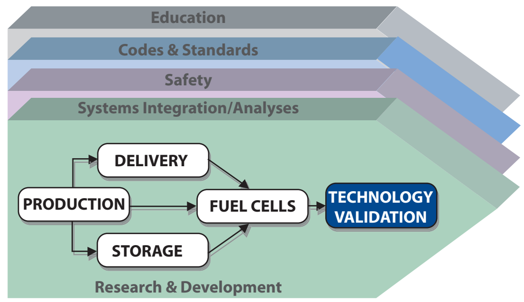
3.5 Technology Validation



Hydrogen fuel cell vehicles (FCVs) are currently in the pre-production stage of development, and the infrastructure to refuel them does not currently exist. In the past, efforts to introduce new energy technologies in the transportation sector have been thwarted by the classic "chicken and egg" dilemma of which comes first; in this case, hydrogen infrastructure or hydrogen FCVs. The Technology Validation program element will initiate resolution of this dilemma by developing and testing complete system solutions that will address all elements of infrastructure and vehicle technology and investigate novel new approaches such as Power Parks, which marry the transportation and electricity generation markets in synergistic ways.

3.5.1 Technical Goal and Objectives

Goal

Validate integrated hydrogen and fuel cell technologies for transportation, infrastructure, and electric generation in a systems context under real-world operating conditions.

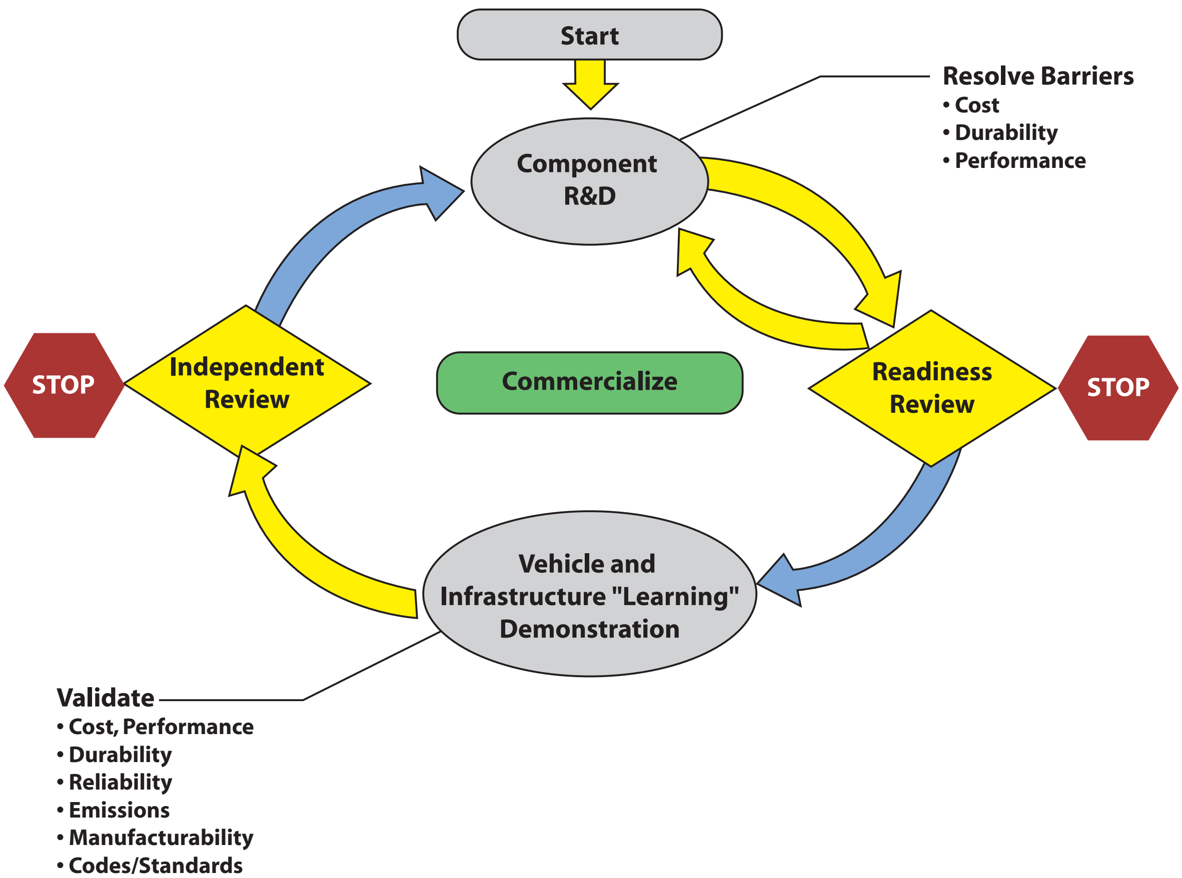
Objectives

- By 2008, validate an electrolyzer that is powered by a wind turbine at a capital cost of $300/kWe when built in quantity.
- By 2008, validate hydrogen vehicles, which have greater than a 300-mile range, 2,000-hour fuel cell durability, and $3.00/kg hydrogen production cost (untaxed), and which can be safely and conveniently refueled by trained drivers.
- By 2008, validate stationary fuel cell and hydrogen internal combustion engine (ICE) systems that coproduce hydrogen and electricity from nonrenewable and renewable resources, with a 30,000-hour durability, greater than 32% efficiency, and a price of $1,250/kW or less (for volume production).
- By 2010, validate an integrated biomass/wind or geothermal electrolyzer-to-hydrogen system to produce hydrogen for $3.30/kg at the plant gate (untaxed and unpressurized).
- By 2015, validate hydrogen PEM fuel cell vehicles, achieving 300+ mile range and 5,000 hours fuel cell system durability, and which can be safely and conveniently refueled by trained drivers.

3.5.2 Technical Approach

Technology validation is defined as confirmation that component technical targets for a given technology have been incorporated into a complete system solution, and that system performance and operation are met under realistic operating scenarios. The Technology Validation program element will implement integrated, complex systems (i.e., hydrogen production facilities and tests of hydrogen vehicles) and collect data from them to determine whether the technical targets have been met under realistic conditions (see Figure 3.5.1) Technology validations will be conducted at several times over the duration of this RD&D Plan. The results of the validations will be used to provide feedback on progress, and to efficiently manage the program element activities and provide redirection as needed.

Figure 3.5.1. The Role of Technology Validation—
"Learning demonstration activity with clearly defined objectives, milestones, and go/no-go decisions"

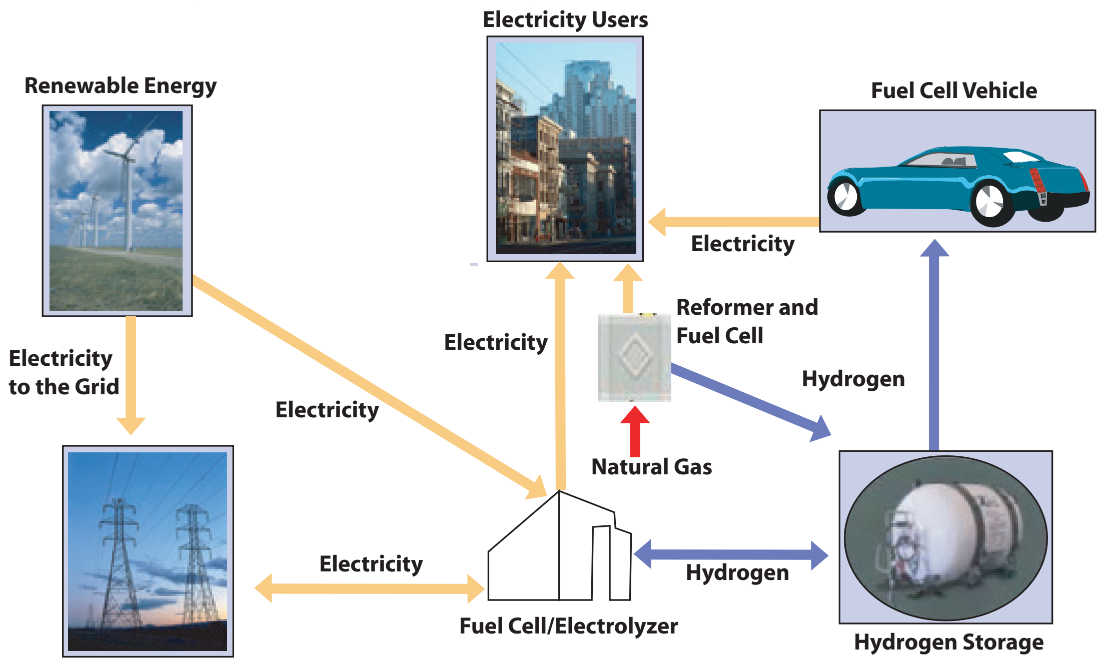


Technology validation projects will be undertaken to evaluate complex integrated hydrogen and fuel cell systems representative of commercial units operating under real-world conditions. Although all the components of complex systems may have met their technical targets and goals, the resulting systems may fail due to unanticipated integration problems or real-world operating conditions that are outside the planned design parameters. Complete validation

will require collecting sufficient data to develop statistical confidence that the systems meet customer expectations for reliability and durability, while satisfying regulatory requirements (e.g., emissions and safety). System and sub-system level models will be developed to help analyze the performance data collected from the integrated hydrogen and fuel cell systems and validate the component technical targets. The complete system models will also be used validate the technical approach being taken and redirect it as necessary.
Small-scale distributed hydrogen production from natural gas is the furthest along in development and is being field evaluated by constructing hydrogen refueling stations. Electrolyzer technology is available today, but using electricity produced from fossil fuels to make hydrogen creates large amounts of greenhouse gases. Power Parks can combine these near-term hydrogen production technologies into a single unit that produces both hydrogen and electricity. Electrolyzers also open the possibility of using electricity made from renewable and nuclear sources to produce carbon-free hydrogen. A demonstration of carbon-free hydrogen using an electrolyzer is planned to validate the technology and the potential of this approach. Future hydrogen production R&D will focus on using fossil fuels with carbon sequestration, and nuclear and renewable resources (i.e., wind, solar, biomass).

The Power Park concept includes steady production of hydrogen and use of a fuel cell to produce electricity. When excess hydrogen is available, it is stored for use when electricity demand is high and to refuel vehicles (see Figure 3.5.2). The advantages of producing both hydrogen and electricity in Power Parks include: it provides access to better natural gas rates because of higher volume than for a refueling facility only; it facilitates staged implementation of refueling components to better match the demand from vehicles; and it allows use of a larger reformer which will lower the per-unit capital costs of hydrogen production. The Power Park concept is amenable to distributed production of hydrogen from natural gas, and opens the possibility of incorporating wind and solar energy effectively. Analysis of the Power Park concept is ongoing and a future test is planned for validation.

Figure 3.5.2. Example of a Power Park Concept



In addition to the Power Park analysis, technical analyses will be initiated and used to assess current and guide future Technology Validation program element activities, including: vehicle component and vehicle systems; synergies between hydrogen pipelines and distributed power generation from those pipelines; and integrated renewable hydrogen production systems that combine electrolysis powered by wind, solar, hydropower, or geothermal with biomass gasification systems (oxygen from electrolysis is used to enhance biomass gasification while waste heat from the gasifier is used to enhance the electrolysis process). In addition, a portfolio analysis activity will be conducted on all R&D program element elements to ensure that the overall program stays on track and needed program element activity achievements are identified to meet FreedomCAR and stationary fuel cell targets.

3.5.3 Programmatic Status

Table 3.5.1 summarizes current Technology Validation activities, which focus on hydrogen infrastructure, Power Park, and renewable/hydrogen system demonstrations.

Current Activities

Table 3.5.1 Current Technology Validation Activities

Hydrogen Infrastructure	
Organization	**Activities**
California Fuel Cell Partnership (CaFCP)	The CaFCP expects to place as many as 60 fuel cell passenger cars and buses on the road by 2003. The partnership is examining fuel infrastructure issues and beginning to prepare the California market for this new technology. SunLine Services Group, Inc. and the Alameda-Contra Costa Transit District (AC Transit), both associate members of the CaFCP, are acquiring fuel cell transit buses using compressed hydrogen.
Los Alamos National Laboratory (LANL)	A hybrid fuel cell-powered personal mobility RD&D vehicle was constructed based on a commercially available standard three-wheeled scooter and fuel cell designs developed at LANL.
Vehicle Projects LLC	The Fuel Cell Propulsion Institute (a nonprofit consortium of industry participants) and Vehicle Projects LLC have developed and are evaluating a fuel cell mine locomotive, which uses a metal hydride hydrogen storage system designed by Sandia National Laboratory.
QUANTUM Technologies	Developed and validated 5,000 pounds per square inch (psi) >5 wt% Type IV composite hydrogen storage tanks and in-tank regulators.
Lawrence Livermore National Laboratory	Designed a new high-pressure, low-temperature (5,000 psi, cryogenic) hydrogen storage tank suitable for vehicle use.
SunLine Services Group, Inc.	Building a hydrogen FCV refueling station in Coachella Valley, California.
Air Products Corporation	Building stations in Las Vegas, Nevada (in cooperation with Plug Power) and at the Pennsylvania State University in State College, Pennsylvania.
City of Chula Vista, California	Installing a refueling station with a mobile electrolyzer by Stuart Energy.

UOP, University of Texas, and Proton Energy, Inc.	Developing and siting 1- to 5-kW hydrogen fuel cells to better understand fuel cell performance, maintenance, operation, and economic viability as uninterruptible power sources.
Power Parks	
Organization	**Activities**
Sandia Natational Laboratory and Air Products Corp.	Performing parametric studies of the components needed, the relative production of hydrogen and electricity, the resulting footprints of these systems, total system cost, and the anticipated cost of the hydrogen and electricity produced.
Hawaiian Electric Company, Detroit Edison and Arizona Public Services	Construction and operation of three Power Park systems in Hawaii, Michigan, and Arizona. Each will determine the relevant codes, safety standards, and engineering data required for Power Parks. The operation of these systems will provide data to better understand the performance, maintenance, operation, and economic viability of Power Parks.
Zoot Enterprises and Gallatin Development Corporation	Installing a 250-kW molten carbonate fuel cell power plant in a building at a high-tech office park near Bozeman, Montana. Waste heat from the fuel cells will be recovered and used in applications such as space heating and water heating.
Renewable/Hydrogen Systems	
Organization	**Activities**
Clark Atlanta University	Developed technology to generate hydrogen from biomass and agricultural residue. Successfully tested 1 kg/hour shift reactor using vapors from peanut shell pyrolysis. This technology is applicable to all forms of biomass.

3.5.4 Technical Challenges

A hydrogen refueling infrastructure needs to be established and vehicle interface issues need to be resolved. The cost of off-board hydrogen refueling is not commercially viable compared with the existing light vehicle refueling infrastructure. Hydrogen fuel cell vehicles face a "chicken and egg" problem because there is no refueling infrastructure and no one wants to build the infrastructure until vehicles are on the road. A distributed hydrogen refueling system built from components that convert natural gas from existing pipelines or electricity from existing grid systems could form the basis to initiate a hydrogen refueling infrastructure. But resources for small, widely distributed hydrogen production systems are limited by the very nature of distributed energy generation requirements. Large, centralized facilities depend upon a smaller number of high-volume centralized production sources. The current infrastructure makes it difficult to provide enough resources for the increased number of smaller systems. Since totally clean (i.e., zero greenhouse gas emissions) solutions are required, large centralized hydrogen production facilities that require new delivery infrastructure to be deployed (i.e., hydrogen pipelines and semicentral regional production facilities), and employ other feedstocks (such as coal with carbon sequestration) or nuclear or renewable energy sources will be necessary. A transition strategy on how to switch to centralized hydrogen production after investment has been made in a distributed system needs to be defined.

3.5.4.1 Technical Targets

The Technology Validation program element does not develop new component technologies, and therefore does not have technology targets. Instead, this program element will validate whether the technical targets for the individual components (developed within the other subprograms) can still be met when integrated into a complex system and review the future requirements for each component in such integrated systems. Specifically, once technical targets for each individual component have been verified under laboratory conditions, they will be verified under real-life conditions, during the phased demonstration of vehicle and infrastructure systems as part of the systems integration effort.

3.5.4.2 Barriers

In addition to the technical barriers being addressed through RD&D in the other subprograms, there are obstacles to successful implementation of fuel cells and the corresponding hydrogen infrastructure that can only be addressed by integrating the components into complete systems. After a technology has validated achievement of its technical targets in the laboratory, the next step is to show that it can work as designed within complete systems, e.g., FCVs and hydrogen refueling infrastructure. To have confidence in these technologies, they must also be evaluated in multiple systems to acquire sufficient data to validate statistical significance. A by-product of this approach to technology validation is that technical and system problems are revealed and component requirements can be better evaluated. The following barriers will be addressed by the Technology Validation program element to pave the way for commercialization of fuel cell and hydrogen infrastructure technologies.

A. **Vehicles.** In the public domain, statistical data for vehicles that are operated under controlled, real-world conditions is very limited (data such as FCV system fuel economy, thermal management integration (cold start efficiency), durability (stack degradation), and system durability). Most or all the information is proprietary. Vehicle drivability, operation, and survivability in extreme climates, and emissions (hydrogen ICE) are also barriers to commercialization. The interdependency of fuel cell subsystems is an important element that must be considered when developing individual subsystems. Development and testing of complete integrated fuel cell power systems is required to benchmark and validate for optimal component development.

B. **Storage.** Statistical cost, durability, fast-fill, discharge performance, and structural integrity data of hydrogen storage systems that are garnered from user sites need to be provided for the community to proceed with technology commercialization. Current technology does not provide 300+ mile range without interfering with luggage or passenger compartment spaces, nor does it provide reasonable cost and volume for stationary applications. An understanding of composite tank operating cycle life and failure due to accident or neglect is lacking. Adequate cycle life of chemical and metal hydride storage systems need to be evaluated in real-world circumstances.

C. **Hydrogen Refueling Infrastructure.** The high cost of hydrogen production, low availability of the hydrogen production systems, and the challenge of providing safe systems including low-cost, durable sensors are early penetration barriers. Shorter refueling times need to be validated for all the storage concepts. Integrated facilities with footprints small enough to be deployed into established refueling infrastructures need to be conceptualized and implemented. The impact of greenhouse gas emissions in tank-to-wheels scenarios is not well understood. Interface technology to fast-fill tanks requires reliable demonstrations. Small factory-manufactured, skid-mounted refueling systems need to be proven reliable options in low-volume production systems, for sparsely populated areas with low anticipated vehicle traffic.

D. Maintenance and Training Facilities. Lack of facilities for maintaining hydrogen vehicles, personnel not trained in handling and maintenance of hydrogen system components, limited certified procedures for fuel cells and safety, and lack of training manuals are all barriers that must be overcome. Lack of real-world data in the public domain on refueling requirements, operations and maintainance (O&M) of FCVs, and lack of data on greenhouse gas emissions are additional barriers.

E. Codes and Standards. Lack of adopted codes and standards that will permit the deployment of refueling stations in a cost-effective and timely manner must be addressed. These are necessary to ensure safety and to determine supplier design goals. Competing international standards prevent U.S. companies from introducing hydrogen technologies. A database also needs to be assembled to ensure that future energy systems based on these technologies can be efficiently installed and operated.

F. Centralized Hydrogen Production from Fossil Resources. There are few data on the cost, efficiencies, and availabilities of integrated coal-to-hydrogen/power plants with sequestration options. Hydrogen delivery systems from such centralized production systems need to be validated and operated. Hydrogen separation at high temperature and high pressure and their integrated impact on the hydrogen delivery system needs to be defined.

G. Hydrogen from Nuclear Power. Data on the chemical reactions at high temperatures, reaction rates, nonequilibrium reactions, and material properties that can contain highly reactive gases at high pressure for the high-temperature production of hydrogen through thermochemical and electrochemical processes are limited. The cost and O&M of such an integrated system needs to be assessed before high-temperature nuclear reactorsn are designed and developed for the hydrogen production. Hydrogen delivery options need to be determined and assessed as part of the system demonstration. Validation of integrated systems is required to optimize component development.

H. Hydrogen from Renewable Resources. There is little operational, durability, and efficiency information for integrated renewable/electrolyzer systems operating with large renewable facilities to produce hydrogen. Biomass systems operating on low-cost biomass fuels need to validate biomass feed systems, catalyst lifetimes, product co production, and availability on large systems. The integration of biomass and other renewable electrolyzer systems needs to be evaluated.

I. Hydrogen and Electricity Coproduction. Cost and durability of hydrogen fuel cell and reformer systems for coproducing hydrogen and electricity need to be statistically validated at user sites. Permitting, codes and standards, and safety procedures need to be established for hydrogen fuel cells located in or around buildings and refueling facilities. These systems have no commercial availability, operational, and maintenance experience.

3.5.5 Technical Task Descriptions

The technical task descriptions for the Technology Validation program element are presented in Table 3.5.2. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate program element. The duration of each task and the barriers associated with it (see Section 3.5.4.2) are also included.

Table 3.5.2 Technical Task Descriptions

Task	Description	Duration/Barriers
1	**Vehicle Field Evaluations** • Support CaFCP demonstration by developing and providing technical guidance for the development of data acquisition plans covering fuel cell transit vehicles and light duty vehicles. • Support acquisition of vehicles for controlled fleet demonstrations in strategic locations to collect data on FCV performance, durability, and reliability under real-world conditions. • Identify maintenance, safety, and refueling requirements, including sensors and refueling connections. • Collect vehicle operating experience, including fuel economy, range, cost, drivability, cold-start, emissions, and durability. Data will be used for modeling, and composite results will be disseminated.	30 Quarters/ Barriers A, B, C, D, E
2	**Hydrogen Infrastructure** • Design and construct early design hydrogen refueling facilities to collect data on the integrated systems that include natural gas reforming and renewable hydrogen production systems to support fleet vehicles. • Document permitting requirements and experiences. • Develop a safety plan and then document its effectiveness, including malfunctions. • Validate efficient integrated systems and their ability to deliver low-cost hydrogen, which includes performance, O&M, purity, and safety. • Collect and disseminate operating data to verify component performance using uniform protocols that include safety procedures, risk mitigation, and communication plans. • Collect and disseminate data from refueling sites in different geographic areas to verify performance and reliability under real-world operating conditions, including fast-fill and driver acceptance.	30 Quarters/ Barriers B, C, D, E, H, I

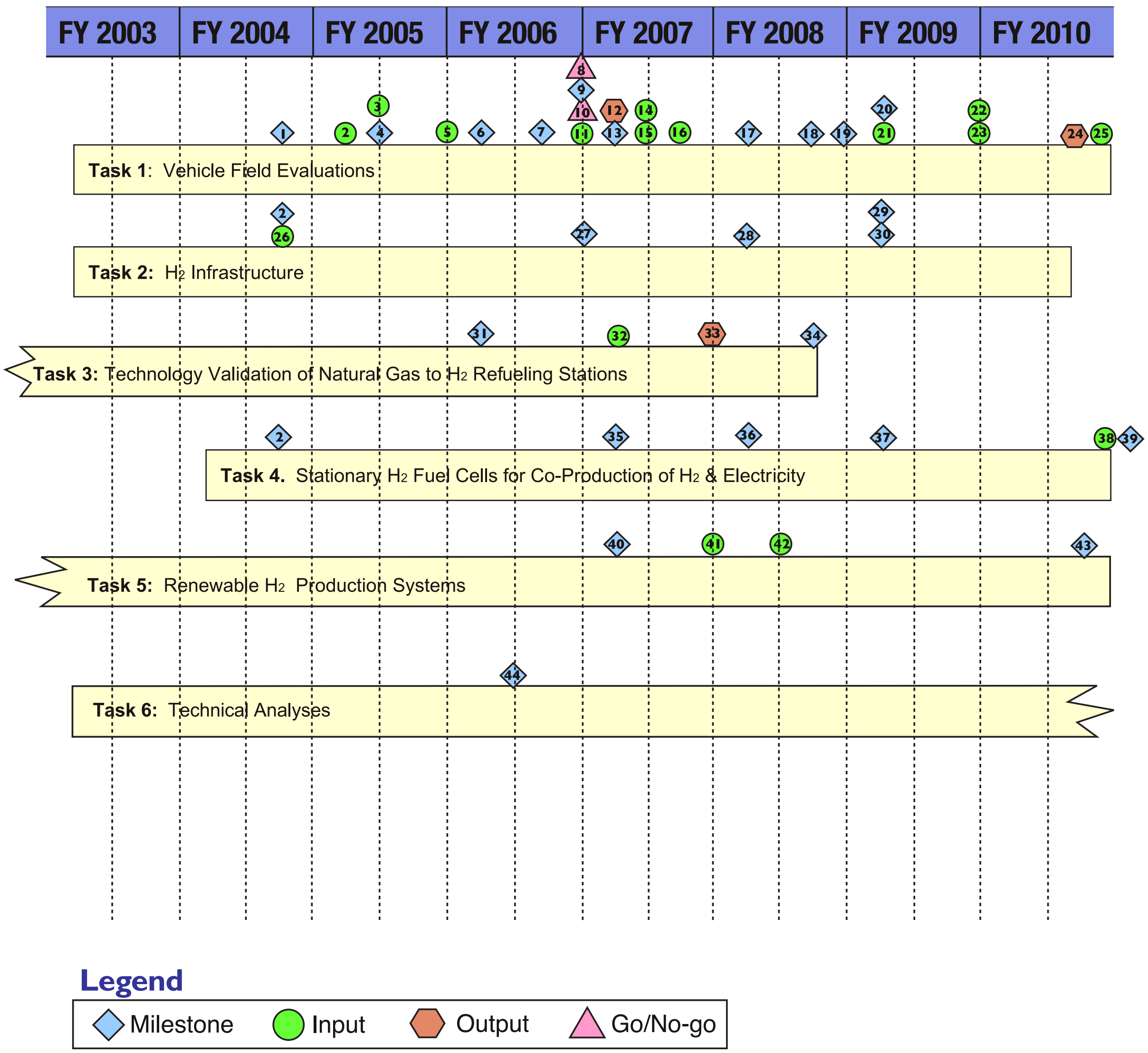
3	**Technology Validation of Natural Gas-to-Hydrogen Refueling Stations** • Build and operate three natural gas-to-hydrogen refueling stations to collect data on reformer performance and reliability under real-world conditions. • Document permitting requirements and experiences. • Develop a safety plan and then document its effectiveness, including malfunctions that are encountered. • Validate the cost of hydrogen produced including all aspects of station O&M. • Collect and disseminate operating data to verify component performance using uniform protocols that include safety procedures. • Collect and disseminate data from refueling sites in different geographic areas to verify performance and reliability under real-world operating conditions including fast-fill and driver acceptance.	16 Quarters/ Barriers B, C, D, E
4	**Stationary Hydrogen Fuel Cells for CoProduction of Hydrogen and Electricity** • Support low-level production of stationary hydrogen fuel cells to collect data on fuel cell performance, reliability, and cost. • Collect statistical data on the durability of the hydrogen fuel cells. • Identify O&M and safety requirements for stationary hydrogen fuel cells. • Determine the economics of hydrogen and electricity coproduction compared to stand-alone hydrogen production facilities.	24 Quarters/ Barriers B, C, I
5	**Renewable Hydrogen Production Systems** • Validate integrated systems and their ability to deliver low-cost hydrogen, which includes system performance, O&M, and durability. • Collect operating data to verify component performance using uniform protocols that include safety procedures. • Collect data from sites in different geographic areas to verify performance and reliability under real-world operating conditions. • Project the capability of renewable hydrogen production systems to supply hydrogen for vehicle use. • Assess the economic limitations of renewable hydrogen production, including system size and siting requirements based on resource location and transport economics.	32 Quarters/ Barriers E, H
6	**Technical Analyses** • Analyze hydrogen and electricity as energy carriers and evaluate potential synergies from “marrying” the electrical transmission and transportation systems. • Analyze integrated renewable hydrogen production systems that combine electrolysis powered by wind, solar, hydropower, or geothermal with biomass gasification systems. • Analyze of advanced Power Parks for production of both hydrogen and electricity.	32 Quarters/ Barriers A, B, C, D, F, G, H, I

Note: The total duration of the program planning period is 32 quarters; tasks that begin before this period or continue beyond it do not reflect durations outside the planning period.

3.5.6 Milestones

Figure 3.5.3 shows the interrelationship of milestones, tasks, supporting inputs from subprograms, and outputs for the Technology Validation program element. This information is also summarized in Table B.5 in Appendix B.

Figure 3.5.3. Technology Validation R&D Network



For chart details see next page.

1. Make awards to start fuel cell vehicle/infrastructure demonstration activity and for hydrogen co-production infrastructure facilities.
2. Input from Safety: Safety requirements and protocols for vehicle safety and stationary refueling
3. Input from Fuel Cells: Laboratory PEM technology with 2,000 hours durability, $125/kW
4. Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles.
5. Input from Storage: Compressed and cryogenic liquid storage tanks achieving the 2005 targets
6. Validate (on a vehicle) 1.5 kWh/kg and 1.0 kWh/L compressed gas and cryogas tank, with projected cost of $10/kWh.
7. Validate (on a vehicle) conformable pressurized and cryogenic tanks that increase effective kWh/L by 20% at 1.2 kWh/l and projected cost of $10/kWh.
8. Go/No-Go: Decision for purchase of additional vehicles based on performance, durability, and cost criteria
9. Validate fuel cell demonstration vehicle range of ~ 200 miles and durability of ~ 1,000 hours.
10. Go/No-Go: Decision on reformers
11. Input from Storage: Vehicle Interface Technology
12. Output to Codes and Standards, Safety, and Education: Final report for first generation vehicles, interim progress report for second generation vehicles on performance, safety, and O&M
13. Validate (on a vehicle) 2.0 kWh/kg and 1.2 kWh/L compressed gas tank, with projected cost of $10/kWh
14. Input from Storage: Bulk off-board storage technology for fueling stations and delivery
15. Input from Storage: Full-cycle, integrated chemical hydride system meeting 2005 targets
16. Input from Storage: Complex hydride integrated system meeting 2005 targets
17. Validate vehicle refueling time of 5 minutes or less.
18. Validate chemical storage on vehicle at 2.0 kWh/L and 2.2 kWh/kg with projected cost of $100/kWh.
19. Validate reversible complex hydride storage.
20. Demonstrate FCVs with 300-mile range, 2,000-hour durability, and $125/kW (based on volume production).
21. Input from Fuel Cells: Laboratory PEM technology with 5,000 hours durability, $45/kW
22. Input from Storage: Verify advanced compressed/cryogenic tank technologies; End tank R&D
23. Input from Storage: Vehicle Interface Technology
24. Output to Codes and Standards, Safety, and Education: Issue final report on vehicle performance, safety, and O&M
25. Input from Fuel Cells: Stationary PEM Systems with 40,000-hour durability
26. Input from Production: Verify hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of $3.00/kg hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
27. Five stations and maintenance facilities constructed with advanced sensor systems and operating procedures.
28. Total of eight stations and two maintenance facilities constructed with advanced sensor systems and operating procedures.
29. Issue final report on safety and O&M of refueling stations
30. Validate maintenance costs for hydrogen FCVs and validate cost of producing hydrogen in quantity of $3.00/kg untaxed.
31. Validate $3/kg hydrogen cost.
32. Input from Production: Verify hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of $2.50/kg hydrogen at the pump, untaxed, no carbon sequestration, assuming 100s of units of production per year.
33. Output to Codes and Standards and Safety: Submit final report on safety and O&M of three refueling stations
34. Validate $2.50/kg hydrogen cost.
35. Operate prototype for 6 months; projected durability >5,000 hours; electrical energy efficiency >30%; availability >0.80.
36. Operate first regional networks with fuel cell systems that project <$1,250/kW
37. Operate second regional networks with fuel cell systems that project <$1,250/kW
38. Input from Production: Verify hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of $1.50/kg hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
39. Achieve network fuel cell statistical values of: 30,000-hour durability; electrical energy efficiency >35%; availability >0.80.
40. Test results from 100,000 scf/day unit with wind turbine, and validation of production cost of $300/kW at 85% efficiency.
41. Input from Production: Verify hydrogen production system making hydrogen for $2.60/kg from biomass at the plant gate
42. Input from Production: $500/kW, 80% efficient technology
43. Validate $3.30/kg hydrogen cost from biomass/wind (untaxed and unpressurized).
44. Results from analysis of examination of synergies from combining hydrogen and electricity energy carrier systems, including advanced Power Parks.