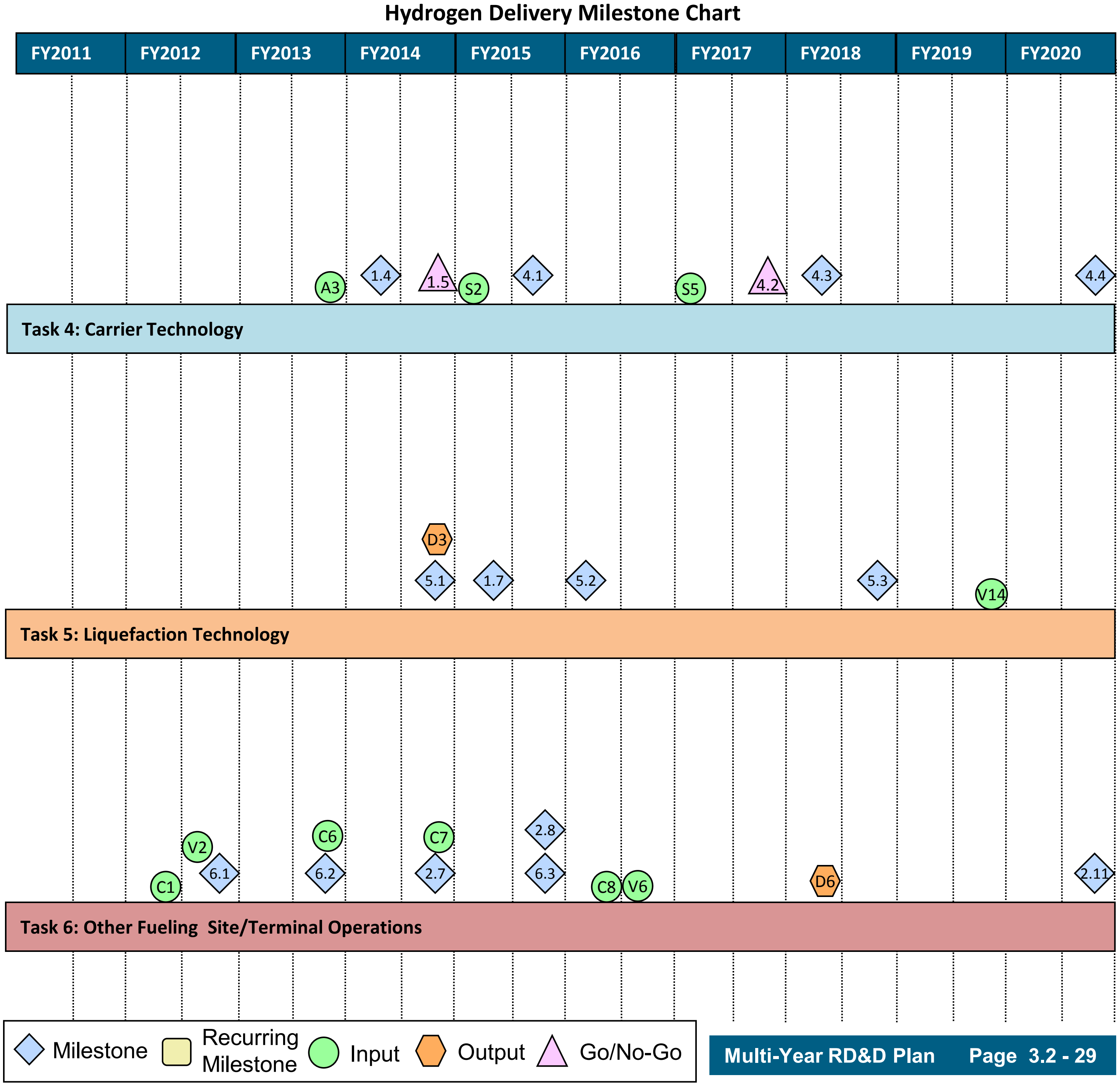
| Table 3.2.5 Technical Task Descriptions (continued) | | |
|---|---|---|
| **Task** | **Description** | **Barriers** |
| 4 | **Low Cost Carrier Technologies (In collaboration with the Hydrogen Onboard Storage Sub-Program)**<br>• Develop novel liquid hydrogen carrier technologies for high volumetric energy density, low-cost hydrogen transport.<br>• Develop novel solid carrier technology for hydrogen bulk stationary storage.<br>• Develop technologies for transport/off-board regeneration of chemical hydrides. | B, C, E, G, I, J, K |
| 5 | **Lower Cost, Energy-Efficient Hydrogen Liquefaction Technology**<br>• Investigate cost and energy efficiency gains for larger scale operations, achieving additional energy integration, and improving refrigeration schemes.<br>• Explore new, potential breakthrough technologies, such as magneto-caloric liquefaction. | H |
| 6 | **Other Fueling Site/Terminal Operations**<br>• Identify and define other potential operational needs for fueling sites and terminals that may include gas cooling, final purification, thermal management during vehicle refueling, robust dispensers, and systems for two-way onboard vehicle storage technologies.<br>• Develop low cost, energy-efficient, and safe technology as appropriate for these operations. | E, I, J, K |

## 3.2.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs from other sub-programs, and technology program outputs for the Hydrogen Delivery sub-program from FY 2011 through FY 2020. The inputs/outputs are also summarized in Appendix B.

## Hydrogen Delivery Milestone Chart




Hydrogen Delivery Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
A3
1.4
1.5
S2
4.1
S5
4.2
4.3
4.4
Task 4: Carrier Technology
D3
5.1
1.7
5.2
5.3
V14
Task 5: Liquefaction Technology
C1
V2
6.1
C6
6.2
C7
2.7
2.8
6.3
C8
V6
D6
2.11
Task 6: Other Fueling Site/Terminal Operations
Milestone
Recurring Milestone
Input
Output
Go/No-Go

| Task 1: Delivery Infrastructure Analysis | |
|---|---|
| 1.1 | Complete deep dive analysis of compression technology. (4Q, 2012) |
| 1.2 | Coordinating with the $H_2$ Production and Storage sub-programs, identify optimized delivery pathways that meet an as-dispensed $H_2$ cost of <$4/gge (~$1.00/100 $ft^3$) for the emerging fuel cell powered MHE market. (4Q, 2012) |
| 1.3 | Coordinating with the $H_2$ Production and Storage sub-programs, identify optimized delivery pathways that meet an as-dispensed $H_2$ cost of <$4/gge for emerging regional consumer and fleet vehicle markets. (4Q, 2013) |
| 1.4 | Complete deep dive analysis of potential hydrogen carrier technology. (2Q, 2014) |
| 1.5 | Go/No-Go on the use of liquid hydrogen carriers as an effective means of hydrogen delivery. (4Q, 2014) |
| 1.6 | Evaluate the projected costs for the transport/off-board regeneration of chemical hydrides. (4Q, 2014) |
| 1.7 | Complete deep dive analysis of potential liquefaction technology. (2Q, 2015) |
| 1.8 | Coordinating with the $H_2$ Production and Storage sub-programs, identify optimized delivery pathways that meet an as-dispensed $H_2$ cost of <$2/gge for use in consumer vehicles. (4Q, 2015) |

| Task 2: Pressurization Technology | |
|---|---|
| 2.1 | Complete performance and cost evaluation of ionic liquid gas compression. (4Q, 2012) |
| 2.2 | Down select two to three $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for near-term markets. (2Q, 2013) |
| 2.3 | Complete performance and cost evaluation of centrifugal gas compression of $H_2$. (4Q, 2013) |
| 2.4 | Complete performance and cost evaluation of electrochemical gas compression. (2Q, 2014) |
| 2.5 | Down select two to three $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for mid-term markets. (2Q, 2014) |
| 2.6 | Complete performance and cost evaluation of liquid $H_2$ reciprocating pump. (4Q, 2014) |
| 2.7 | By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$0.75/100 standard $ft^3$ (~$3/gge). (4Q, 2014) |
| 2.8 | By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge. (4Q, 2015) |
| 2.9 | Down select two to three $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (4Q, 2017) |
| 2.10 | Verify 2020 targeted cost and performance for $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (2Q, 2018) |

| Task 2: Pressurization Technology (continued) | |
|---|---|
| 2.11 | By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <$2/gge. (4Q, 2020) |
| 1.1 | Complete deep dive analysis of compression technology. (4Q, 2012) |

| Task 3: Containment Technology | |
|---|---|
| 3.1 | Complete performance and cost evaluation of glass fiber reinforced tube trailer technology. (4Q, 2012) |
| 3.2 | Complete characterization of the combined effects of fatigue and embrittlement on pipeline steel performance. (4Q, 2013) |
| 3.3 | Complete performance and cost evaluation of carbon fiber reinforced tube trailer technology. (4Q, 2013) |
| 3.4 | Complete performance and cost evaluation of stationary reinforced concrete vessel technology. (4Q, 2013) |
| 3.5 | Verify 2015 targeted cost and performance for hydrogen pipelines. (4Q, 2014) |
| 3.6 | Complete the research to establish the feasibility and define the cost for geologic hydrogen storage. (4Q, 2014) |
| 3.7 | Develop a technology for system mechanical integrity monitoring and leak detection of FRP pipeline. (4Q, 2014) |
| 3.8 | Complete evaluation of FRP pipe for $H_2$ pipeline and storage applications. (4Q, 2015) |
| 3.9 | Verify the feasibility of achieving the 2020 geologic storage cost and performance targets. (4Q, 2020) |
| 2.2 | Down select two to three $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for near-term markets. (2Q, 2013) |
| 2.5 | Down select two to three $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for mid-term markets. (2Q, 2014) |
| 2.7 | By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$0.75/100 standard $ft^3$ (~$3/gge). (4Q, 2014) |
| 2.8 | By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge. (4Q, 2015) |
| 2.9 | Down select two to three $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (4Q, 2017) |
| 2.10 | Verify 2020 targeted cost and performance for $H_2$ pressurization and/or containment technologies that minimize delivery pathway cost for long-term markets. (2Q, 2018) |
| 2.11 | By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <$2/gge. (4Q, 2020) |

| Task 4: Carrier Technology | |
|---|---|
| 4.1 | Initial down select of potential carrier systems for hydrogen delivery and bulk storage based on Go/No-Go decision. (3Q, 2015) |
| 4.2 | Go/No-Go on the economic viability of liquid hydrogen carriers for minimizing hydrogen delivery cost. (4Q, 2017) |
| 4.3 | Down select on hydrogen delivery carrier system technologies to achieve the 2020 cost and performance targets. (2Q, 2018) |
| 4.4 | Verify 2020 targeted cost and performance for $H_2$ carrier technologies that minimize delivery pathway cost for long-term markets. (4Q, 2020) |
| 1.4 | Complete deep dive analysis of potential liquid carrier technology. (2Q, 2014) |
| 1.5 | Go/No-Go on the use of liquid hydrogen carriers as an effective means of hydrogen delivery. (4Q, 2014) |

| Task 5: Liquefaction Technology | |
|---|---|
| 5.1 | Complete performance and cost evaluation of magneto caloric liquefaction technology. (4Q, 2014) |
| 5.2 | Down select one to two alternative improvements to liquefaction technologies. (1Q, 2016) |
| 5.3 | Verify 2020 targeted cost and performance for hydrogen liquefaction. (4Q, 2018) |
| 1.7 | Complete deep dive analysis of potential liquefaction technology. (2Q, 2015) |

| Task 6: Other Fueling Site/Terminal Operations | |
|---|---|
| 6.1 | Define potential R&D activities for other near-term market fueling/terminal needs. (4Q, 2012) |
| 6.2 | Define potential R&D activities for other mid-term market fueling/terminal needs. (4Q, 2013) |
| 6.3 | Define potential R&D activities for other long-term market fueling/terminal needs. (4Q, 2015) |
| 2.7 | By 2014, reduce the cost of hydrogen delivery from the point of production to the point of use for fuel cell powered MHE to <$0.75/100 $ft^3$ (~$3/gge). (4Q, 2014) |
| 2.8 | By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets to <$4/gge. (4Q, 2015) |
| 2.11 | By 2020, reduce the cost of hydrogen delivery from the point of production to the point of use in consumer vehicles to <$2/gge of hydrogen. (4Q, 2020) |

## Outputs

D1 Output to Technology Validation, Market Transformation, and Systems Analysis: Delivery pathways that can meet an as-dispensed hydrogen cost of <$4/gge ($1/100ft3) for emerging fuel cell powered early markets. (1Q, 2013)

D2 Output to Technology Validation: Provide candidate station compression technologies for potential technology validation. (1Q, 2014)

D3 Output to Technology Validation: Provide candidate liquefaction technologies for potential validation. (4Q, 2014)

D4 Output to Technology Validation: Recommended pipeline technology for validation. (4Q, 2014)

D5 Output to Technology Validation, Market Transformation, and Systems Integration: Provide options that meet <$4/gge for hydrogen delivery from the point of production to the point of use for emerging regional consumer and fleet vehicle markets. (4Q, 2015)

D6 Output to Safety, Codes and Standards: Technology and material characteristics of advanced delivery systems. (2Q, 2018)

D7 Output to Technology Validation, Market Transformation, and Systems Integration: Provide options that meet <$2/gge for hydrogen delivery from the point of production to the point of use in consumer vehicles. (4Q, 2020)

## Inputs

A3 Input from Systems Analysis: Preliminary well-to-wheel power plant efficiency analysis for advanced material systems. (4Q, 2013)

A4 Input from Systems Analysis: Analysis for costs for optimal hydrogen pressure contributions at each point in the system from production to dispensing at point of use. (4Q, 2013)

C1 Input from Safety, Codes and Standards: NFPA2: Hydrogen code document. (2Q, 2012)

C2 Input from Safety, Codes and Standards: Hydrogen fuel quality standard (SAE J2719). (3Q, 2012)

C6 Input from Safety, Codes and Standards: Updated materials compatibility technical reference manual. (4Q, 2013)

C7 Input from Safety, Codes and Standards: Materials reference guide and properties database. (4Q, 2014)

C8 Input from Safety, Codes and Standards: National indoor fueling standard. (2Q, 2016)

S2 Input from Storage: Technical and economic update from storage on promising storage material system. (1Q, 2015)

S5 Input from Storage: Projected performance of materials-based systems for onboard hydrogen storage. (1Q, 2017)

V2 Input from Technology Validation: Validate achievement of a refueling time of 3 minutes or less for 5 kg of hydrogen at 5,000 psi using advanced communication technology. (3Q, 2012)

V6 Input from Technology Validation: Validate 700-bar fast fill fueling stations against DOE fueling targets. (3Q, 2016)

V7 Input from Technology Validation: Validate novel hydrogen compression technology durability and efficiency. (4Q, 2016)

V11 Input from Technology Validation: Validate station compression technology provided by the delivery team. (4Q, 2019)

V14 Input from Technology Validation: Validate liquefaction technology provided by the delivery team. (4Q, 2019)

V15 Input from Technology Validation: Validate pipeline technology provided by the delivery team. (4Q, 2019)