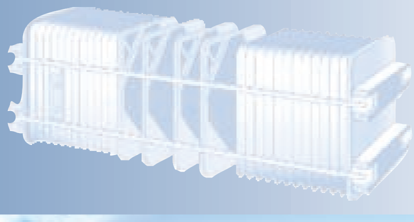
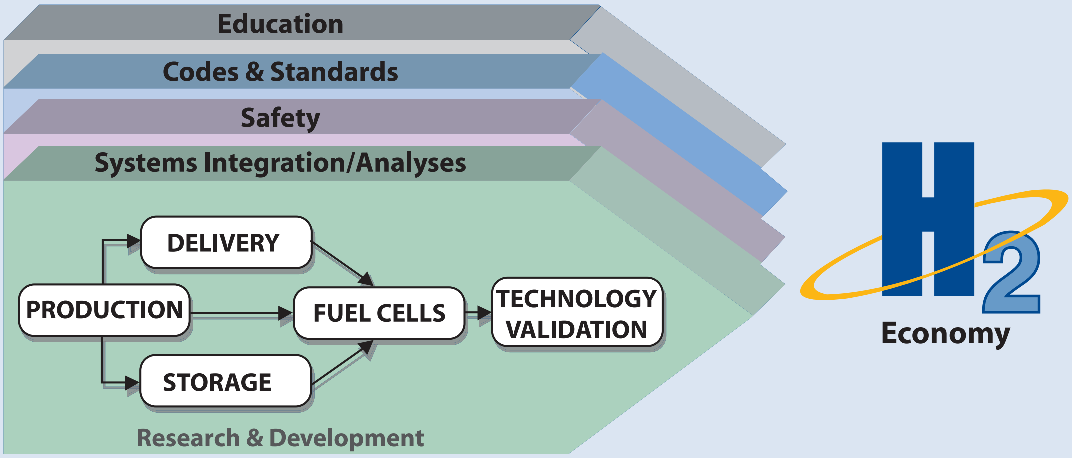
Paving the way
toward a hydrogen
energy future



Hydrogen, Fuel Cells & Infrastructure Technologies Program

Multi-Year Research, Development and Demonstration Plan

Planned program activities for 2003-2010



U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Energy Secretary Spencer Abraham on the Future of Personal Transportation

Hydrogen offers the long-term potential for a highly efficient energy system that produces near-zero emissions and is based on domestically available resources. Hydrogen can be produced from fossil, nuclear, and renewable resources, thus encouraging diversity in the nation's energy supplies. It can be produced from abundant fossil fuels such as coal without undesirable CO_2 *emissions by the use of carbon management approaches such as sequestration.*

The day of the hydrogen economy, while not imminent, is now within sight . . . It promises the kind of transformation not seen since the nineteenth and early twentieth centuries, when the world experienced the last energy revolution.

We in the U.S. government, along with our governmental partners around the world, will work to promote and support cooperation and collaboration. But, as always, we look to the genius of the private sector . . . to bring us a better future.

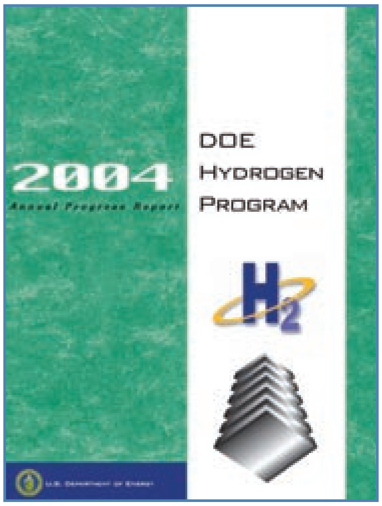
We are faced with a mammoth task but I can't think of anything that any group of people can do that will have more lasting benefit for more people than working to create an energy-transportation revolution. I'm sure you agree that the challenge we have set for ourselves will have historic consequences—and that it is a privilege to be among those who have the opportunity to contribute in some way to meeting that challenge.

Foreword

In his 2003 State of the Union Address, President Bush announced a $1.2 billion Hydrogen Fuel Initiative to reverse America's growing dependence on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells—a way to power cars, trucks, homes and businesses that could significantly reduce pollution and greenhouse gas emissions. Since then, the U.S. Department of Energy has established a coordinated and focused Hydrogen Program that will make this vision a reality. The DOE Program integrates activities in hydrogen production, delivery and storage with transportation and stationary fuel cell research, development and demonstration across DOE's Offices of Energy Efficiency and Renewable Energy (EERE); Fossil Energy; Nuclear Energy, Science and Technology; and Science. EERE has lead management responsibility for the DOE Hydrogen Program.

This Multi-Year Research, Development and Demonstration Plan details the goals, objectives, technical targets, tasks and schedule for EERE's contribution to the DOE Hydrogen Program. Similar detailed plans exist for the other DOE offices that make up the Hydrogen Program. The integrated plan for all four offices involved in the President's Initiative can be found in the DOE Hydrogen Posture Plan at http://www.hydrogen.energy.gov/pdfs/hydrogen_posture_plan.pdf. EERE has responsibility for implementing research, development and demonstration activities of the Hydrogen Fuel Initiative and the FreedomCAR and Fuel Cell Partnership. These activities are mainly split between two programs - the EERE Hydrogen, Fuel Cells & Infrastructure Technologies Program, which conducts the hydrogen infrastructure and polymer electrolyte membrane (PEM) fuel cell research, and the EERE FreedomCAR and Vehicle Technologies Program, which conducts the advanced internal combustion engine and hybrid vehicle component research.

This Hydrogen, Fuel Cells & Infrastructure Technologies Multi-Year Research, Development and Demonstration Plan is a living document, which will periodically be updated to reflect advances in technology, as well as changes to and within the system. The intended audience for this document is the research community and policy makers. The first version of the Plan was released as a draft in June 2003 and was reviewed by a panel of the National Research Council and the National Academy of Engineering of the National Academies. This January 2005 version reflects recommendations made by the panel. This version also reflects progress made since the draft release. Details on every project funded by the Program can be found in the 2004 Annual Progress Report available at http://www.eere.energy.gov/hydrogenandfuelcells/annual_report04.html.



Document Revision History

Foreword

This page summarizes the revisions to the Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan.

Date	Description
June 6, 2003	Draft prepared for review by the National Academies' Committee on Alternatives and Strategies for Future Hydrogen Production and Use.
January 21, 2005	Finalized plan reflecting recommendations made by the National Academies and progress made since the June 6, 2003 draft release.

Executive Summary

President Bush launched the Hydrogen Fuel Initiative to ensure our nation's long-term energy security and a clean environment. Using hydrogen to fuel our economy can reduce U.S. dependence on imported petroleum, diversify domestic energy sources, and reduce pollution and greenhouse gas emissions. Fuel cells are an important enabling technology for a future hydrogen economy and have the potential to revolutionize the way we power our nation, offering cleaner, more efficient alternatives to today's technology.

Energy Security: The U.S. uses about 20 million barrels of oil per day (60% of which is imported), at a cost of about $6 billion a week (assumes a cost of $45 per barrel of oil). Much of this oil is used to power highway vehicles. Over 97% of our transportation energy is from petroleum. Because hydrogen can be derived from a variety of domestically-available primary sources (hydrogen itself is not a primary resource), including fossil fuels, renewable resources, and nuclear power, its use would allow us to diversify our transportation energy supply and make us less reliant upon foreign energy sources.

Additionally fuel cells are significantly more energy efficient than combustion-based power generation technologies. Internal combustion engines in today's automobiles convert less than 30 percent of the energy in gasoline into engine power for moving the vehicle. Vehicles using electric motors powered by hydrogen fuel cells have 2-2.5 times the thermal efficiency of internal combustion engines.

Environmental Benefits: Fuel cells powered by pure hydrogen emit no harmful pollutants, only pure water. Hydrogen generation and carbon-management technologies can be developed, which can significantly reduce pollutants and greenhouse gases from fossil-based hydrogen production. As a transportation fuel, it will be much easier to manage and contain greenhouse gas emissions from stationary hydrogen generation sources than from the tailpipe of internal combustion engine vehicles. Using renewable or nuclear-based hydrogen in high-efficiency fuel cells to fuel our vehicles and to generate power could virtually eliminate greenhouse gas emissions and air pollution.

Economic Competitiveness: Heavy dependence on imported oil threatens America's economic well-being. Small changes in the price of crude oil or disruptions to oil supplies can have big impacts on our economy, from trade deficits, to industrial investment, to employment levels. Hydrogen's diversity in production and flexibility in use offers opportunities for new technologies and players in energy markets, broadening our

> ***"With a new national commitment, ... the first car driven by a child born today could be powered by hydrogen, and pollution-free."***
>
> **– President Bush**
> **State of the Union Address**
> **January 28, 2003**

energy choices and increasing economic growth both at home and around the world. In addition, developing and leading the way in hydrogen fuel cell technologies for automobiles will help the U.S. to maintain its future economic competitiveness in the worldwide automotive industry.

Path Forward: Addressing Barriers to a Hydrogen Economy

The transition of our current energy infrastructure to a clean and secure energy infrastructure based on hydrogen will take decades. The technology, economic and institutional barriers pose difficult challenges. The "critical path" barriers to a hydrogen economy are:

Technology Barriers

- Hydrogen storage systems for vehicles are inadequate to meet customer driving range expectations (>300 miles) without intrusion into vehicle cargo or passenger space.
- Hydrogen is currently three to four times as expensive as gasoline.
- Fuel cells are about five times more expensive than internal combustion engines and do not maintain performance over the full useful life of the vehicle.

Economic and Institutional Barriers

- Investment risk of developing a hydrogen delivery infrastructure is too great given technology status and current hydrogen vehicle demand.
- Uniform model codes and standards to ensure safety, insurability and fair global competition are lacking.
- Local code officials, policy makers and the general public lack education on hydrogen benefits and on safe handling and use.

Defining Success and Measuring Progress

Success for the Hydrogen, Fuel Cells & Infrastructure Technologies Program is defined as validation, by 2015, of technology for:

- Hydrogen storage systems enabling greater than 300-mile vehicle range while meeting identified packaging, cost and performance requirements
- Hydrogen production from diverse pathways to safely and efficiently deliver hydrogen to consumers at competitive costs with gasoline without adverse environmental impacts
- Fuel cells to enable engine costs of less than $50/kW (in high volume production) and stationary power production at $400-700/kW while meeting performance and durability requirements

If these indicators are met, there is a high probability of success that customer requirements can be met, and that industry will

> ***"Government coordination of this huge undertaking will help resolve one of the difficulties associated with the development of a commercially viable hydrogen fuel-cell vehicle:… Which comes first, the vehicle or the infrastructure of manufacturing plants, distribution and storage networks, and the convenient service stations needed to support it?…[The Department will work with all stakeholders] to develop both the vehicle and the infrastructure in parallel—and by so doing, advance a commercialization decision by 15 years, from 2030 to 2015."***
>
> **— Energy Secretary Abraham**
> **2004 DOE Budget Submission**
> **February 3, 2003**

begin to realize a business case for proceeding with a positive commercialization decision regarding hydrogen infrastructure and fuel cell vehicles. While the full extent of life-cycle cost and energy and environmental impacts will not be achieved for decades, a positive commercialization decision in 2015 will begin to yield national benefits as early as 2025.

To assist in measuring interim progress towards the 2015 commercialization decision, the following program objectives have been established with industry input. Key milestones will be monitored by the Office of Management and Budget within the Executive Office of the President:

Hydrogen Production

- Reduce the cost of distributed production of hydrogen from natural gas to $1.50/gge[1] (delivered, untaxed) at the pump (without carbon sequestration) by 2010 and reduce the cost of distributed hydrogen production from biomass-derived renewable liquids to $2.50/gge (delivered, untaxed) at the pump by 2015.
- Verify grid-connected distributed water electrolysis at a projected delivered hydrogen cost of $2.85/gge by 2010, and by 2015, verify central hydrogen production from renewable energy sources at a projected cost of $2.75/gge delivered.
- Reduce the cost of hydrogen produced from biomass to $1.60/gge at the plant gate ($2.60 delivered) by 2015.
- Develop advanced renewable photoelectrochemical and biological hydrogen generation technologies. By 2015, verify the feasibility of these technologies to be cost-competitive in the long term.
- Research and develop high-temperature thermochemical cycles driven by concentrated solar power processes to produce hydrogen with a projected cost of $3.00/gge at the plant gate ($4.00 delivered) by 2015.

Hydrogen Delivery

- By 2010, develop technologies to reduce the cost of hydrogen delivery from central and semi-central production facilities to the gate of refueling stations and other end users to <$0.90/gge of hydrogen and to reduce the cost of compression, storage and dispensing at refueling stations and stationary power facilities to <$0.80/gge of hydrogen.
- Develop enabling technologies to reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen by 2015.

"There are two paths we need to follow: research and development, and public outreach to capture the imagination of the American people. This will be a long journey and process, and the Department of Energy will work with you as we move forward."

David Garman, Assistant Secretary for Energy Efficiency and Renewable Energy
National Hydrogen Energy Roadmap Workshop
April 2-3, 2002

---

[1] Currently under evaluation. One gallon of gasoline is approximately equal to one kilogram of hydrogen on an energy basis.

Hydrogen Storage

- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and $4/kWh. By 2015, 3 kWh/kg (9 wt%), 2.7 kWh/L, and $2/kWh.

Fuel Cells

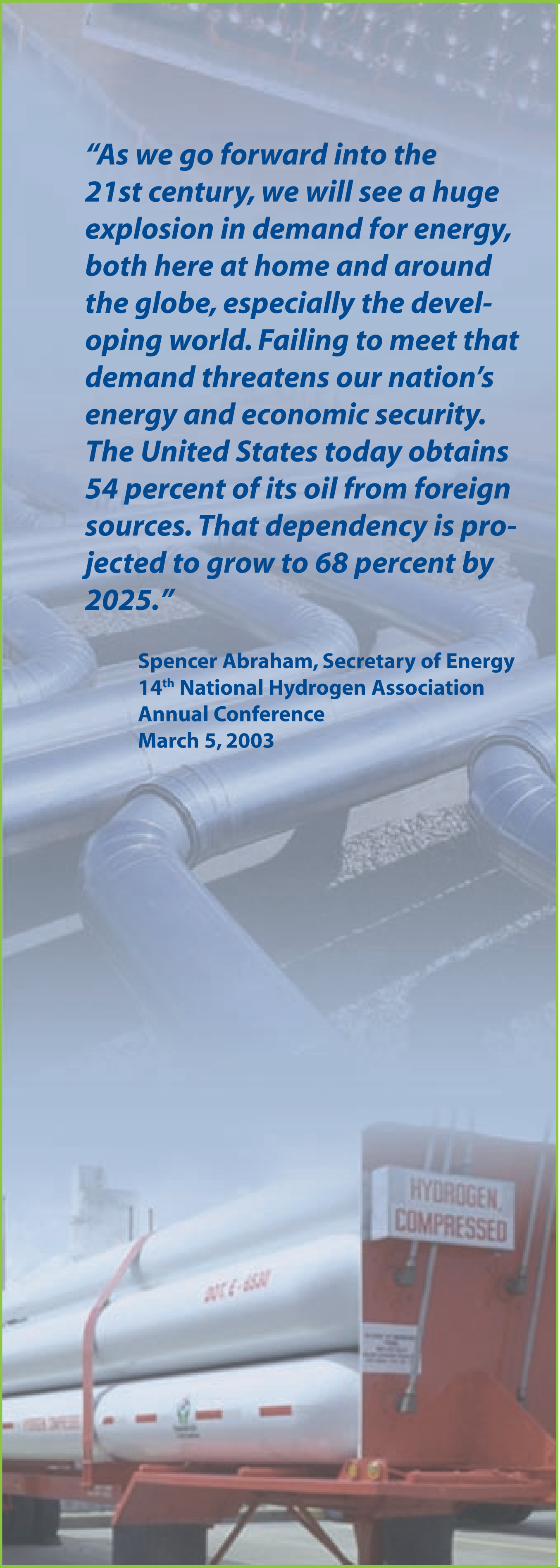
- Develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW by 2010 and $30/kW by 2015.
- Develop a distributed generation polymer electrolyte membrane (PEM) fuel cell system operating on natural gas or liquid petroleum gas that achieves 40% electrical efficiency and 40,000 hours durability at $400-$750/kW by 2010.

Technology Validation

- By 2009, validate hydrogen vehicles that have greater than 250-mile range and 2,000-hour fuel cell durability, with hydrogen infrastructure that results in a hydrogen production cost of less than $3.00/gge (untaxed); by 2015, vehicles that have 300+ mile range and 5,000 hours fuel cell durability, with a hydrogen production cost of $1.50/gge (untaxed).
- Validate an electrolyzer that is powered by a wind turbine at a capital cost of the electrolyzer of $400/kWe and 65% efficiency, including compression to 5,000 psi, when built in quantities of 1,000 by 2008.
- Validate an integrated biomass/wind or geothermal electrolyzer system to produce hydrogen for $2.85/gge at the plant gate (untaxed) by 2011.

Codes and Standards

- By 2006, complete research and development on hydrogen release scenarios, providing a sound basis for model code development and adoption.
- Support and facilitate the drafting and adoption of model building codes for hydrogen applications by the National Fire Protection Association and the ICC by 2007.
- Support and facilitate the completion of the ISO standards for hydrogen refueling and on-board storage by 2007.
- Support and facilitate development of Global Technical Regulations (GTR) for hydrogen vehicle systems by 2010.
- By 2015, ensure necessary codes and standards are completed that support the commercialization of hydrogen technologies.



> ***"As we go forward into the 21st century, we will see a huge explosion in demand for energy, both here at home and around the globe, especially the developing world. Failing to meet that demand threatens our nation's energy and economic security. The United States today obtains 54 percent of its oil from foreign sources. That dependency is projected to grow to 68 percent by 2025."***
>
> **Spencer Abraham, Secretary of Energy**
> **14th National Hydrogen Association**
> **Annual Conference**
> **March 5, 2003**

Safety

- In collaboration with industry, develop a comprehensive hydrogen safety plan by 2005 that establishes Program safety policy and guidelines.
- Integrate safety procedures into new DOE project-funding procurements to ensure that all projects incorporate hydrogen safety requirements.
- Publish a handbook of "Best Management Practices for Safety" by 2007.
- Continuously develop supporting research and development program to provide critical hydrogen behavior data and hydrogen sensor and leak detection technologies to support the establishment of building codes.
- Continuously promote widespread sharing of safety-related information, procedures and lessons-learned to first responders, jurisdictional authorities and other stakeholders.

Education

- By 2010, achieve a fourfold increase (from 2004 baseline) in the number of state and local government representatives, students and teachers, and a twofold increase in the number of large-scale end users who understand the concept of a hydrogen economy, and how it may affect them.
- Launch a comprehensive and coordinated public education campaign about the hydrogen economy and fuel cell technology by 2010.

Systems Analysis

- Through analysis, support the integration of the Program within a balanced, overall DOE national energy R&D effort addressing the role of hydrogen in context of the overall energy infrastructure.
- By 2007, identify and evaluate transition scenarios consistent with developing infrastructure and hydrogen resources, including an assessment of timing and sequencing issues.
- Provide and/or coordinate appropriate and timely analysis of environmental and technoeconomic issues to support decision-making tied to Program schedules, targets and milestones.
- By 2008, develop a macro-system model of the hydrogen fuel infrastructure to support transportation systems. By 2010, enhance the model to include the stationary electrical generation and infrastructure for a full hydrogen economy.
- Support a spectrum of analyses, including financial and environmental assessments, across and within Program elements—from individual unit/subsystem elements to a fully integrated system and infrastructure.

Educating consumers, industry leaders, and public policy makers about the benefits of hydrogen is critical to achieving the vision.

Systems Integration

- By 2005, establish an integrated technical and programmatic baseline, and maintain and utilize the baseline to support programmatic decisions and ensure research and development directions satisfy needs.
- Verify that the system being developed satisfies the Program requirements, projects are meeting performance and milestone objectives, and progress toward technical targets is substantiated.
- Provide analyses and recommend DOE-sponsored activities to enable the commercial sector to deploy a well-integrated hydrogen system that satisfies needs while continually monitoring system performance to identify potential improvements.

Tracking Progress and Achieving Success

Putting it all together is the ultimate challenge. To achieve the goal of commercially-viable hydrogen and fuel cell systems in the 2015 timeframe:

- R&D efforts must be focused on the most promising technologies
- Customer requirements must be validated in a fully-integrated operating system

DOE has identified the key Program milestones necessary to meet these technical targets (see Appendix B). These milestones support the critical path technologies outlined by DOE. Each of the timelines specify a delivery date for the given technology development, improvement or demonstration. As technologies evolve and economic and systems analyses data become available, these targets will be refined.

The Hydrogen, Fuel Cells & Infrastructure Technologies Program is emphasizing a results-driven management approach, in accordance with the principles laid out in the President's Management Agenda, to ensure that efforts are continually refocused on technologies that are most likely to achieve the goals of the Program. The technical targets provide clear quantifiable measures, which can be used to track progress and to show the return on investment of taxpayer dollars. Periodic milestones and Go/No-Go decision points ensure that performance is linked to budget and that funds will be used only for the most promising technology approaches as performance goals are being met along the way. The technological advancements in each Program element and lessons learned from successful demonstrations of hydrogen and fuel cell technologies must be integrated to work together as a fully functional system.

> ***"It is important that all aspects of the various conceivable hydrogen system pathways be adequately modeled to understand the complex interactions between components, system costs, environmental impacts of individual components and the system as a whole, societal impacts (e.g., offsets of imported oil per year), and possible system trade-offs."***
>
> **–National Academies' Committee on Alternatives and Strategies for Future Hydrogen Production and Use, April 2003 Letter Report**

As we look to the future, hydrogen and fuel cell technologies appear to be viable in meeting the long-term energy needs of the nation. The DOE is building partnerships with universities, national laboratories, industry and the international community to speed up the development of hydrogen technologies. Together, we will realize our vision of a hydrogen energy future.

> *"The effective management of the Department of Energy hydrogen program will be far more challenging than any activity previously undertaken on the civilian energy side of the DOE."*
>
> **– National Academies' Report,**
> **"The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs"**
> **February 2004**

Table of Contents

Appendices

Acronyms, Abbreviations and Formulas

ANL	Argonne National Laboratory
ANSI	American National Standards Institute
APCI	Air Products and Chemical, Inc.
APU	Auxiliary power unit
ASHRAEW	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASME	American Society of Mechanical Engineers
atm	Atmosphere
BOCA	Building Officials and Code Administrators International
Btu	British thermal unit
ºC	Degrees Celsius
CaFCP	California Fuel Cell Partnership
CGA	Compressed Gas Association
CH_4	Methane
Chl	Chlorophyll
CHP	Combined heat and power
cm^2	Square centimeter
CO	Carbon monoxide
CO_2	Carbon dioxide
CSA	Canadian Standards Association International of America
CY	Calendar year
dB	Decibel

dB(A)	Decibel ampere
DC	Direct current
DFMA	Design for Manufacture and Assembly
DG	Distributed Generation
DMFC	Direct methanol fuel cell
DOC	U.S. Department of Commerce
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
ECE WP29	United Nations Economic Commission for Europe Working Party 29
EERE	Energy Efficiency and Renewable Energy
EIHP	European Integrated Hydrogen Project
EPA	U.S. Environmental Protection Agency
EPAct	Energy Policy Act
ºF	Degrees Fahrenheit
FC	Fuel cell
FE	Fossil Energy
FEMP	Federal Energy Management Program
FMEA	Failure Mode and Effects Analysis
ft^2	Square foot
FY	Fiscal year
g	Gram

gal	Gallon
GATE	Graduate Automotive Technology Education (a DOE program)
GDL	Gas diffusion layer
gge	Gallon of gasoline equivalent
GHG	Greenhouse gas
GRPE	Global Technical Regulations on Pollution and Energy
GTR	Global Technical Regulations
HAMMER	Hazardous Materials Management and Emergency Response
H_2	Molecular hydrogen
H_2O	Water
H_2S	Hydrogen Sulfide
HCG	Hydrogen Coordinating Group
HDV	Heavy duty vehicle
HHV	Higher heating value
HQ	Headquarters
hr	Hour
HTAP	Hydrogen Technical Advisory Panel
HTM	High temperature membrane
HVAC	Heating, ventilating, and air conditioning
IAPMO	International Association of Plumbing and Mechanical Officials
IB	Integrated Baseline
ICBO	International Conference of Building Officials

ICC	International Code Council, Inc.
ICE	Internal combustion engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IL	Illinois
in^2	Square inch
IPHE	International Partnership for the Hydrogen Economy
IRR	Internal rate of return
ISO	International Organization for Standardization
K-12	Kindergarten through twelfth grade
kg	Kilogram
kW	kilowatt
kWe	Kilowatt-electric
kWh	Kilowatt-hour
L	Liter
lb	Pound
LDV	Light duty vehicle
LHV	Lower heating value
LPG	Liquefied petroleum gas
mA	Milliampere
MEA	Membrane electrode assembly
min	Minute

MJ	Megajoule
µm	Micron
MMBtu	Million British thermal unit
mmb	Million Barrels
MMTCE	Million tons carbon equivalent
msec	millisecond
MSM	Macro-System Model
mV	Millivolt
N_2	Molecular Nitrogen
NASA	National Aeronautics and Space Administration
NE	Nuclear Energy, Science and Technology
NEP	National Energy Policy
NETL	National Energy Technology Laboratory
NFPA	National Fire Protection Association
NGI	Natural Gas Institute
NH_3	Ammonia
NHTSA	National Highway Traffic Safety Administration
NMHC	Non-methane hydrocarbon
NO_x	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
NSF	National Science Foundation
O&M	Operation and maintenance

O_2	Molecular oxygen
OEM	Original equipment manufacturer
OMB	Office of Management and Budget
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
Pa	Pascal
PART	Program Assessment Rating Tool
PB	Programmatic Baseline
PBA	Planning, Budget and Analysis
PEM	Proton exchange membrane; polymer electrolyte membrane
PEMFC	Polymer electrolyte membrane fuel cell
PM	Particulate matter
PNGV	Partnership for a New Generation of Vehicles – former partnership between the DOE and USCAR, replaced by FreedomCAR
ppb	Parts per billion
ppm	Parts per million
PSA	Pressure swing adsorption
psi	Pounds per square inch
psig	Pounds per square inch gauge
Pt	Platinum
Q	Quarter
R&D	Research and development
RD&D	Research, development, and demonstration

RH	Relative humidity
s	Second
S	Siemens
SAE	Society of Automotive Engineers
SBCCI	Southern Building Code Congress International
Sc	Science
Scc	Standard cubic centimeter
scf	Standard cubic feet
scfh	Standard cubic feet per hour
SDO	Standards development organization
sec	Second
SECA	Solid State Energy Conversion Alliance (a program of the DOE Office of Fossil Energy)
SMS	Strategic Management System
SO_2	Sulfur dioxide
SOFC	Solid oxide fuel cell
SOP	Standard operating procedures
SO_x	Oxides of sulfur
SwRI	Southwest Research Institute
TAG	Technical Advisory Group
TB	Technical Baseline
TBD	To be determined
TC	Technical committee

U.S.	United States
UC Berkeley	University of California at Berkeley
UL	Underwriters Laboratories
USCAR	U.S. Council for Automotive Research, and organization founded by Ford, General Motors, and DaimlerChrysler to manage collaboration on pre-competitive research
V	Volt
vol	Volume
W	Watt
WFCA	Western Fire Chiefs Association
wt	Weight

1.0 Introduction

Today, after decades of dependence on imported petroleum to fuel the United States' transportation sector, our nation has a new vision for our future– a form of domestically-derived, clean energy to power not only our vehicles but our industries, buildings and homes. This form of energy for the future is hydrogen.

President Bush is providing the leadership to help make this vision a reality. In his 2003 State of the Union address, the President proposed the Hydrogen Fuel Initiative to reverse America's growing dependence on foreign oil by developing the technology needed for commercially viable hydrogen-powered fuel cells (see back cover). Through this initiative, President Bush has committed $1.2 billion for the first five years (FY2004-2008) of a long-term research and development effort for hydrogen infrastructure and polymer electrolyte membrane (PEM) fuel cell technologies. This commitment is $1.7 billion over five years when hybrid vehicle technologies are included.

The Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE's) Hydrogen, Fuel Cells & Infrastructure Technologies Program is implementing the technology development efforts needed to realize the vision of a hydrogen economy. This Multi-Year Research, Development and Demonstration (RD&D) Plan, covering the period 2003 through 2010, provides a description of the activities that the Hydrogen, Fuel Cells & Infrastructure Technologies Program will undertake to implement the first years of the President's Initiative. The Plan addresses technologies for hydrogen production, delivery, storage and infrastructure, and fuel cells for transportation and stationary applications. As detailed in this Plan, the nation's resources will be applied to these RD&D activities, and government resources will be fully leveraged through partnerships with industry as we move toward a hydrogen future. The planned Program is designed to bring technologies to a point where the private sector can make their business decisions on commercializing hydrogen infrastructure and fuel cell vehicles by 2015.

FreedomCAR and Fuel Partnership

In January 2002, Secretary of Energy Spencer Abraham established the FreedomCAR Partnership as a research and development partnership between the Department of Energy and the U.S. Council for Automotive Research (USCAR - a partnership between Ford Motor Company, DaimlerChrysler Corporation, and General Motors Corporation). In September

Vision for the Hydrogen Economy

Hydrogen is America's clean energy choice. Hydrogen is flexible, affordable, safe, domestically produced, used in all sectors of the economy and in all regions of the country.

2003, the Partnership was expanded to the FreedomCAR and Fuel Partnership by bringing the major energy companies (BP America, ChevronTexaco Corporation, ConocoPhillips, Exxon/Mobil Corporation and Shell Hydrogen) to the table.

The Partnership examines the pre-competitive, high-risk research needed to develop the vehicle and infrastructure technologies to enable a full range of affordable cars and light trucks. These technologies will reduce the dependence of the nation's personal transportation system on imported oil and minimize harmful vehicle emissions, without sacrificing freedom of mobility and freedom of vehicle choice.

The "Freedom" principle is framed by:

- Freedom from dependence on imported oil
- Freedom from pollutant emissions
- Freedom for Americans to choose the kind of vehicle they want to drive, and to drive where they want, when they want
- Freedom to obtain fuel affordably and conveniently

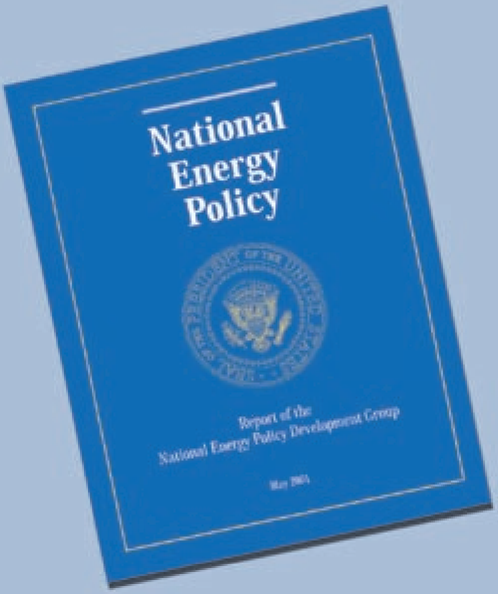
1.1 Scope of Multi-Year RD&D Plan

This Multi-Year RD&D Plan details near-term tasks and milestones, and thus, represents a snapshot in time of DOE's Hydrogen, Fuel Cells & Infrastructure Technologies Program, which is focused on longer-range objectives. Planned activities are focused on technologies for hydrogen production, delivery, and storage; fuel cells for transportation and stationary applications; technology validation; codes and standards; safety; education; systems analysis; and systems integration. For each of these Program elements, goals, objectives and technical targets are identified through 2015, and milestones and schedules are identified for the years 2003 through 2010. While the government's role is key to advancing hydrogen and fuel cell research and technologies in the early stages of development, once the technical targets are validated in a systems context, government's role ends and industry takes over commercialization of the technologies. To keep moving efficiently toward the goal of commercialization, the Plan will be updated periodically to reflect advances in technology, changes to and within the system, and policy decisions.

1.2 Background

The Hydrogen, Fuel Cells & Infrastructure Technologies Program Multi-Year RD&D Plan describes the details of the technology development, requirements, and schedule in support of the National Energy Policy, the National Hydrogen Energy Vision

"The NEPD Group recommends that the President direct the Secretary of Energy to develop next-generation technology-including hydrogen and fusion."

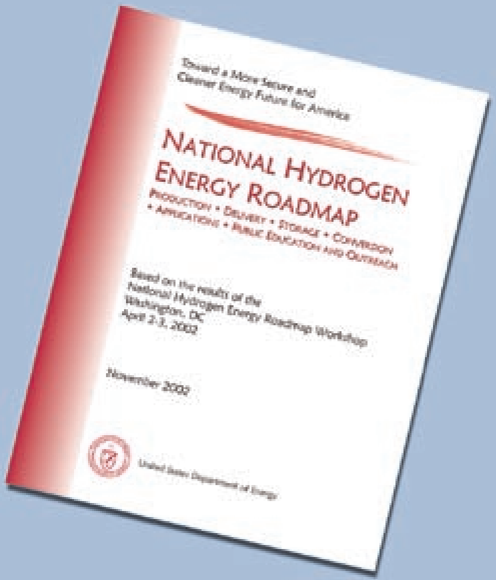


National Energy Policy

Report of the National Energy Policy Development Group

May 2001

"This Roadmap provides a blueprint for the coordinated, long-term, public and private efforts required for hydrogen energy development."



Toward a More Secure and Cleaner Energy Future for America

NATIONAL HYDROGEN ENERGY ROADMAP

PRODUCTION • DELIVERY • STORAGE • CONVERSION • APPLICATIONS • PUBLIC EDUCATION AND OUTREACH

Based on the results of the National Hydrogen Energy Roadmap Workshop
Washington, DC
April 2-3, 2002

November 2002

United States Department of Energy

and Roadmap, DOE Strategic Plans, DOE Hydrogen Posture Plan, and the FreedomCAR and Fuel Partnership Plan.

National Energy Policy

The Administration's National Energy Policy, released in May 2001, outlines a long-term strategy for developing and using leading-edge technology within the context of an integrated national energy, environmental, and economic policy. It specifically highlighted the potential of hydrogen with the following recommendations:

- Focus research and development efforts on integrating current programs regarding hydrogen, fuel cells and distributed energy.
- Develop an education campaign that communicates the benefits of alternative forms of energy, including hydrogen.

In addition, the administration is recommending and implementing a number of actions that could help reduce our nation's dependence upon imported petroleum in the near term as hydrogen energy technologies are developed for the long term. Among these actions are:

- Promote energy efficiency through research and development of technologies to improve fuel economy (i.e., advanced gasoline/diesel hybrid technology development under the Office of FreedomCAR and Vehicle Technologies).
- Reduce petroleum demand by reducing fuel consumption of long-haul trucks by implementing alternatives to idling when parked.

National Hydrogen Energy Vision and Roadmap

In response to recommendations within the National Energy Policy, in November 2001, DOE organized a meeting of 50 visionary business leaders and policy makers to formulate a National Hydrogen Vision. ***A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond*** was published in February 2002 as a result of the Hydrogen Vision Meeting. This document summarizes the potential role for hydrogen systems in America's energy future, outlining the common vision of the hydrogen economy.

In April 2002, DOE followed up with a larger group of over 200 technical experts from industry, academia, and the national laboratories to develop a ***National Hydrogen Energy Roadmap.*** This roadmap, released in November 2002, describes the principal challenges to be overcome and recommends paths forward to achieve our National Vision.

The mission of the Hydrogen, Fuel Cells & Infrastructure Technologies Program is to research, develop, and validate fuel cell and hydrogen production, delivery, and storage technologies for transportation and stationary applications.

DOE Strategic Planning

Building on the recommendations of the National Energy Policy and the National Hydrogen Energy Vision and Roadmap, DOE's and EERE's strategic plans provide the broad direction under which this Multi-Year RD&D Plan was formulated.

A strategic goal in the ***Department of Energy's Strategic Plan*** is to protect our national and economic security by promoting a diverse supply and delivery of reliable, affordable and environmentally sound energy. Development of hydrogen and fuel cell technologies is identified as a key strategy in attaining this strategic goal.

EERE's Strategic Plan (2002) supports DOE's Strategic Plan. EERE's Plan describes its response to Secretary Abraham's challenge to "leapfrog the status quo" and to pursue "dramatic environmental benefits" in its approach to energy efficiency and renewable energy technologies. Four goals that are specified in EERE's Strategic Plan and are particularly relevant to the Hydrogen, Fuel Cells & Infrastructure Technologies Program are:

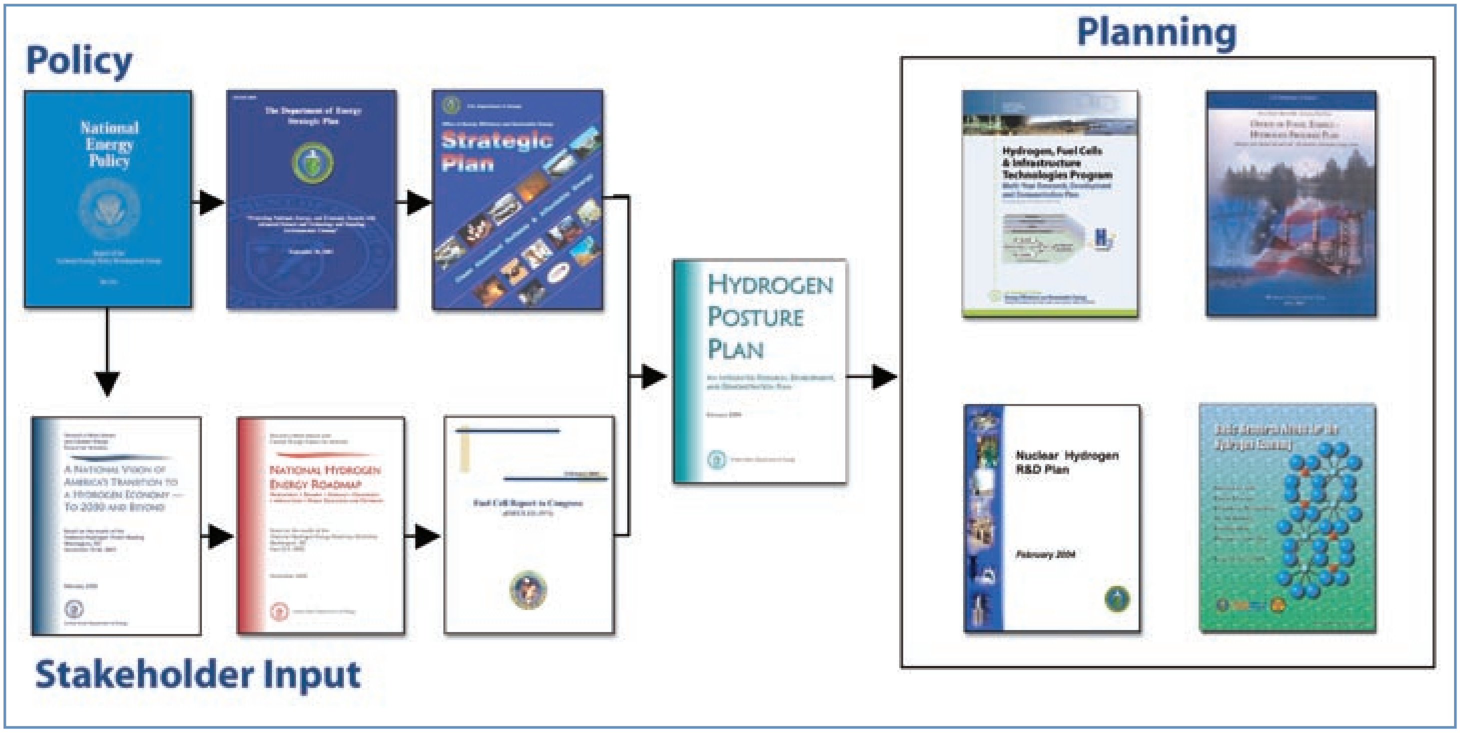
- Dramatically reduce dependence on foreign oil
- Promote the use of diverse, domestic and sustainable energy resources
- Reduce carbon emissions from energy production and consumption
- Increase the reliability and efficiency of electricity generation

In March 2004, DOE published its ***Hydrogen Posture Plan,*** which describes DOE's "plan for successfully integrating and implementing technology research, development and demonstration activities needed to cost-effectively produce, store and distribute hydrogen for use in fuel cell vehicles and electricity generation." Research, development and demonstration efforts across the DOE Offices of EERE; Nuclear Energy, Science and Technology; Fossil Energy; and Science are described and are consistent with the recommendations in the National Hydrogen Energy Roadmap. The DOE Posture Plan became the key supporting document used to launch the President's Hydrogen Fuel Initiative.

Another document that provides a framework for this Multi-Year RD&D Plan is ***DOE's Fuel Cell Report to Congress*** (February 2003). This report summarizes the technical and economic barriers to the use of fuel cells in transportation, portable power, stationary and distributed power generation applications, and provides a preliminary assessment of the need for public-private cooperative programs to demonstrate the use of fuel cells in

> ***"This project supports FreedomCAR by providing the means for learning about hydrogen infrastructure technologies necessary for clean energy-efficient vehicles."***
>
> **David K. Garman**
> **Opening of the world's first energy station featuring hydrogen and electricity coproduction in**
> **Las Vegas, Nevada**
> **November 15, 2002**

Figure 1.1. The Multi-Year RD&D plan is built upon several predecessor planning documents and is integrated with other DOE office plans.



commercial-scale applications by 2015. Specifically, the report recommends adjusting federally-sponsored programs to:

- Focus on advanced materials, manufacturing techniques and other advancements that will lower costs, increase life and improve reliability of fuel cell systems
- Increase emphasis on hydrogen production and delivery infrastructure, storage, codes and standards development, and education
- Develop public-private learning demonstrations, namely, a transportation and infrastructure partnership, as an integrated means to addressing commercialization barriers by collaboration between energy and auto industries

1.3 Hydrogen, Fuel Cells & Infrastructure Technologies Program

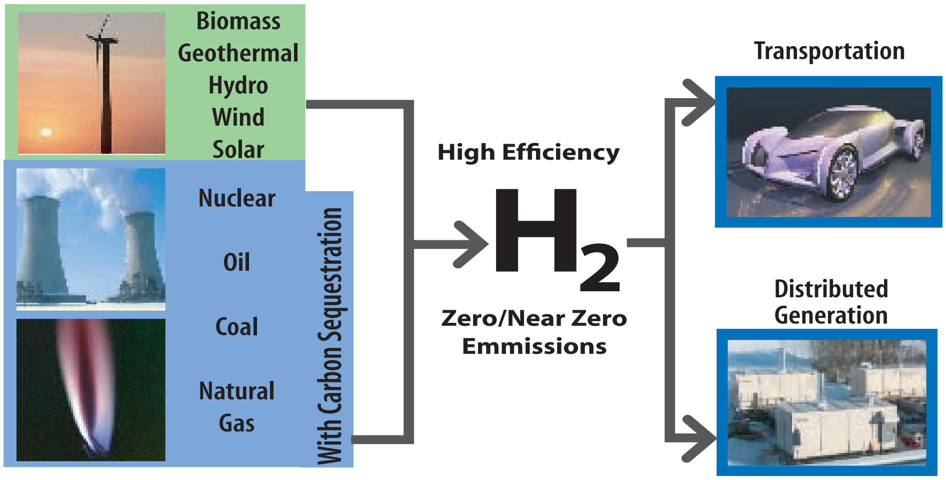
The EERE Hydrogen, Fuel Cells & Infrastructure Technologies Program is the lead for directing and integrating R&D activities in hydrogen production, storage, delivery and end use for transportation and stationary applications.

This Program responds to recommendations in the President's National Energy Policy, the National Hydrogen Energy Vision and Roadmap, and DOE Strategic Plans. The Program works in partnership with industry, academia and national laboratories,

and in close coordination with the FreedomCAR and Vehicle Technologies Program and other DOE Programs to achieve the four EERE strategic goals that were cited previously.

The four EERE strategic goals can be realized with a domestic hydrogen energy system, and are consistent with broader DOE policy goals. As illustrated in Figure 1.2, hydrogen can be produced from a diverse set of domestic resources including fossil, nuclear and renewable resources, helping to attain the first three strategic goals. High efficiency and low emissions through use of fuel cells in both transportation and distributed electric power generation help attain the last two strategic goals.

Figure 1.2. A domestic hydrogen energy system will help DOE's EERE meet four strategic goals.



Program Elements

The Program conducts its research, development and validation activities through key Program components. The detailed technical targets and milestones that have been identified for each element are identified in this RD&D Plan.

Figure 1.3. The Hydrogen, Fuel Cells & Infrastructure Technologies Program is conducted through interrelated elements.

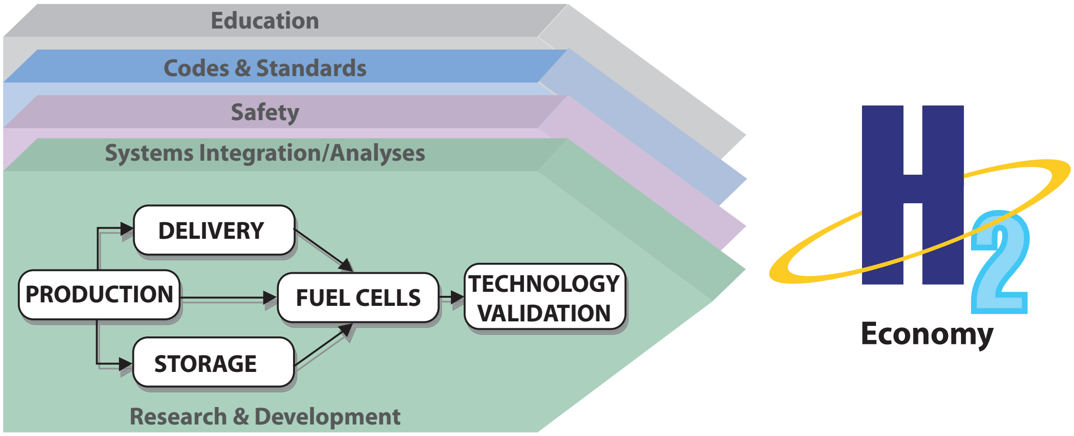


Table 1.1 The Hydrogen, Fuel Cells & Infrastructure Technologies Program Elements

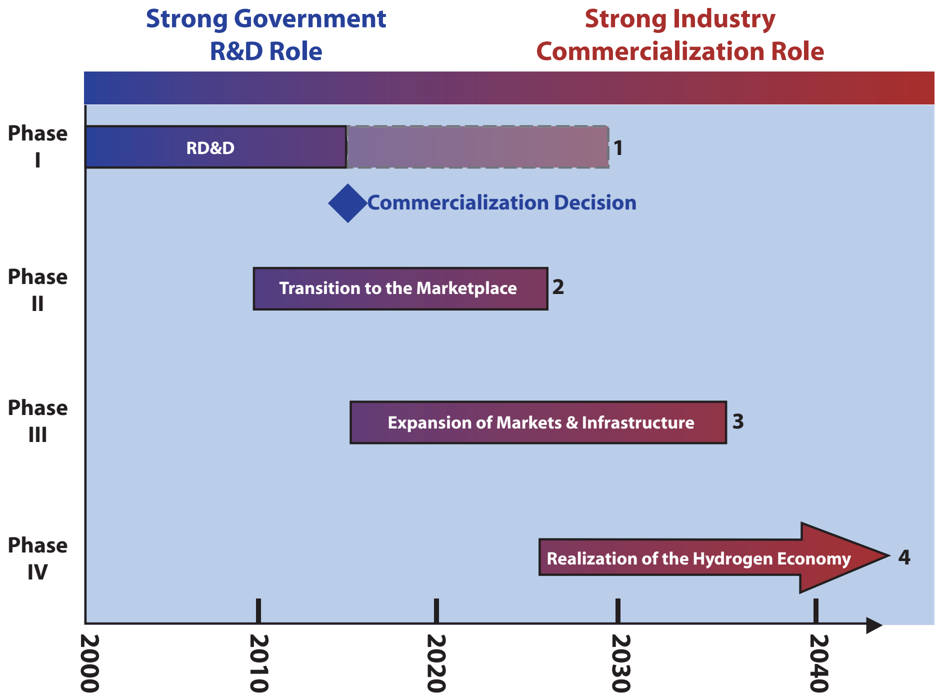
Production	Production of hydrogen from domestic resources minimizing environmental impacts
Delivery	Distribution, storage and dispensing of hydrogen from centralized or within distributed sites of production
Storage	Storage of hydrogen (or its precursors) on vehicles or within the distribution system
Fuel Cells	Conversion of hydrogen to electricity or heat; use of hydrogen to power vehicles (primary propulsion), for auxiliary power units for vehicles, and stationary and portable applications
Technology Validation	Technical validation of system performance, durability and availability in real-world environments
Safety	Safety assurance in DOE-sponsored R&D activities and in the marketplace
Codes and Standards	Research to enable development of model codes and standards for domestic and international production, distribution, storage and utilization of hydrogen
Education	Education of key target audiences—including teachers and students, state and local governments, safety and code officials, large-scale end users and the public—about the hydrogen economy and how it can affect them
Systems Analysis	Analysis of existing and emerging technologies for their ability to meet the needs of the future hydrogen economy, providing direction, focus and support to the development and introduction of hydrogen production, storage and end-use technologies
Systems Integration	Establishment of a disciplined approach that ensures program requirements are identified, met and validated in the context of dynamic commercial market requirements, while minimizing the impact on cost and schedule of unanticipated events and interactions.

Government and Industry Roles in Developing Hydrogen Technologies

The Hydrogen, Fuel Cells & Infrastructure Technologies Program funds research, development and validation activities linked to public-private partnerships. The government's current role is to concentrate its funding on high-risk, pre-competitive research in the early phases of development. As activities progress through the stages of developing technology to validating technical targets, the government's cost share will diminish. The government's role as co-funder will bring technologies to the point where the private sector can make informed decisions on whether or not, and how best to commercialize technologies.

The timeframe to attain self-reliance in meeting our nation's energy needs will be long and will require substantial investment. In the next two decades, conservation and increased efficiency through the use of gasoline-electric hybrid vehicles are the best options for reducing oil use and emissions. Ultimately, though, fuel substitution will be required to achieve energy independence while minimizing environmental impacts. DOE envisions four phases in the transition to a hydrogen economy, each of which requires and builds on the success of its predecessor. The bulk of the work for each phase will take place in the timeframe indicated in Figure 1.4; in addition, the work in progress will continue on as the next phase begins. The transition to a hydrogen economy will take several decades, and this transition will require strong public and private partnerships, commitment and resolve.

Figure 1.4. Hydrogen Economy Timeline



1. **Technology Development Phase**

   Research to meet customer requirements and establish business case lead to a commercialization decision

2. **Initial Market Penetration Phase**

   Portable power and stationary/ transport systems begin commercialization; infrastructure investment begins with government policies

3. **Infrastructure Investment Phase**

   H_2 power and transport systems commercially available; infrastructure business case realized

4. **Fully Developed Market and Infrastructure Phase**

   H_2 power and transport systems commercially available in all regions; national infrastructure

In Phase I, government and private organizations will research, develop and demonstrate "critical path" technologies and work to establish comprehensive safety guidelines and codes and standards prior to investing heavily in infrastructure. This phase is now underway, and it will enable industry to make decisions on commercialization by 2015. Following a positive commercialization decision, research will continue on advanced hydrogen and fuel cell technologies. Throughout the RD&D phase, exploratory research in materials sciences and engineering, chemistry, geosciences and molecular biosciences, will be carried out in close collaboration with the DOE Office of Science and other federal agencies.

Phase II is the Initial Market Penetration Phase. This could begin as early as 2010 for applications such as portable power and some stationary applications, and continue as hydrogen-related technologies meet or exceed customer requirements.

As these markets become established, government can foster their further growth by playing the role of "early adopter," and by creating policies that stimulate the markets. This leads to Phase III, the Infrastructure Investment Phase, in which there is expansion of markets and infrastructure. The start of Phase III is consistent with a positive commercialization decision for fuel cell vehicles in 2015. A positive decision will attract investment in infrastructure for manufacturing fuel cells and for producing and distributing hydrogen. Government policies still may be required to nurture this infrastructure expansion phase.

Phase IV, which could begin around 2025, is the Fully Developed Market and Infrastructure Phase. In this phase, national benefits in terms of energy security and improved environmental quality will be achieved, and industry will receive adequate return on investment and compete globally. Phase IV provides the transition to a full hydrogen economy by 2040.

Phase I will not abruptly end if industry makes a positive commercialization decision in 2015. Just as DOE still conducts research and explores the underlying science for internal combustion engines today, DOE will continue to research hydrogen technologies in the future, as indicated by the dotted lines in Figure 1.4. This research will be more fundamental in nature, and will be focused more on long-term pathways, such as photolytic production of hydrogen.

> ***"And despite the progress of recent decades, we must further address the environmental concerns surrounding the production and use of energy, including those related to transportation, which uses more than two-thirds of the 20 million barrels of oil Americans consume each day."***
>
> **Energy Secretary Spencer Abraham**
> **14th Annual National Hydrogen Association Conference**
> **March 5, 2003**

1.4 National Academies' Hydrogen Economy Report

The Department of Energy commissioned the National Academies to review the June 2003 draft RD&D Plan. Almost all of the recommendations have been or are being incorporated into the Program. Some of the significant changes are:

- Recommendation: Establish a comprehensive systems analysis capability to drive technology development decisions relevant to energy, environmental and economic criteria. Action: A new Technology Analyst position has been established to build up and manage DOE's capability in this area.
- Recommendation: Establish an independent systems integration effort to ensure that the various Program elements (i.e., production, delivery, storage, etc.) fit together seamlessly. Action: To help address the complex management challenges, DOE asked the National Renewable Energy Laboratory to establish a small group of engineers (who are "firewalled" from the research organizations) to assist the program in developing an integrated baseline (see Systems Integration section); controlling technical requirements, cost and schedule; and helping manage risks. A new Chief Engineer position has been established to oversee these critical program management functions as well as to improve integration with other agencies and other DOE offices involved in hydrogen development.
- Recommendation: Increase emphasis on hydrogen safety to understand how hydrogen systems must be designed, built and operated differently than today's vehicles and infrastructure. Action: A hydrogen safety expert panel has been formed to help DOE audit safety plans and practices within the Program. In addition, the research program to develop safety data and information has been expanded.
- Recommendation: Engage universities to play a much bigger role in the research program. Action: In 2004, dozens of universities were selected to conduct hydrogen production and storage research. This indicates the gradual shift from hardware development to more fundamental research as the Program succeeds in overcoming barriers and as more private investment occurs.

Consistent with the National Academies' findings, DOE made a "no-go" decision on on-board fuel processing. The rationale for this decision can be found in section 3.4. Furthermore, in response to a National Academies' recommendation, DOE has established a 2010 Go/No-Go Decision for stationary PEM fuel cell research.

> ***"A transition to hydrogen as a major fuel in the next 50 years could fundamentally transform the U.S. energy system, creating opportunities to increase energy security through the use of a variety of domestic energy sources for hydrogen production while reducing environmental impacts, including atmospheric CO_2 emissions and criteria pollutants."***
>
> **– National Academies' Report, "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs" February 2004**

1.5 Coordination with Others

The DOE Hydrogen Program coordinates its activities with different countries through the International Partnership for the Hydrogen Economy (IPHE), other federal agencies across the government by leading the Interagency Task Force on Hydrogen R&D, and by participating in state efforts like the California Hydrogen Highway Network and the California Fuel Cell Partnership.

In November 2003, the United States hosted the inaugural Ministerial meeting of IPHE – bringing together 15 countries and the European Commission and helping to launch international cooperation on vital hydrogen-related research activities. The IPHE provides a mechanism to organize, evaluate and coordinate multinational research, development and deployment programs that advance the transition to a global hydrogen economy. The IPHE leverages limited resources; identifies promising directions for RD&D and commercial use; provides technical assessments for policy decisions; prioritizes, identifies gaps and develops common recommendations for international codes, standards and safety protocols; and maintains communications with the key stakeholders to foster public-private collaboration that addresses the technological, financial and institutional barriers to a cost-competitive, standardized, widely accessible, safe and environmentally-benign hydrogen economy.

The White House Office of Science and Technology Policy's (OSTP) Hydrogen R&D Interagency Task Force was established in early 2003 and serves as the key mechanism for collaboration among eight federal agencies that fund hydrogen-related R&D. Co-chaired by OSTP and DOE, it also includes the Departments of Transportation, Defense, Agriculture and Commerce; Environmental Protection Agency; National Aeronautics and Space Administration; National Science Foundation; and, from the Executive Office of the President, Office of Management and Budget, and Council on Environmental Quality. Launching "Hydrogen.gov," a website that will serve as a central source of information on important federal R&D activities related to hydrogen and fuel cells, and completing a comprehensive 10-year coordination plan, including opportunities for joint solicitations, are near-term priorities.

Additionally, the Program is closely coordinating with state and local efforts. For example, DOE is participating on an advisory panel for California's Hydrogen Highway Network and participates in the California Fuel Cell Partnership.

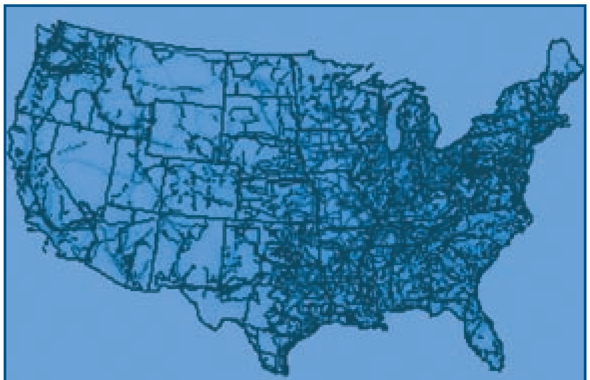
> ***"Through this Partnership, we have established a comprehensive framework on which to structure global hydrogen research and development. We can begin to take the concrete steps necessary to ensure that the scientific and technological work that is to come is best directed toward our ultimate goal - a secure, environmentally friendly energy future."***
>
> **– Spencer Abraham, Secretary of Energy**
> **IPHE Ministerial Meeting**
> **November 18-21, 2003**

2.0 Program Benefits[1]

The Hydrogen Fuel Initiative is designed to reverse America's growing dependence on foreign oil by developing the technology for hydrogen-powered fuel cell vehicles and the infrastructure to support them. This approach was chosen not only because of the energy security benefits associated with a transportation fuel that can be produced domestically from a diversity of feedstocks, but also because of the potential environmental benefits in transportation applications and stationary markets.

2.1 Energy Security

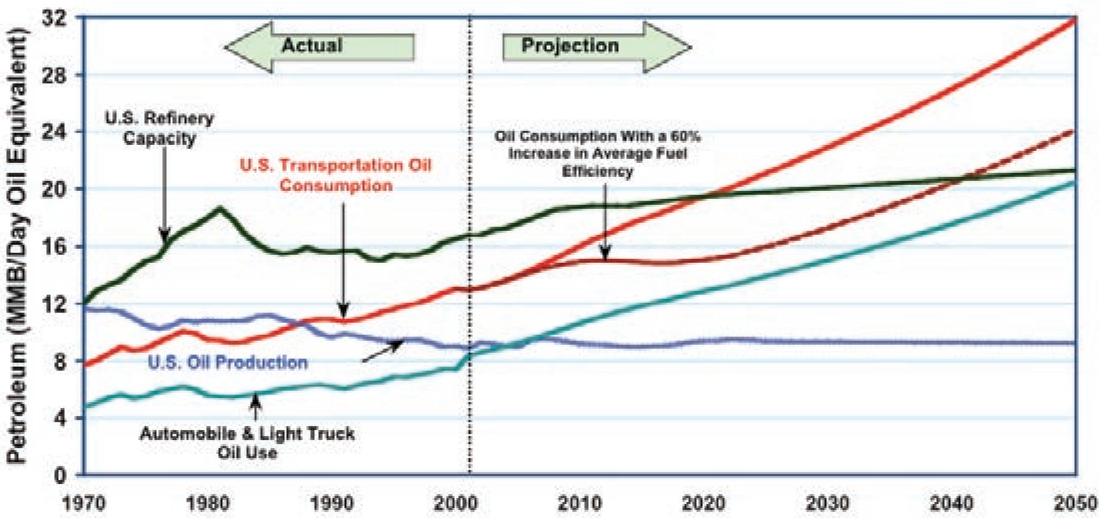
The U.S. currently imports more than half of its oil (compared to only a third during the 1973 oil crisis), and imported oil is expected to increase as demand continues to rise and domestic oil production continues to decline. In addition to crude oil import concerns, current U.S. oil refining is at nearly 97% capacity, and further expansion of domestic U.S. refining capacity is hindered due to environmental constraints (American Petroleum Institute). As a result, the growing U.S. oil consumption beyond 2004 will be supplied primarily from refined fuel imports versus crude oil imports (see Figure 2.1.1).



> ***"…hydrogen can be produced from domestic sources -- initially, natural gas; eventually, biomass, ethanol, clean coal, or nuclear energy…One of the greatest results of using hydrogen power, of course, will be energy independence for this nation…"***
>
> **–President George W. Bush**
> **The National Building Museum**
> **February 16, 2003**

By 2025, the share of oil imports is expected to reach nearly 70% of the total oil consumed in the U.S. This imbalance presents a major concern for our nation's energy security. Two-thirds of the oil used in the U.S. goes to support our transportation fleet. To significantly reduce or end our dependency on oil imports, we must make a major change in the fuel used for the transportation sector. Even with the significant energy efficiency benefits that gasoline-electric hybrid vehicles and diesels can provide, we ultimately must find an alternative fuel that can be domestically produced.

Figure 2.1.1. U.S. Transportation Oil Gap



---

[1] References for this section are listed in Appendix C.

U.S. Dependence on Foreign Crude Oil and Transportation Fuel Imports

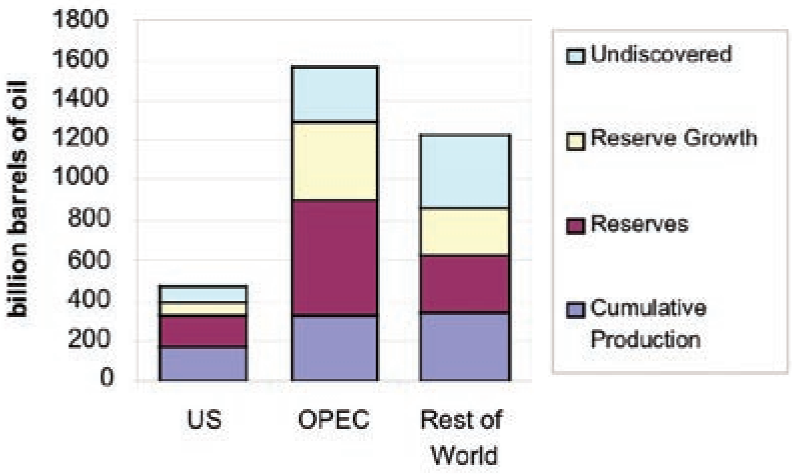
The divergence between oil used in the transportation sector and that produced and refined domestically (see Figure 2.1.1) is a result of a number of factors. U.S. crude production peaked in 1970, and has declined steadily since the mid-1980s. Even the addition of oil from other domestic sources has not changed this long-term decline in U.S. oil production. By the late-1980s, the transportation sector alone used more oil than was produced domestically. And by the late 1990s, the growing fleet of light duty cars and trucks (pickups, SUVs, and mini-vans) for personal transportation resulted in increased fuel use by light-duty vehicles.

The growing fuel consumption of the transportation sector not only has caused the U.S. to import more crude oil, but has forced a transition to a refined products import position. The fuel demand has outpaced the domestic crude oil refining capacity because of domestic refinery shutdowns, limited expansion of existing refineries and a lack of construction of new domestic refineries (the last new domestic refinery was constructed in the 1970s). As a result, increasing amounts of oil supplied for the U.S. transportation sector will be in the form of refined transportation fuels.

In an effort to manage the growing fuel demand, even a 60% increase in the average fuel efficiency for light-duty vehicles (to about 38 mpg) would not reduce the oil consumption, only slow the growth rate for a short period of time. Continued growth in the number of vehicles and the amount of travel will overwhelm the beneficial effects within a few years without continued vehicle fuel economy improvements. The addition of other domestic oil resources also provides a partial solution to meeting the nation's petroleum needs. However, the combination of efficiency improvements and increased domestic oil production does not close the transportation oil gap, which will widen again unless the transportation system eventually moves to a non-petroleum fuel.

From a global perspective, the finite levels of global petroleum resources further compound the energy security issue. As shown in Figure 2.1.2, a recent U.S. Geological Survey (2000) estimates that there are 3 trillion barrels of recoverable oil worldwide. About one-fourth has already been produced and consumed, while roughly an equal amount has been discovered and "booked as reserves." Thus, the remaining half of the identified global oil resources are categorized as either reserve growth or probable, but undiscovered, resources. While data do not suggest an imminent global oil shortage, increasing petroleum consumption does present some concerns. World petroleum resources are finite and U.S. reserves are small compared to OPEC and the rest of the world. Although petroleum resources are relatively abundant, the geographic distribution is uneven and distant from most major consumers, and of particular concern, oil is concentrated in regions that have either political or environmental sensitivities.

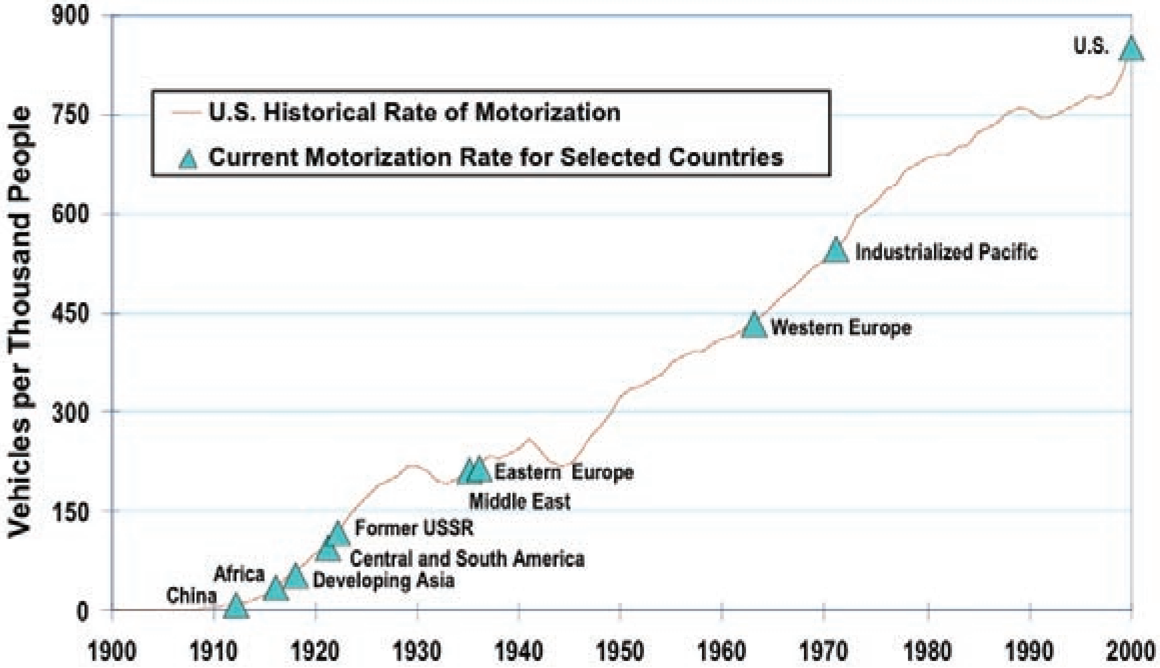
Figure 2.1.2. Global Distribution of Petroleum Resources



Global Transportation Trends

The worldwide growth in transportation as countries modernize and improve economically will accelerate oil consumption, resulting in the realization of a critical need to develop alternative energy sources. Some of the most rapidly developing countries are also the most populous, e.g., China and India. In terms of motor vehicles per thousand people, China is where the U.S. was in 1913 (Figure 2.1.3), and growing rapidly. During the 1990s, automobile registrations in China and India increased at an annual rate of 9.1% and 7.6%, respectively, while the growth rates for trucks and buses were 8.8% and 8.2%, respectively. For comparison, the U.S. growth rates for automobile registrations for the same decade declined by 0.5% while truck registrations (including SUVs, pickups, and mini-vans) and buses increased by 4.5%.

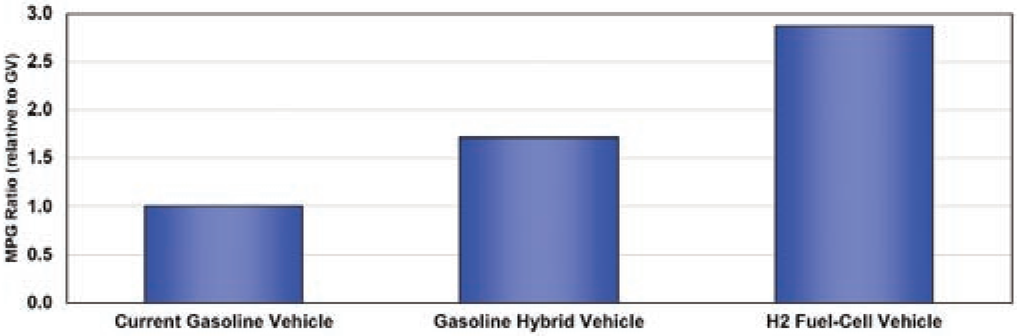
Figure 2.1.3. Current Global Motorization Rates Compared to U.S. Historical Rates



Advanced Vehicles Technologies Comparison

Improving the nation's energy security primarily depends on the degree that the transportation system can improve its energy efficiency and utilize domestic non-petroleum fuels. Success in the marketplace for advanced vehicle technologies will depend in part on the fuel economy advantages that can be achieved. Figure 2.1.4 (fuel economy estimates from Argonne National Laboratory) illustrates that fuel cell vehicles offer advantages over gasoline vehicles, even allowing for technological improvements in conventional powertrains.

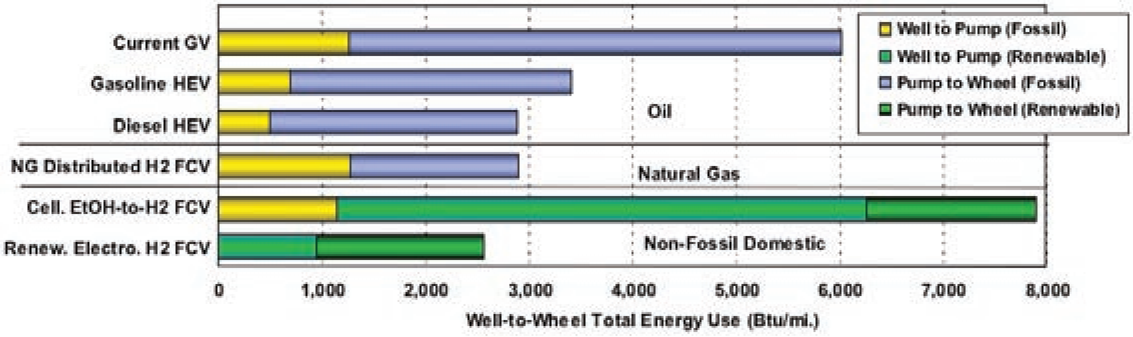
Figure 2.1.4. Relative Fuel Economies for Advanced Vehicle Technologies



Vehicle efficiency is not the sole measure used to compare the various technology options; upstream fuel processing, delivery and refueling needs must also be considered. Total energy well-to-wheels (WTW) cycle analysis is used to make informed decisions when comparing technology choices or applications within a given feedstock. The well-to-wheels analysis tells a complete energy story for hydrogen fuel cell vehicles as well as for alternative powertrains when different feedstocks are compared.

Figure 2.1.5 presents the full WTW energy use per mile of future light-duty vehicles using several prominent powertrain/fuel options. This figure shows that even with fuel production factored in, a fuel cell vehicle powered by hydrogen from natural gas offers improved efficiency over conventional gasoline-hybrid options. In addition, the fuel cell vehicle powered by hydrogen from renewable electrolysis offers improved efficiency over both gasoline- and diesel-hybrid vehicle options. This figure also illustrates that, as fuel cell vehicles and hydrogen infrastructure are developed, gasoline and diesel hybrid electric vehicles can offer significant energy savings over current gasoline vehicles. As mentioned, however, improving efficiency cannot fully address the long-term petroleum dependency problem; a move toward alternative energy resources is needed. For example, in addition to the two hydrogen-based options exhibited, hydrogen from solar, nuclear and renewable liquids (e.g., cellulosic ethanol) provides opportunities for reductions in petroleum use.

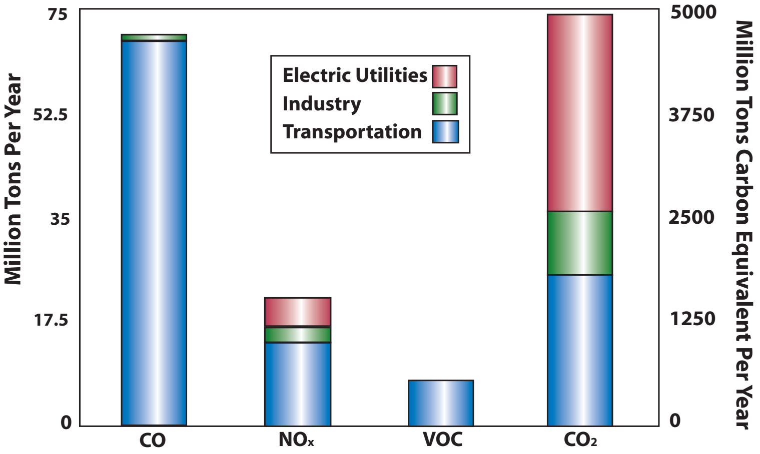
Figure 2.1.5. Comparative Vehicle Technologies: Well-to-Wheels Energy Use



2.2 Environmental Benefits

While addressing the energy security issue, we must also address our environmental viability. Air quality is a major national concern. It has been estimated that 60% of Americans live in areas where levels of one or more air pollutants are high enough to affect public health and/or the environment. As shown in Figure 2.2.1, personal vehicles and electric power plants are significant contributors to the nation's air quality problems. Most states are now developing strategies for reaching national ambient air quality goals and bringing their major metropolitan areas into attainment with the requirements of the Clean Air Act. The State of California has been one of the most aggressive in their strategies and has launched a number of programs targeted

Figure 2.2.1. Emissions from Fossil Fuel Combustion



at improving urban air quality, since 90% of the state's population breathes unhealthy levels of one or more air pollutants during some part of the year.

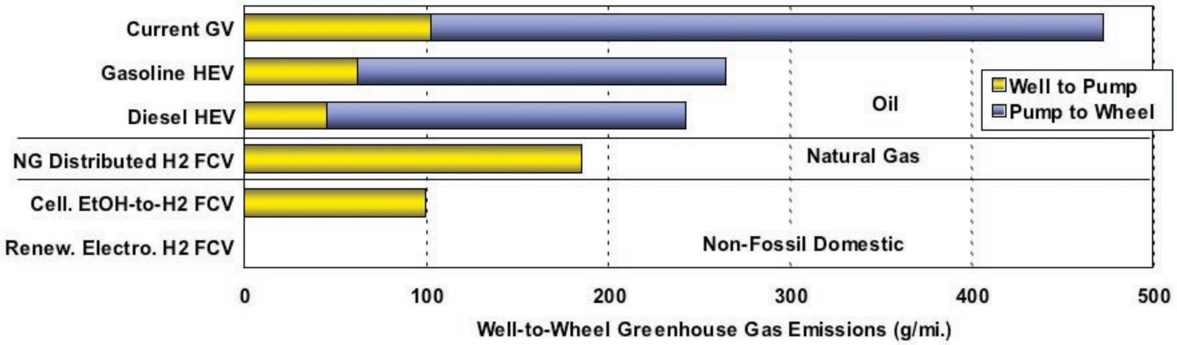
Criteria Pollutants

Internal combustion engines (both conventional and hybrid drives) will continue to have some on-road emissions. Although emission control technologies such as on-board diagnosis (OBD) systems can reduce the likelihood of vehicles that have high emissions rates due to on-road deterioration of engine performance and emission control devices, they cannot eliminate the so-called "high emitters." Consequently, widespread use of fuel cell vehicles, because they are zero-emission vehicles and have no on-road emission deterioration, could be expected to have a measurable effect on reducing nitrogen oxides, volatile organic compounds, and particulate matter produced by light-duty vehicles. Although hydrogen production from certain feedstocks will generate some pollutants, emissions from stationary sources such as hydrogen production plants are easier to control and monitor than are deterioration in emissions control on vehicles.

Greenhouse Gases

Emission of greenhouse gases (GHGs), like carbon dioxide and methane, has been cited as a major global concern. Build-up of these gases in the atmosphere is thought to have detrimental effects on the global climate. Although there is not yet agreement on what the exact impact will be, when it will be realized, or how best to address the problem, there is agreement that emissions of these gases need to be reduced. Hydrogen offers a unique opportunity to address this problem, since carbon emissions can be decoupled from energy use and power generation; used in a fuel cell, the only emission is water. Efficient hydrogen production technologies and the possibility of carbon sequestration make natural gas and coal viable feedstock options, even in a carbon-constrained environment. In the case of renewable and nuclear options, greenhouse gases are essentially only the product of materials for construction, and of feedstock collection, preparation, storage, and delivery. The well-to-wheels analysis illustrated in Figure 2.2.2 confirms that hydrogen fuel cell vehicles can offer significant greenhouse gas benefits, even in the case of natural gas without carbon sequestration.

Figure 2.2.2. Comparative Vehicle Technologies: Well-to-Wheel Greenhouse Gas Emissions



2.3 Economic Competitiveness

Abundant, reliable, and affordable energy is an essential component in a healthy economy. When energy prices spike, as has occurred several times recently due to supply interruptions and/or high demand, Americans suffer economically, particularly those in lower-income brackets. Looking at the expenditures for energy across all income levels, the average percentage of personal income that was spent on energy in 2003 was 4.8% (U.S. Department of Commerce, Bureau of Economic Analysis). Lower-income families spend nearly as many dollars as those in higher-income brackets to heat their homes and fuel their cars (the average energy expense for low-income families is 12.6% of income). The number of American families requesting assistance with heating bills has risen significantly; in the winter of 2000, 5 million families applied to receive Low Income Home Energy Assistance. Hydrogen offers unique opportunities to drastically increase the efficiency with which we generate and use energy. And because it can be produced from a wide variety of domestically-available resources, we can reduce the impact of externalities on energy prices. Hydrogen's diversity in production, and flexibility in use, also opens the door for new players in energy markets. In addition to the energy security benefits, this has economic equity implications due to broadening energy choices and increasing competition.

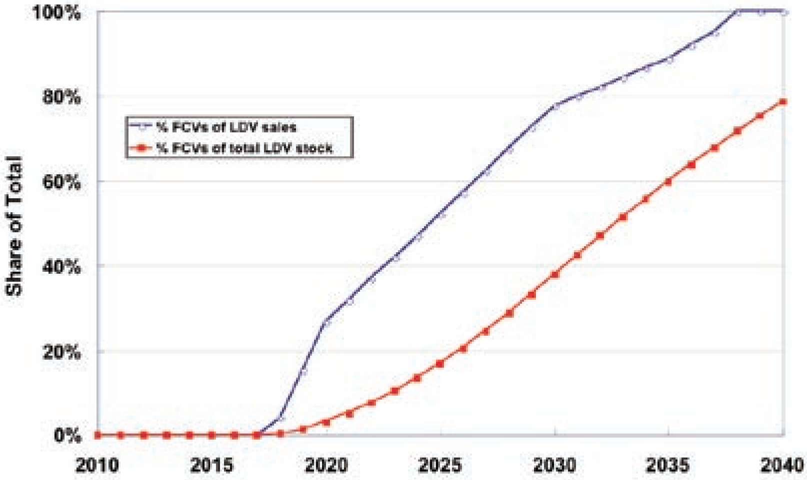
The technical and economic success of hydrogen-based distributed energy systems will catalyze new business ventures. Hydrogen power parks will provide an economic development path for the integrated production of energy services such as electricity, transportation fuels, and heating and cooling. This will lead to the creation of high-tech jobs to build and maintain these systems. Hydrogen also offers a wide variety of opportunities for the development of new centers of economic growth in both rural and urban areas that are currently too far off line to attract investment in our centralized energy system.

The competitiveness of U.S. industry is also of vital importance to the well-being of our people and of the nation as a whole. For example, the U.S. auto industry is the largest automotive industry in world, producing 30% more vehicles than the second largest producer, Japan. The auto industry is a highly productive one (ranked fourth) and is accompanied by relatively high levels of compensation; in 1998, the average autoworker earned $65,000, compared to $48,000 for the average in the manufacturing sector and $38,000 for the average worker nationwide. The auto industry is also a major exporter, accounting for 12% of all non-agricultural exports. For every worker directly employed by an auto manufacturer, there are nearly seven spin-off jobs. America's automakers are also among the largest purchasers of aluminum, copper, iron, lead, plastics, rubber, textiles, vinyl, steel and computer chips. The auto industry ranks near the top of U.S. industries in terms of investment in R&D. Remaining competitive in the international market is essential to the auto industry and the U.S. economy as a whole.

2.4 Potential Impact of Fuel Cell Vehicle Introduction

The rate of market penetration of the fuel cell vehicle will determine its impact on future U.S. petroleum consumption. A penetration scenario is provided in Figure 2.4.1, which is based on a market model of past U.S. transportation fuel transition, and assumes the necessary RD&D to overcome the technical and cost barriers is completed by 2015. If the commercialization decision is positive, then vehicle sales could begin three years later in 2018. Meeting the milestones in this plan means that the fuel cell vehicles are not just competitive with conventional vehicles in both performance and cost, but also provide additional energy and environmental benefits, making rapid market acceptance feasible such that by 2025 half of all new light duty vehicle sales are fuel cell vehicles. Rapid market penetration could also be stimulated by government policies that provide incentives to consumers.

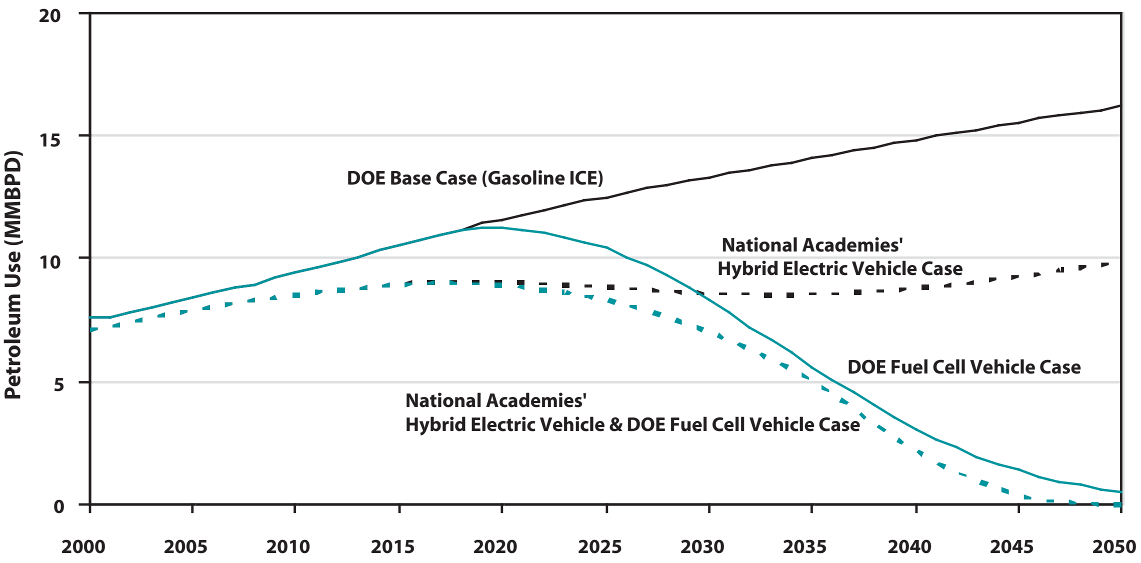
Figure 2.4.1 A Scenario: Market Penetration of Fuel Cell Vehicles



Based on the optimistic scenario described above, the impact of fuel cell vehicle and gasoline hybrid vehicle penetration in reducing petroleum use is illustrated in Figure 2.4.2. As shown, the gasoline hybrid vehicle will temporarily slow the growth in oil consumption. But as the population continues to grow, gasoline demand will return to historic consumption growth rates. In contrast, the penetration of hydrogen fuel cell vehicles, or a combination of gasoline hybrids and hydrogen fuel cell vehicles, will begin to slow petroleum use and eventually cause the decline approximately in 2025, if a substantial number of light duty fuel cell vehicles are on the road.

The rate of projected transition of fuel use illustrated here was compared to historical rates of fuel transition in the U.S. in an analysis by Argonne National Laboratory. This comparison illustrated that this rate is well within the range of transportation fuel switch transition rates that have occurred in the U.S. over the last two centuries. Note that the projected eventual elimination of oil use in light duty vehicles would not by itself mean that oil use in the transportation sector would disappear, as oil would still be needed for other parts of the transportation system. However, our reliance on foreign sources of oil would be significantly reduced.

Figure 2.4.2. Potential Impact of Fuel Cell Vehicles on U.S. Light-Duty Vehicle Petroleum Use



Domestic Resources

One of the principal energy security advantages of hydrogen as an energy carrier is diversity – the potential for producing it from a variety of domestic resources. But do we have enough domestic resources to provide the hydrogen we need? Assuming an average vehicle mileage of 60 mpg, 150 million fuel cell vehicles (approximately one-half of the U.S. light-duty vehicle fleet) will require around 40 million tons of hydrogen annually. In a worst case situation, we would need to produce all of this hydrogen from just one resource, for example, natural gas. Current annual U.S. consumption is 495 million tons of natural gas. An additional 130 million tons of natural gas would be needed to produce the 40 million tons of hydrogen; this represents a 27% increase in consumption. As of January 2000, remaining technically recoverable natural gas reserves were estimated at 28 billion tons, or 46 times the needed annual consumption. If, instead, we produced the 40 million tons of hydrogen from our abundant domestic coal resources (approximately 4 trillion recoverable tons), annual coal consumption would increase by less than 30%. Other options include:

- **Biomass:** The current agricultural and forest products residues, organic municipal solid waste, urban tree residues, livestock residues and potential energy crops would be sufficient to produce 40 million tons of hydrogen.
- **Wind-Electrolysis:** 555 GW of installed wind would be needed to produce 40 million tons of hydrogen. Only around 4 GW of wind is currently installed in the U.S., but this figure is growing rapidly with improved designs and lowering costs. The estimated wind capacity in the U.S. is around 3,250 GW; 555 GW represents the available capacity of North Dakota.
- **Solar-Electrolysis:** 740 GW, approximately 3,750 square miles (equivalent to 3% of the land area of Arizona), of flat-plate photovoltaics would be needed to produce 40 million tons of hydrogen.
- **Nuclear energy:** Nuclear power can also provide electricity to produce hydrogen via electrolysis of water. Around 200 conventional 1 GW_e reactors would be needed to produce 40 million tons of hydrogen annually. This would require tripling the number of currently-deployed nuclear reactors. Instead of generating electricity, advanced nuclear reactor concepts (Gen IV) could be used to produce heat that would permit high-temperature electrolysis or thermochemical cycles. In this case, only 125 new reactors would be needed.

The following provides a brief description of the key attributes of some of the various resources from which hydrogen can be produced.

Natural Gas. One of the most widely used energy sources is natural gas. It is used for space heating and cooling, water heating, cooking, electricity generation, transportation, and in industry provides the base ingredients, such as hydrogen, for such varied products as plastics, fertilizers, anti-freeze, and fabrics. Reforming of natural gas makes up nearly 50% of the world's hydrogen production and is the source of 95% of the hydrogen produced in the U.S. Steam reforming is a thermal process, typically carried out over a nickel-based catalyst that involves reacting natural gas or other light hydrocarbons with steam. Large-scale commercial units capable of producing hydrogen are available as standard "turn-key" packages.

Coal. Another widely used energy source is coal; major uses include electricity production, iron and steel manufacturing, and cement production. Currently, more than 70 gasification plants are operating throughout the world using coal or petroleum coke as a feedstock. Advanced systems are also the subject of RD&D. DOE's FutureGen Initiative, led by the Office of Fossil Energy, is a plan to build a prototype of the fossil fuel power plant of the future—a plant that combines electricity generation and hydrogen production with the virtual total elimination of harmful emissions and greenhouse gases. Current plans call for the 275 MW plant to be designed and built over the next ten years, then operated for at least five years beyond that.

Biomass. Renewable feedstocks can be used to produce hydrogen, either directly or through intermediate carriers (e.g., ethanol). Some biological organisms can produce hydrogen through fermentation. Alternatively, fermentation could be used to produce methane or sugar alcohols that can be reformed to hydrogen. Thermal processing (pyrolysis or gasification) can also be used and the techniques for biomass and fossil fuels (reforming, water gas shift, gas separation) are similar. Approximately 10 kg of biomass are required to produce 1 kg of hydrogen. For comparison, around 3 billion gallons of ethanol is produced for fuel use and 200 million tons of biomass is used to produce heat, power and electricity annually.

Wind. In some parts of the country, wind energy is supplementing more conventional forms of electricity production. California now produces more than 10% of the world's wind-generated electricity. Wind turbines have been connected to electrolysis systems that can operate with high efficiency (~70%) to produce hydrogen. Construction costs have dropped to about $1 million per MW, which works out to about 4 to 6 cents per kWh and this price is expected to drop even further in the coming years.

Solar. Sunlight can provide the necessary energy to split water into hydrogen and oxygen. Photovoltaic arrays can be used to generate electricity that can then be used by an electrolyzer to produce hydrogen. Some semiconductor materials can also be used to directly split water in a single monolithic device, eliminating the need for separate electricity-generation and hydrogen-production steps. Similarly, a number of biological organisms have the ability to directly produce hydrogen as a product of metabolic activity. Finally, solar concentrators can be used to drive high-temperature chemical cycles that split water. Like wind, there are huge solar resources in the U.S., especially in the southwestern portion of the nation, where one acre of land could potentially supply 15,000 kilograms of hydrogen per year using today's commercial photovoltaics.

Nuclear Energy. Current nuclear technology generates electricity that can be used to produce hydrogen via electrolysis of water. Advanced nuclear reactor concepts (Gen IV) are also being developed that will be more efficient in the production of hydrogen. These advanced technologies provide heat at a temperature that permits high-temperature electrolysis (where heat energy replaces a portion of the electrical energy needed to dissociate water) or thermochemical cycles that use heat and a chemical process to dissociate water. The thermodynamic efficiencies of thermochemical cycles for the direct production of hydrogen with Gen-IV reactors may be as high as 45%. This contrasts with the 33% efficiency of the existing reactors for electric power production. By bypassing the inefficiencies of electric power production and electrolysis losses, the overall efficiency of converting heat energy to hydrogen energy is increased significantly.

Fusion Energy. Fusion power, if successfully developed, could be the ultimate source of a clean, safe, abundant, and carbon-free domestic resource for hydrogen production. The DOE Office of Science will lead the U.S. efforts in the International Thermonuclear Experimental Reactor (ITER) project, whose mission is to demonstrate the scientific and technological feasibility of fusion energy within the next 35 years. The United States will work with Great Britain and several European nations, as well as Canada, Japan, Russia and China, to build a fusion test facility and create the largest and most advanced fusion experiment in the world. Fusion energy releases vast amounts of heat, which can be used to produce hydrogen from water by means of thermolysis (thermally driven dissociation of water) or by thermochemical cycles.

The reality is that a transition from petroleum to hydrogen will be gradual and a variety of technologies and feedstocks will be used to meet the growing demand. Near-term production needs will likely begin with natural gas. Electrolysis will find markets where lower-cost and off-peak electricity is available. Biomass could meet mid-term needs in regions where agriculture and forest products are the mainstay. Over time, we will see the costs of renewable power generation technologies drop and gain growing shares of the electrolysis markets. Direct water splitting and high temperature technologies will begin to be demonstrated and find their place in the market, as well. The share of each technology will be a function of cost, regional markets and resource availability. Policy and environmental constraints will also dictate the penetration rates of the various options.

2.5 Realizing the Benefits

In addition to addressing the major challenge of energy security, hydrogen fuel cell systems can address many of our nation's other energy-related needs. To meet our growing electrical demands, it is estimated that electricity generation will have to increase by 2% per year. At this rate, 330 GW of additional electricity generation capacity will be needed by 2020. Along with an aging transmission and production infrastructure, requirements for reliable premium power and market deregulation, this increasing demand opens the door for hydrogen power systems.

Hydrogen power systems provide unique opportunities for increasing the diversity of the electricity market. Currently, grid stability and intermittency issues are major limitations for the penetration of renewables like wind and solar into the electricity market. By combining these generation technologies with hydrogen production and storage, intermittent renewables could potentially capture a larger share of the power production market without major upgrades to the existing grid.

Hydrogen systems can be extremely efficient over a large range of sizes (from one kilowatt to hundreds of megawatts). Some systems can achieve overall efficiencies of 80% or more when heat production is combined with power generation. Additionally, smaller-scale distributed hydrogen systems offer combined heat, power and fuel opportunities. Fuel cell systems integrated with hydrogen production and storage can provide fuel for vehicles, energy for heating and cooling, and electricity to power our communities. These clean systems offer a unique opportunity for energy independence, highly reliable energy services and economic benefits.

While enormous, the benefits of a hydrogen economy cannot be realized overnight. A transition is necessary; however, hydrogen has the flexibility and robustness to meet the challenge. To realize the benefits, several things must occur. Fuel cell technologies and hydrogen storage systems must be advanced so that hydrogen fuel cells can be a cost-competitive choice for the consumer when they go to buy a new vehicle, or when communities evaluate energy options. Hydrogen production options require additional research and implementation for cost parity with today's fuels. And the existing hydrogen infrastructure needs to grow to a point where all consumers can conveniently obtain hydrogen. If we are successful in developing hydrogen technologies to their full potential, we could significantly reduce U.S. demand for oil and greenhouse gas emissions.

3.0 Technical Plan

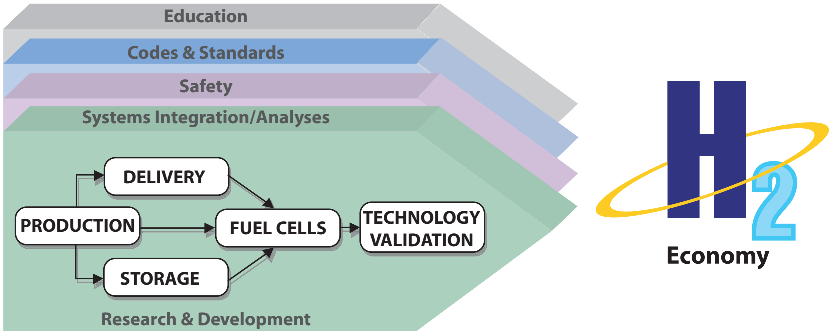
This section of the Plan provides a detailed outline of the various activities occurring within the technical Program elements of the Hydrogen, Fuel Cells & Infrastructure Technologies Program, as follows:

3.1 Hydrogen Production
3.2 Hydrogen Delivery
3.3 Hydrogen Storage
3.4 Fuel Cells
3.5 Technology Validation
3.6 Hydrogen Codes and Standards
3.7 Hydrogen Safety
3.8 Education

For each section, a brief introduction is followed by the specific goal and objectives of the Program element. The remainder of the section presents the Program element's strategy for achieving success and measuring progress. This begins with an overview of the technical approach and review of the current activities within the Program element. Next, each section lays out specific targets that will lead a pathway toward the objectives, the barriers to achieving these targets, and the specific tasks and milestones used to direct their efforts and gauge their progress.

Activities within each of the Program elements must be coordinated and integrated to achieve the ultimate commercialization goals of the Program. Interrelationships between all Program elements, including Systems Analysis and Systems Integration, are represented in Figure 3.0.1; specific inputs and outputs between Program elements are identified in the milestone charts and tables. Systems Analysis and Systems Integration (see Sections 4.0 and 5.0) will be used to identify, analyze, and evaluate these complex interdependencies and to guide decision making for the Hydrogen, Fuel Cells & Infrastructure Technologies Program Manager. Program Management and Operations are discussed in Section 6.0.

Figure 3.0.1. Hydrogen, Fuel Cells & Infrastructure Technologies Program

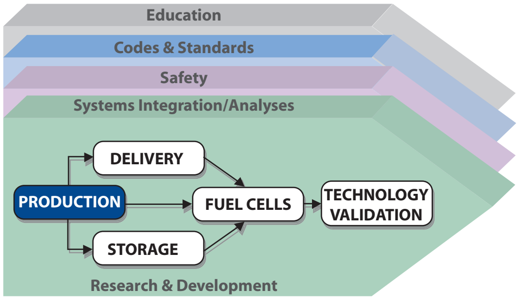


Each Program element is also actively involved in coordination activities with the DOE Hydrogen Program, which includes hydrogen and fuel cell research and development efforts within the Offices of Energy Efficiency and Renewable Energy (EERE); Fossil Energy (FE); Nuclear Energy, Science and Technology (NE); and Science (SC). In particular, EERE Programs that perform research on technologies that can be used to produce or use hydrogen are an important component of research taking place within the Hydrogen, Fuel Cells & Infrastructure Technologies Program. These include:

- Wind and Hydropower Technologies Program
- Geothermal Technologies Program
- Solar Energy Technology Program
- Biomass Program
- FreedomCAR and Vehicle Technologies Program
- Building Technologies Program
- Federal Energy Management Program

Each of these programs is pursuing technologies that will efficiently and affordably enhance the nation's access to clean, domestic energy supplies. Hydrogen can play a key role in the realization of these technologies, and will certainly benefit from the research and development taking place in each program. Advanced electrolysis technologies, conversion of biomass to hydrogen, PEM fuel cell development, and application of hydrogen for stationary energy needs are examples of areas in which collaboration between the Hydrogen, Fuel Cells & Infrastructure Technologies Program and other EERE Programs is vital to the technical targets identified in this chapter.

3.1 Hydrogen Production



Hydrogen can be produced from a diversity of energy resources, using a variety of process technologies. Energy resource options include fossil, nuclear and renewables. Examples of process technologies include thermochemical, biological, electrolytic and photolytic.

3.1.1 Technical Goal and Objectives

Goal

Research and develop low-cost, highly efficient hydrogen production technologies from diverse, domestic sources, including natural gas and renewable sources.[1]

Objectives

- By 2010, reduce the cost of distributed production of hydrogen from natural gas to $1.50/gge[2] (delivered, untaxed) at the pump (without carbon sequestration).[3]
- By 2015, reduce the cost of distributed hydrogen production from biomass-derived renewable liquids to $2.50/gge (delivered, untaxed) at the pump.
- By 2010, verify distributed grid-connected water electrolysis at a projected delivered hydrogen cost of $2.85/gge. By 2015, verify renewable central hydrogen production at a projected cost of $2.75/gge delivered.
- By 2015, reduce the cost of hydrogen produced from biomass to $1.60/gge at the plant gate ($2.60/gge delivered) by developing reforming technologies for gasification and pyrolysis processes.
- Develop advanced renewable photoelectrochemical and biological hydrogen generation technologies. By 2015, verify the feasibility of these technologies to be competitive in the long term.
- By 2015, develop high-temperature thermochemical cycles driven by concentrated solar power processes to produce hydrogen with a projected cost of $3/gge at the plant gate ($4.00/gge delivered).[4]
- Evaluate other new technologies that have the potential for cost-effective sustainable production of hydrogen and fund appropriate research and development in promising areas.

3.1.2 Technical Approach

Hydrogen production research is focused on meeting the objectives outlined in Section 3.1.1. by conducting R&D through industry, national laboratory, and university projects.

---

[1] Coal-based and nuclear-based hydrogen production are being addressed by the DOE Offices of Fossil Energy and Nuclear Energy, Science and Technology, respectively.

[2] The energy content of a gallon of gasoline and a kilogram of hydrogen are approximately equal on a lower heating value basis; a kilogram of hydrogen is approximately equal to a gallon of gasoline equivalent (gge) on an energy content basis.

[3] $1.50 is the estimated cost for hydrogen to be competitive for transportation systems in the 2015 timeframe. This estimate is currently under evaluation.

[4] Collaboration with DOE's Office of Nuclear Energy, Science and Technology.

An array of feedstocks and technologies for hydrogen production will be necessary to address energy security and environmental needs. This program element addresses multiple feedstock and technology options for hydrogen production for the short and long terms. The research focus for the transition to a hydrogen infrastructure is on distributed reforming of natural gas and renewable liquid fuels, and on electrolysis to meet initial lower volume hydrogen needs with the least capital investment. The research focus is on renewable feedstocks and energy sources for the long term, with more emphasis on centralized options to take advantage of economies of scale when an adequate hydrogen delivery infrastructure is in place. There is a strong collaboration with DOE's Office of Fossil Energy to develop centralized production from coal with carbon sequestration, and with DOE's Office of Nuclear Energy, Science and Technology to develop centralized production from advanced nuclear energy-driven high-temperature thermochemical cycles and high temperature electrolysis. DOE's Office of Science is a collaborator on long-term technologies such as biological and photoelectrochemical hydrogen production.

The planned development of a national hydrogen production infrastructure will take multiple pathways. Some of these pathways and their roles within the strategy of the Hydrogen Production Program element are described below.

Distributed Production Pathway

Distributed production of hydrogen may be the most viable approach for introducing hydrogen as an energy carrier. It requires less capital investment for the smaller volume of hydrogen needed initially, and it does not require a substantial hydrogen transport and delivery infrastructure.

Two distributed hydrogen production technologies that have the best potential for development and commercialization during a transition to a hydrogen economy are 1) reforming of natural gas or liquid fuels, including renewable liquids such as ethanol and bio-oil, and 2) small-scale water electrolysis located at the point of use, i.e., refueling stations and stationary power generation sites. Of these technologies, natural gas reformers are in the most mature stage of development and are the closest to meeting the hydrogen production cost targets. Research will focus on developing these technologies through 2010, and then on applying them to reforming renewable liquid feedstocks for a competitive hydrogen cost. Distributed reforming using renewable liquids offers near-zero net greenhouse gas emissions. The second research focus is on small-scale electrolyzers for splitting water. Electrolyzers present the opportunity for non-carbon-emitting hydrogen production when a renewable electricity source such as wind or hydro power is used. When off-peak electricity is used, greater economic opportunities may be presented by energy stations that produce both fuel and electricity.

Figure 3.1.1 Centralized Hydrogen Production Facility

Centralized Production Pathway

Large hydrogen production facilities that can take advantage of economies of scale will be needed in the long term to meet hydrogen fuel demand (see Figure 3.1.3). Central hydrogen production allows management of greenhouse gas emissions through strategies like carbon sequestration. In parallel with the distributed production effort, DOE is pursuing central production of hydrogen from a variety of resources-fossil, nuclear and renewable. Coal and natural gas are possibly the least expensive feedstocks, and carbon sequestration is required to reduce or eliminate greenhouse gas emissions. Reforming of biomass gases or liquids offers a renewable option and near-zero greenhouse gas emissions. Centralized natural gas is not being pursued for the long-term because of energy security issues. Biomass reforming of gas or oils offers renewable feedstocks with near-zero net greenhouse gas emissions. Photoelectrochemical and biological hydrogen production are long-term technologies that have the potential to produce hydrogen with sunlight, but they can currently only produce small amounts of hydrogen at high cost. Centralized water electrolysis is a viable approach where there is inexpensive and low-carbon electricity. However, as the cost of capital equipment is reduced through advanced development, the cost of electricity becomes the dominant factor in the cost of hydrogen. High-temperature thermochemical hydrogen production that uses concentrated solar heat may be viable with the development of appropriate water-splitting chemical process cycles and materials. Other feedstocks and technologies for hydrogen production that show promise may also be considered.

Central production of hydrogen could potentially include a more diversified feedstock base, but to be commercially viable it would require development of a distribution infrastructure for hydrogen. The Program is pursuing projects to identify a cost-effective, energy-efficient, safe infrastructure for the delivery of hydrogen or hydrogen carriers from centrally located production facilities to the point of use (see section 3.2).

Other Production Pathways

Another pathway being explored is combined production of hydrogen, heat, and electric power. In this scenario, hydrogen would be produced for use in a higher temperature stationary fuel cell to produce electricity and heat as well as for use as a transportation fuel in fuel cell vehicles or hydrogen internal combustion engines. This allows two markets for the hydrogen in a swing plant operation, which could help to initiate the use of hydrogen when hydrogen demand is small. As the demand grows, more of the hydrogen could be produced for vehicle fuel rather than used for power production.

Much of the research is applicable to several of the production options. For example, advanced technology for reforming, shift, hydrogen separations, and hydrogen purification broadly applies to natural gas, coal, and biomass feedstocks and to both distributed and central production situations. Advanced hydrogen separation and purification technology is also common to many hydrogen production routes.

The Hydrogen Production Program element will develop the technologies to produce hydrogen for transportation and stationary applications. System validations will be performed by the Technology Validation Program element. Results of validation projects will guide continued R&D efforts.

3.1.3 Programmatic Status

Current Activities

Major Hydrogen Production Program element activities are listed in Table 3.1.1.

Table 3.1.1. Major Hydrogen Production Program Element Activities

Challenge	Approach	Activities
Cost reduction of distributed hydrogen production from natural gas and renewable liquids	- Improve reforming and separation efficiencies - Identify more durable reforming catalysts - Incorporate breakthrough separations technology - Reduce space needed - Optimize system operation - Intensify and consolidate the number of steps, unit operations	**Praxair:** Low-cost production platform using design for manufacture and assembly **Air Products and Chemicals Inc:** Hydrogen refueling station using advanced natural gas steam methane reforming technologies **General Electric:** Fuel-flexible autothermal cyclic reformer **National Renewable Energy Laboratory (NREL):** Lower-cost technology for distributed reforming of biomass pyrolysis-derived bio-oils **Pacific Northwest National Laboratory (PNNL):** Lower-cost technology to reform biomass-derived liquids such as sugars, sugar alcohols, and ethanol via liquid-phase or gas-phase reforming **Argonne National Laboratory (ANL):** Novel technology to reform natural gas using high-temperature membranes and water splitting **ANL:** High-pressure ethanol reforming technology combined with more efficient separations and purification **Virent Energy Systems, LLC, U. of Wisconsin, Archer Daniels Midland, UOP:** Novel one-step liquid-phase reforming of carbohydrates **H_2Gen Innovations, Süd-Chemie, Inc., Naval Research Lab :** Advanced Steam Methane Reformer and Pressure Swing Adsorption Turn-Key Hydrogen Production System **GE Global Research, University of Minnesota, Argonne National Laboratory:** Integrated short-contact-time natural gas/bio-derived feedstock, compact reformer **The BOC Group, Inc., Membrane Reactor Technologies Ltd., HERA USA Inc.:** Integrated hydrogen production, purification and compression system **Ohio State University Research Foundation:** Ethanol steam reforming
Biomass-to-hydrogen	- Develop advanced, lower-cost reforming technologies for hydrogen production from biomass gasification/pyrolysis	**Gas Technology Institute, NETL, U. of Cincinnati, Allegheny Technology Company:** Novel technology for one-step gasification, reforming, shift, and H_2 separation **United Technologies Research Center, U. of North Dakota:** Innovative integrated slurry-based biomass hydrolysis and reforming process for low-cost hydrogen production

Biological production of hydrogen[5]	• Develop modifications to green algae, cyanobacteria, photosynthetic bacteria, and dark fermentative microorganisms that will facilitate efficient production of hydrogen • Develop biochemical and process methods to facilitate efficient production of hydrogen • Identify and develop cost-effective components such as transparent, hydrogen-impermeable materials for photoreactors	**NREL, Oak Ridge National Laboratory (ORNL), UC Berkeley, IBEA, Montana State University, and Advanced Bionutrition**: Identification of the physical and chemical variables needed to optimize biological systems based on new algal, cyanobacterial, photosynthetic bacterial, and dark fermentative microorganism strains; research the feasibility of various materials for photoreactors **Benneman Associates:** High-rate and yield hydrogen fermentation (SBIR)
Photoelectrochemical hydrogen production from water (direct water splitting)[5]	• Develop high-efficiency materials • Improve the durability of materials • Develop photoelectrochemical devices and systems • Identify and develop cost-effective components such as transparent, hydrogen-impermeable materials for photoreactors	**NREL, University of Hawaii, UC Santa Barbara, SRI, MV Systems, GE Global Research, and Midwest Optoelectronics:** Identify and develop durable and efficient photoelectrochemical material(s), devices and systems
Hydrogen production from water via electrolysis	• Reduce electricity costs of hydrogen production by developing new materials and systems to improve efficiency • Reduce capital costs of electrolysis system through new designs with lower cost materials • Develop low-cost hydrogen production from electrolysis using wind and other renewable electricity sources	**Teledyne Energy Systems:** New alkaline electrolysis materials for higher efficiencies and pressures **Proton Energy Systems:** Higher pressure PEM electrolysis system and renewable integration **Giner Electrochemical Systems:** PEM electrolysis system capable of electrochemical pressurization to 5000 psi with reduced capital costs; low-cost solid membranes (SBIR) **Arizona State University:** Combinatorial development of water-splitting catalysts for high efficiency electrolysis **Ceramatec, Inc.**: Large area cell for hybrid solid oxide hydrogen co-generation process **General Electric:** High-temperature reversible electrolysis materials and system development **SRI International:** Modular high-temperature system for hydrogen generation **National Renewable Energy Laboratory:** Research on renewable electrolysis power electronics integration **Sandia National Laboratory:** New high-efficiency, high-current-density alkaline membrane and electrode materials **Avalence:** High-efficiency ultra high-pressure electrolysis with direct linkage to photovoltaic arrays (SBIR) **Ceramatec, Inc.:** Novel bidirectional power controller for regenerative fuel cells.

---

[5] In collaboration with DOE Office of Science.

High-temperature, solar-driven thermochemical cycles for splitting water to produce hydrogen[6]	•Utilize the high-temperature energy from concentrated solar power to produce hydrogen through thermochemical cycles	**Stirling Energy Systems, Inc., U. of Alabama, Weizmann Institute, CT LLC, U. of Massachusetts-Boston:** Novel technology for solar-powered, low-voltage, high-efficiency production of hydrogen from water **Science Applications International Corporation, Florida Solar Energy Center, U. of Turabo, U. of Central Florida:** Evaluation of solar-driven carbon dioxide cycles for hydrogen production; pilot-scale testing of most promising system **University of Colorado:** Manganese-based solar-driven high-temperature thermochemical cycle to split water
Separation and purification systems (cross-cutting research)[7]	• Develop separation technology for distributed and central hydrogen production	**Praxair:** Integrated ceramic membrane system **Sandia National Laboratories (SNL):** Defect-free thin film membranes for hydrogen separation and purification **Oak Ridge National Laboratory (ORNL):** Inorganic membrane porous support tube fabrication and pyrochlore/perovskite ion transport membrane **Media and Process Technologies, Johnson Matthey Catalyst, ChevronTexaco, University of Southern California**: Carbon molecular sieve; membrane in a single-step shift reactor **Pall Corporation, ChevronTexaco, Colorado School of Mines, Oak Ridge National Laboratory:** Palladium alloy membrane **U. of Cincinnati, Ohio State University, New Mexico Institute of Technology:** Zeolite membrane reactor for single-step water gas shift reaction

3.1.4 Technical Challenges

The overarching technical challenge to hydrogen production is reducing cost. Hydrogen currently (as of 2003) costs $5/gge delivered to a car at a refueling station (see Table 3.1.2) based on distributed production using natural gas, compared to the goal of $1.50/gge (untaxed) in 2010. Estimates of the delivered cost of hydrogen using currently available technology for all production feedstocks is considerably higher than that required for hydrogen to be a cost-competitive primary energy carrier.

The capital costs of current electrolysis systems, along with the high cost of electricity in many regions, limit widespread adoption of electrolysis technology for hydrogen production. Electrolyzer capital cost reductions and efficiency improvements are required along with the design of utility-scale electrolyzers capable of grid integration and compatible with low-cost, near-zero emission electricity sources. Electrolytic production of hydrogen, where coal is the primary energy resource, will not lead to carbon reduction without carbon sequestration technologies.

Hydrogen can be produced from biomass either by distributed reforming of bio-derived liquids or through gasification or pyrolysis of biomass feedstocks. The costs of currently-available bio-derived liquids such as ethanol or sugar alcohols (e.g. sorbitol) need to be reduced. Significant improvements in ethanol reforming and new technologies need to be developed for other bio-derived liquids to reduce the capital and operating costs

---

[6] In collaboration with DOE Office of Nuclear Energy, Science and Technology.

[7] In collaboration with DOE Office of Fossil Energy.

for this production option to become competitive. The efficiencies of biomass gasification or pyrolysis and reforming need to be increased and the capital costs need to be reduced by developing improved technologies and approaches.

Biological hydrogen production is in an early stage of research and presents many technical challenges, beginning with molecular engineering of microorganisms that can produce hydrogen at high rates. However, the advantages of biological hydrogen production are that high-purity water is not required and toxic or polluting byproducts are not generated.

Photoelectrochemical hydrogen production (direct water splitting), also in an early stage of development, depends on a breakthrough in materials development and could require large areas of land. Research in this area is progressing on three fronts: 1) the study of high-efficiency materials in order to attain the basic science understanding needed for improving lower-efficiency lower-cost materials; 2) the study of low-cost durable materials in order to attain the basic science understanding needed for modifying higher-efficiency lower-durability materials; and 3) the development of multijunction devices incorporating multiple material layers to achieve efficient water splitting.

High-temperature, solar-driven, thermochemical hydrogen production using water-splitting chemical cycles is in an early stage of research. Research is also needed to cost-effectively couple the thermochemical cycles with advanced concentrated solar power technology. If these efforts are successful, high-temperature thermochemical processes may provide a clean, efficient, and sustainable route for producing hydrogen from water.

3.1.4.1 Technical Targets

A variety of feedstocks and processes are being researched and developed for producing hydrogen fuel. Each technology is in a different stage of development, and each offers unique opportunities, benefits, and challenges. Economics favor certain technologies more than others in the near term, but other technologies are expected to become economically viable as the technologies mature and market conditions shift.

Tables 3.1.1 through 3.1.12 list the DOE technical targets for hydrogen production from a variety of feedstocks. All targets were developed through preliminary hydrogen production analyses and will be refined further as the technology matures and trade-offs are identified. The targets and timeline for each technology reflect a number of factors, including the expected size of a production unit, the stage of technology development, and the costs and characteristics of the feedstock.

Targets for 2010 and 2015 are R&D milestones for measuring progress and are not necessarily the targets required for successful commercialization of the technology. For hydrogen to become a major energy carrier, the combination of its cost and that of the power system it is used in, must be competitive with the alternatives available in the market. For personal transportation light duty vehicles, this means that the combination of the hydrogen cost, and its use in a hydrogen fuel cell vehicle, must be competitive with gasoline internal combustion engine powered vehicles, or other alternatives, on a cost/mile basis to the consumer. The estimated cost of hydrogen needed to be competitive with gasoline is $1.50/gge delivered (untaxed) at the dispenser. This estimate is currently being re-evaluated to reflect projected fuel costs and vehicle power system energy efficiencies on a cost per mile basis. The ultimate target for all of the production technologies being researched is a hydrogen cost that will be competitive for transportation on a well-to-wheels basis, regardless of the production pathway.

All targets must be achieved simultaneously; however, status is not neccessarily reported from a single system.

Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas [a, b]

Characteristics	Units	Calendar Year 2003[c] Status	Calendar Year 2005[d] Target	Calendar Year 2010[d] Target
Total Energy Efficiency[e]	%(LHV)	65.0	65.0	75.0
Production Energy Efficiency	%(LHV)	69.0	69.0	80.0
Storage, Compression, and Dispensing Energy Efficiency[f]	%(LHV)	94.0	94.0	94.0
Total Hydrogen Cost	\$/gge H_2	5.00	3.00	1.50
Detailed Cost Breakdown – These calculations are for guidance only and not necessarily the research targets to achieve the total energy efficiency and cost goals.				
Capital Cost Contribution	\$/gge H_2	2.70	1.40	0.30
Production	\$/gge H_2	1.90	0.60	0.10
Storage, Compression, Dispensing[f]	\$/gge H_2	0.80	0.80	0.20
Fixed O&M Cost Contribution	\$/gge H_2	1.20	0.60	0.30
Feedstock Cost Contribution	\$/gge H_2	0.90	0.80	0.70
Other Variable O&M Cost Contribution	\$/gge H_2	0.20	0.20	0.20

[a] Economic parameters used were for a production design capacity of 1500 kg/day of hydrogen: 20 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, and MACRS 7-year depreciation. A 70% capacity factor was used for 2003 and 2005. A 90% capacity factor was used for 2010. The results in 2000\$ were inflated by 6% to yield 2003\$.

[b] The natural gas price was set to \$4.50/MMBTU in 2000\$, based on the levelized price for natural gas between 2005 and 2025 based on the EIA AEO 2004 for industrial rates. The electricity price was set at \$.07/kWhr in 2000\$ based on the levelized price between 2005-2025 based on the EIA AEO 2004 for commercial rates.

[c] For the 2003 analysis it was assumed the units would be built a few at a time.

[d] For the 2005 and 2010 analysis it was assumed that Design for Manufacture and Assembly (DFMA) would be employed and that on the order of 500 units per year would be produced.

[e] Energy efficiency is defined as the energy of the hydrogen out of the process (LHV) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed. The electrical energy utilized does not include the efficiency losses from the production of the electricity.

[f] Storage capacity for 1100 kg of hydrogen at the forecourt is included. It is assumed that the required hydrogen pressure for refueling is 5000 psi for 2003 and 2005. It is assumed that in 2015, the pressure for hydrogen refueling is 1500 psi.

Table 3.1.3. Technical Targets: Distributed Production of Hydrogen from Bio-Derived Renewable Liquids [a,b]

Characteristics	Units	Calendar Year			
		2003[c] Status	2005[c] Target	2010[c] Target	2015[d] Target
Total Energy Efficiency[e]	%	46.0	46.0	66.0	70.0
Production Energy Efficiency	%	49.0	49.0	70.0	
Storage, Compression, Dispensing Energy Efficiency[f]	%	94.0	94.0	94.0	
Total Hydrogen Cost	$/gge	6.70	5.90	3.60	2.50
Detailed Cost Breakdown – These calculations are for guidance only and not necessarily the research targets to achieve the total energy efficiency and cost goals.					
Capital Cost Contribution	$/gge	1.90	1.30	0.90	
Production	$/gge	1.10	0.50	0.50	
Storage, Compression, Dispensing[f]	$/gge	0.80	0.80	0.40	
Fixed O&M Cost Contribution	$/gge	0.70	0.50	0.40	
Feedstock Cost Contribution[g]	$/gge	3.80	3.80	1.80	
Other Variable O&M Cost Contribution	$/gge	0.30	0.30	0.50	

[a] Economic parameters used were 20 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, MACRS 7-year depreciation, 70% capacity factor. 2000$ calculations were inflated by 6% to yield 2003$.

[b] The electricity price was set at $.07/kWhr in 2000$ based on the levelized price between 2005-2025 based on the EIA AEO 2004 for commercial rates.

[c] The 2003 status, 2005, and 2010 target are based on an initial analysis of distributed reforming of ethanol at a design capacity of 1500 kg/day of hydrogen based on available information.

[d] The 2015 target is based on what might be achievable with breakthroughs in technology and alternative bio-derived renewable liquids.

[e] Energy efficiency is defined as the energy of the hydrogen out of the process (LHV) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed. The electrical energy utilized does not include the efficiency losses from the production of the electricity.

[f] Storage capacity for 1100 kg of hydrogen at the forecourt is included. It is assumed that the required hydrogen pressure for refueling is 5000 psi for 2003 and 2005. It is assumed that in 2015, the pressure for hydrogen refueling is 1500 psi.

[g] For 2003 and 2005 the price of ethanol used is $1.15/gallon in 2003$. This is a typical price for ethanol in the fuel market over the past 5 years. For 2010, the price of ethanol used is $.85/gallon in 2003$. It is assumed that this cost reduction is possible based on using less purified and wet ethanol (i.e. only using a single distillation step rather than two distillation steps and molecular sieve drying currently used in ethanol manufacture from corn), further improvements in ethanol production from corn and/or the introduction of other lower cost ethanol production technology such as from cellulosic biomass.

Table 3.1.4. Technical Targets: Water Electrolysis[a]

			1500 kg/day refueling station			Central Renewable[b]
Characteristics		Units	2003 Status	2005 Target	2010 Target	2015 Target
Power Conversion, Cell Stack, Balance of Plant[c]	Cost	\$/gge H_2	0.95	0.80	0.39	0.24
	Total Cell Efficiency	%	66	68	76	77
Compression, Storage, Dispensing[d]	Cost	\$/gge H_2	0.83	0.77	0.19	0.08
	Efficiency	%	94	94	99	99.5
Electricity[e]	Cost	\$/gge H_2	2.57	2.47	1.89	1.32
O&M	Cost	\$/gge H_2	0.80	0.71	0.38	0.11
Total[f]	Cost	\$/gge H_2	5.15	4.75	2.85	2.75[g]
	Efficiency	%	62	64	75	76

[a] Economic parameters used were: 20 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, MACRS 7-year depreciation, 70% capacity factor. The H2A results in 2000$ were inflated by 6% to yield 2003$.

[b] Renewable Option: Calculation base on delivering 50,000 gge hydrogen per day (1000+ gge modules) with option of electricity co-production. Electricity back up provided by grid.

[c] Includes power conversion, cell stack and balance of plant (efficiency based on AC electric input to hydrogen output on a LHV basis).

[d] Compression improvements result from integral electrochemical or other system compression to reduce or eliminate mechanical compression. Lower pressure storage assumed in 2015.

[e] Electricity at EIA projected industrial electricity rate for 2003-2005. $.04 per kWh assumed in 2010 based on regional industrial electricity rate and new renewable technologies on the grid. $.03 per kWh assumed in 2015 with central wind and grid back up. $.03 per kWh also corresponds to the Office of Wind and Hydropower 2012 production cost goal for class 4 wind resources.

[f] Based on system capital cost per kWe of $700, $600 and $250 for the refueling station in 2003, 2005 and 2010, respectively, and $200 for the central station in 2015. Assumes high volume annual production (1,000 units for all purposes and all markets) of electrolyzer units in 2010-2015 and centralized facility benefiting from scale on installation.

[g] Includes $1.00 per gge delivery charge (transportation to the station, hauling and dispensing).

Hydrogen separation is a key component that cross-cuts most, if not all of the hydrogen production technology options. The separation membranes described in Tables 3.1.5 and 3.1.6 have multiple applications requiring an array of system configurations. Separations systems that best reduce the cost to produce hydrogen more efficiently from diverse feedstocks will be downselected. These separations sub-system components must be optimized to achieve the cost and hydrogen quality requirements. Tables 3.1.5 and 3.1.6 present targets for three major hydrogen separation technology pathways and reflect the current stage of development for each as well as the need to achieve performance requirements within the timeframe of the 2015 commercialization decision. The performance requirements presented are based on a preliminary set of assumptions with regard to system configuration (feedstock composition, temperature, pressure, and product composition). Ultimately, though, success will be determined based on analysis of the actual system configuration and its requirements.

Table 3.1.5. Technical Targets: Dense Metallic Membranes for Hydrogen Separation and Purification

Performance Criteria[a]	Units	Calendar Year			
		2003 Status[b]	2005 Target	2010 Target	2015 Target
Flux Rate[c]	scfh/ft^2	60	100	200	300
Membrane Material and All Module Costs[d]	\$/ft^2 of membrane	2,000	1,500	1,000	<500
Durability[e]	hr	<8,760[f]	8,760	26,280	>43,800
ΔP Operating Capability[g]	psi	100	200	400	400-1,000
Hydrogen Recovery	% of total gas	60	>70	>80	>90
Hydrogen Quality[h]	% of total (dry) gas	>99.9	>99.9	>99.95	99.99

[a] The membranes must be tolerant to impurities. This will be application specific. Common impurities include sulfur and carbon monoxide.

[b] Based on membrane shift reactor with syngas.

[c] Flux at 20 psi hydrogen partial pressure differential with a minimum permeate side total pressure of 15 psi, preferably >50 psi and 400 ^{o}C.

[d] The membrane support structure is approximately three times membrane material costs.

[e] Intervals between membrane replacement.

[f] Hydrogen membranes have not been demonstrated to date, only laboratory tested.

[g] Delta P operating capability is application dependent. There are many applications that may only require 400 psi or less. For coal gasification 1000 psi is the target.

[h] Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787.

Notes: Revised targets take into consideration input received at the September, 2004 H_2 Separations Workshop. These targets are undergoing detailed engineering analysis. Membrane systems should be demonstrated within a temperature range between 250-1,000 degrees Celsius. Also, parasitic power requirements (that used to recompress the hydrogen downstream of the membrane due to potential pressure drops across the membrane) should be minimized.

Table 3.1.6 Technical Targets: Microporous Membranes for Hydrogen Separation and Purification

Performance Criteria[a]	Units	2003 Status	2005 Target	2010 Target	2015 Target
Flux Rate[b]	scfh/ft^2	100	100	200	300
Membrane Material and All Module Costs[c]	\$/ft^2 of Membrane	450-600	400	200	<100
Durability[d]	hr	<8,760[e]	8,760	26,280	>43,800
ΔP Operating Capability[f]	psi	100	200	400	400-1000
Hydrogen Recovery	% of total gas	60	>70	>80	>90
Hydrogen Quality[g]	% of total (dry) gas	$\geq$90	95	99.5	99.99

[a] The membranes must be tolerant to impurities. This will be application specific. Common impurities include sulfur and carbon monoxide.

[b] Flux at 20 psi hydrogen partial pressure differential with a minimum permeate side total pressure of 15 psi, preferably >50 psi and 400 ^{O}C.

[c] The membrane support structure cost is approximately three times more than membrane material costs.

[d] Intervals between membrane replacement.

[e] Hydrogen membranes have not been demonstrated to date, only laboratory tested.

[f] Delta P operating capability is application dependent. There are many applications that may only require 400 psi or less. For coal gasification 1000 psi is the target.

[g] Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787.

Note: Revised targets take into consideration input received at the September, 2004 H_2 Separations Workshop. These targets are undergoing detailed engineering analysis. Membrane systems should be demonstrated within a temperature range between 250-1,000 Degrees Celsius. Also, parasitic power requirements (that used to recompress the hydrogen downstream of the membrane due to potential pressure drops across the membrane) should be minimized.

Table 3.1.7. Technical Targets: Biomass Gasification/Pyrolysis Hydrogen Production[a]

Characteristics	Units	Calendar Year			
		2003 Status	2005 Target	2010 Target	2015 Target
Energy Efficiency[b]	%	44	47	50	52
Total Hydrogen Cost	\$/gge H_2	2.10	1.90	1.75	1.60
Detailed Cost Breakdown – These calculations are for guidance only and not necessarily the research targets to achieve the total energy efficiency and cost goals.					
Capital Cost Contribution	\$/gge H_2	0.70	0.60	0.55	0.50
Feedstock Cost Contribution[c]	\$/gge H_2	0.70	0.65	0.60	0.50
Fixed O&M Cost Contribution	\$/gge H_2	0.40	0.40	0.35	0.35
Other Variable O&M Cost Contribution	\$/gge H_2	0.30	0.25	0.25	0.25

[a] Economic parameters used were: 40 yr. analysis period, 10% IRR after taxes, 100% equity financing, 1.9% inflation, 38.9% total tax rate, MACRS 20-year depreciation. The results in 2000$ were inflated by 6% to yield 2003 dollars. These costs are at the plant gate. The cost target for delivery of hydrogen from the plant gate to the point of refueling at a refueling station in 2015 is $1.00/gge (See Section 3.2).

[b] Energy efficiency is defined as the energy of the hydrogen out of the process (LHV) divided by the sum of the energy into the process from the feedstock (LHV) and all other energy needed. The electrical energy utilized does not include the efficiency losses from the production of the electricity.

[c] For 2003 and 2005 a biomass feedstock cost of $46/dry ton in 2000$ was used. For 2010 a feedstock cost of $44/dry ton was used. For 2015 a feedstock cost of $42/dry ton was used.

Table 3.1.8. Technical Targets: Photolytic Biological Hydrogen Production from Water[a]

Characteristics	Units	2003 Status	2010 Target[b]	2015 Target[c,d]
Utilization Efficiency of Incident Solar Light Energy (E0*E1)[e]	%	10	15	20
Efficiency of Incident Light Energy to Hydrogen from Water (E0*E1*E2)[f]	%	0.1	2	5
Duration of Continuous Photoproduction[g]	Time Units	not available[g]	30 min	4 hr
O_2 Tolerance (half life in air)	Time Units	1 sec	10 min	2 hr

$$\text{Solar Light} \xrightarrow{E0} \text{Absorbed Light} \xrightarrow{E1} \text{Electrons} \xrightarrow{E2} H_2$$

[a] Hydrogen cost will be evaluated as part of the research and development Go/No-Go decision in 2015 (see Appendix B). The targets in this table are for research tracking. The final targets for this technology are to reach costs that are competitive with traditional fuels for transportation applications and with other hydrogen production technologies.

[b] 2010 target is based on analysis of best technologies available, theoretically integrated into a single organism.

[c] 2015 targets are based on analysis of best technologies available, actually integrated into a single organism.

[d] Near commercialization targets (beyond 2015) are 25% utilization efficiency of incident solar light energy (E0*E1), 10% efficiency of incident light energy to H_2 from water (E0*E1*E2), ≥12h (O_2 tolerant) duration of continuous photoproduction, and 6h O_2-tolerance (half-life in air).

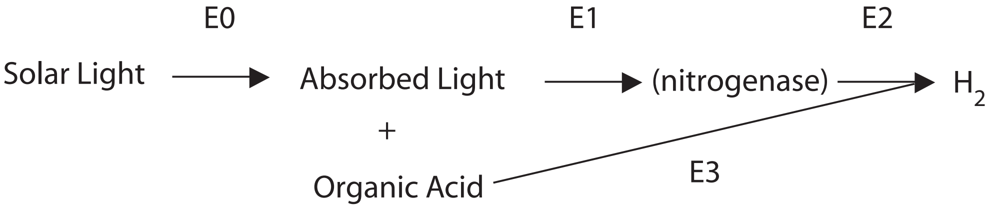
[e] E0 reflects the light collection efficiency of the photoreactor and the fact that only a fraction of solar incident light is photosynthetically active (theoretical maximum is 45%). E1 is the efficiency with which algae convert the energy of absorbed photons to chemical energy (i.e. chemical potential; theoretical maximum is 71%). E0*E1 represents the efficiency of conversion of incident solar light to chemical potential (theoretical maximum is 32%).

[f] E2 reflects the efficiency with which the chemical potential generated by the absorbed photons is converted to hydrogen (theoretical maximum is 41%). E0*E1*E2 represents the efficiency of conversion of incident solar light to H_2 (theoretical maximum is 13% when water is the substrate); only peak efficiencies are meant.

[g] Duration reflects continuous production in the light, not necessarily at peak efficiencies. Targets reflect oxygen tolerant system.

Table 3.1.9. Technical Targets: Photosynthetic Bacterial Hydrogen Production[a]

Characteristics	Units	2003 Status	2010 Target	2015[b] Target
Efficiency of Incident Solar Light Energy to H_2 (E0*E1*E2)[c] from organic acids	%	1.9[d]	3	4.5
Molar Yield of Carbon Conversion to H_2 (depends on nature of organic substrate) E3[e]	% of maximum	42[e]	50	65
Duration of continuous photoproduction[f]	Time	6 days[g]	30 days	3 months



[a] Hydrogen cost will be evaluated as part of the research and development Go/No-Go decision in 2015 (see Appendix B). The targets in this table are for research tracking. The final targets for this technology are to reach costs that are competitive with traditional fuels for transportation applications and with other hydrogen production technologies.

[b] Near commercialization targets (beyond 2015) are 5.5% efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, 80% of maximum molar yield of carbon conversion to H_2 (depends on nature of organic substrate) E3, and 6 months duration of continuous photoproduction.

[c] E0 reflects the light collection efficiency of the photoreactor and the fact that only a fraction of incident solar light is photosynthetically active (theoretical maximum is 68%, from 400 to 1000 nm). E1*E2 is equivalent to the efficiency of conversion of absorbed light to primary charge separation then to ATP; both are required for hydrogen production via the nitrogenase enzyme. E0*E1*E2 represents the efficiency of conversion of incident solar light to hydrogen through the nitrogenase enzyme (theoretical maximum is 10% for 4-5 electrons). This efficiency does not take into account the energy used to generate the carbon substrate.

[d] Average from data presented by Akkerman, I., M. Janssen, J. Rocha, and R. H. Wijffels. 2002. Intl. J. Hydrogen Energy 27: 1195-1208.

[e] E3 represents the molar yield of H_2 per carbon substrate (the theoretical maximum is 7 moles per mol carbon in the substrate, in the case of acetate and butyrate). Average of data presented by Koku, H., I. Eroglu, U. Gunduz, M. Yucel, and L. Turker. 2002. Intl. J. Hydrogen Energy 27: 1315-1329.

[f] Duration reflects continuous production in the light, not necessarily at peak efficiencies. It includes short periods during which ammonia is re-added to maintain the system active.

[g] Average from data presented by Koku, H., I. Eroglu, U. Gunduz, M. Yucel, and L. Turker. 2002. Intl. J. Hydrogen Energy 27: 1315-1329.

Table 3.1.10. Technical Targets: Dark Fermentative Hydrogen Production[a]

Characteristics	Units	2003 Status	2010 Target	2015 Target[b]
Yield of H_2 production from glucose[c]	$\frac{\text{mol } H_2}{\text{mol glucose}}$	2[d]	4	6
Feedstock Cost[e]	cents/lb sugar	13.5	10	8
Duration of continuous production	Time	17days[f]	3 months	6 months

[a] Hydrogen cost will be evaluated as part of the research and development Go/No-Go decision in 2015 (see Appendix B). The targets in this table are for research tracking. The final targets for this technology are to reach costs that are competitive with traditional fuels for transportation applications and with other hydrogen production technologies.

[b] Near commercialization targets (beyond 2015) are 10 molar yield of H_2 Production from glucose, 6 cents/lb sugar feedstock cost, and 12 months duration of continuous production.

[c] The theoretical maximum from known fermentative pathways is 4, although the H_2 content of 1 mole of glucose is 12. Clearly, in order to achieve molar yields greater than 4, the feasibility of developing new pathways or discovering new microbes needs to be assessed.

[d] DOE Workshop on Hydrogen Production via Direct Fermentation (June 2004) and Boundary Analysis for H_2 Production by Fermentation, publications in preparation.

[e] Targets set by the DOE Biomass Program for glucose from lignocellulosic biomass. NREL Report TP-510-32438 http://www.nrel.gov/docs/fy02osti/32438.pdf; NREL E Milestone #586, May 2004.

[f] Van Ginkel, S., and S. Sung. 2001. Environ. Sci. Technol.,35: 4726-4730.

Table 3.1.11. Technical Targets: Photoelectrochemical Hydrogen Production[a]

Characteristics	Units	2003 Status	2010 Target	2015 Target[b]
Usable semiconductor bandgap[c]	eV	2.8	2.3	2.0
Chemical conversion process efficiency (EC)[d]	%	4	10	12
Plant solar-to-hydrogen efficiency (STH)[e]	%	not available	8	10
Plant durability[f]	hr	not available	1000	5000

[a] Hydrogen cost will be evaluated as part of the research and development Go/No-Go decision in 2015 (see Appendix B). The targets in this table are for research tracking. The final targets for this technology are to reach costs that are competitive with traditional fuels for transportation applications and with other hydrogen production technologies.

[b] Near commercialization targets (beyond 2015) are 16% plant solar-to-hydrogen efficiency (STH) and 15,000 hours plant durability.

[c] The bandgap of the interface semiconductor establishes the photon absorption limits. Useable bandgaps correspond to systems with adequate stability, photon absorption and charge collection characteristics for meeting efficiency, durability and cost targets.

[d] EC reflects the process efficiency with which a semiconductor system can convert the energy of absorbed photons to chemical energy [based on AM (Air Mass) 1.5 insolation] and is a function of the bandgap, IPEC and electronic transport properties. A multiple junction device may be used to reach these targets.

[e] Solar-to-hydrogen (STH) is the projected plant-gate solar-to-hydrogen conversion efficiency based on AM (Air Mass) 1.5 insolation. Both EC and STH represent peak efficiencies, with the assumption that the material systems are adequately stable.

[f] Durability reflects projected duration of continuous photoproduction, not necessarily at peak efficiencies.

Table 3.1.12. Solar-Driven High-Temperature Thermochemical Hydrogen Production[a]

Characteristics	Units	2005 Target	2010 Target	2015 Target
Solar-Driven High-Temperature Thermochemical Cycle Hydrogen Cost	$/gge H_2	10	6	3
Solar Concentrator Capital Cost (installed cost)[b]	$/m^2	200	170	130
Process Energy Efficiency[c]	%	30	40	45

[a] Based on initial analysis. Two potential high temperature cycles were examined: the Westinghouse modified sulfur cycle with electrolysis, and a zinc oxide cycle. The capacity basis was central production of 150,000 kg/day of hydrogen. All targets are expressed in 2003 dollars. These costs are at the plant gate. The cost target for delivery of hydrogen from the plant gate to the point of refueling at a refueling station in 2015 is $1.00/gge (See Section 3.2)

[b] These capital cost targets are consistent with those of the EERE Solar Program for a heliostat field and tower. They do not include the receiver.

[c] The process energy efficiency is defined as the energy of the hydrogen produced (LHV) divided by the sum of the energy from the solar concentrator plus any other net energy required for the process. The solar concentrator energy efficiency targets are the same as for the EERE Solar Program.

3.1.4.2 Barriers

The following sections detail the technical and economic barriers that must be overcome to attain the Hydrogen Production goal and objectives. The barriers are divided into sections depending on the hydrogen production method.

3.1.4.2.1 Distributed Hydrogen Production from Natural Gas or Renewable Liquid Feedstocks

A. **Fuel Processor Capital Costs**. Current small-scale distributed natural gas and renewable liquid feedstock reforming technologies have capital costs that are too high to achieve the targeted hydrogen production cost. Multiple unit operations and low energy efficiencies are key contributors to the high capital costs. Improved reforming and shift catalysts are needed to reduce side reactions and improve performance. Shift, separation, and purification costs need to be reduced. Process intensification by combining steps could significantly reduce costs. For example, combining the current two step shift and PSA separation into a one-step shift with integrated hydrogen separation could significantly reduce capital costs.

B. **Fuel Processor Manufacturing.** Distributed reforming units are currently designed and built one at a time, particularly for large industrial applications. Efforts such as Design for Manufacture and Assembly (DFMA) need to be applied to develop more compact, appliance-type units that can be produced using low-cost, high-throughput manufacturing methods.

C. **Operation and Maintenance (O&M)**. O&M costs for distributed reforming hydrogen production from natural gas and renewable feedstocks are too high. Robust systems that require little maintenance and that include remote monitoring capability need to be developed.

D. **Feedstock Issues**. Availability of some feedstocks is limited in certain areas. Feedstock-flexible reformers are needed to address location-specific feedstock supply issues. Effects of impurities on the system from multiple feedstocks as well as the effects of impurities from variations in single feedstocks need to be addressed in the reformer design.

E. **Carbon Dioxide Emissions**. Distributed natural gas reformers emit greenhouse gases. Cost-effectively sequestering these relatively smaller volume and highly distributed carbon emissions is significantly more challenging than at central hydrogen production facilities that use fossil fuels. Feedstocks and/or technologies that can approach near zero net greenhouse gas emissions are needed.

F. **Control and Safety.** Control and safety issues are associated with natural gas and renewable feedstock reforming, including on-off cycling. Effective operations control strategies are needed to minimize cost and emissions, maximize efficiencies, and enhance safety. Hydrogen leakage is addressed within the Delivery and Safety Program elements.

3.1.4.2.2 Hydrogen Generation by Water Electrolysis

G. **Capital Cost**. The capital costs of electrolysis systems are prohibitive to widespread adoption of electrolysis technology for hydrogen production. R&D is needed to develop lower cost materials with improved manufacturing capability to lower capital while improving the efficiency and durability of the system. Development of larger systems is also needed to improve economies of scale.

H. System Efficiency. New membrane, electrode and system designs are needed to improve system efficiency. Mechanical high-pressure compression technology exhibits low energy efficiency and often reduces hydrogen purity while adding significantly to the system cost. Efficiency gains can be realized using electrochemical compression in the cell stack. Low-cost, high-pressure materials need to be developed to provide integral electrochemical or other high-pressure compression technologies to replace some or all mechanical compression stages. Development is needed for low-cost cell stack optimization considering efficiency, electrochemical compression, and durability.

I. Grid Electricity Emissions. The current grid electricity mix in most locations increases greenhouse gas emissions in large-scale electrolysis systems. Low-cost, carbon-free electricity sources are needed.

J. Renewable Integration. More efficient integration with renewable electricity sources is needed to reduce costs and improve performance. Development of integrated renewable electrolysis systems is needed, including optimization of power conversion and other system components from renewable electricity to provide high-efficiency, low-cost integrated renewable hydrogen production. Novel concepts for carbon-free electrolytic hydrogen production need to be evaluated.

K. Electricity Costs. High-temperature solid oxide electrolysis can use lower cost energy in the form of steam for water splitting to decrease electricity consumption. Technically viable systems for low-cost manufacturing need to be developed for this technology. Electrolysis systems that can produce both hydrogen and electricity need to be evaluated. (Renewable electricity costs will be addressed by the DOE EERE renewable power programs – Solar, Wind, Hydropower, Geothermal and Biomass.)

3.1.4.2.3 Separations and Other Cross-Cutting Hydrogen Production

There are a number of technology options available that can be used to separate and purify hydrogen. The following is a set of broad, cross-cutting barriers that must be overcome to reduce the cost and increase the efficiency of these separation technologies.

L. Durability. Since hydrogen is noncorrosive, special materials of construction are not usually required; however, hydrogen embrittlement occurs in some metals. Hydrogen can embrittle certain types of membranes used in separation technologies, inducing a phase change. Embrittlement reduces the durability and effectiveness of the membrane for selectively separating hydrogen. Thermal cycling can cause failure in some membranes, reducing their durability and operating life. This is especially problematic in distributed applications that are subject to frequent start-up and shut-down cycles. Finally, materials do not perform optimally. Support structures with more uniform pore sizes and less surface roughness are needed to avoid membrane defects. Interactions between membrane and support structure materials need to be better understood. Fundamental materials science work is needed to understand microstructural evolution during operation and effect on membrane permeance, selectivity, and failure modes. Combinatorial methods are needed for rapid testing and evaluation of novel materials and alloys.

M. Impurities. The presence of trace contaminants as well as CO, water, and CO_2 in the exit gas from a gasifier or reformer can reduce the hydrogen flux across different types of membranes. It is not understood whether these effects are caused by competitive adsorption or compositional changes on the membrane surface. Additionally, some membranes exhibit poor thermochemical stability in carbon dioxide environments, resulting in the conversion of membrane materials into carbonates. In solvent systems, impurities can cause less effective absorption and may lead to excessive loss of solvent, which will increase cost. Non-reversible adsorption of impurities onto the surface of metallic membranes can poison the membrane and lead to total failure. Researchers and membrane developers need a better understanding of the concentrations of all trace components in the feed gas stream so that membrane systems can be designed and tested for tolerance to these contaminants. PEM fuel cells require a highly pure hydrogen product containing: CO <1 ppm, CO_2 <100 ppm, S <10 ppb, NH_3 <1 ppm, non-methane hydrocarbons <100 ppm and O_2, N_2, Ar <2%.

N. **Defects.** Oxidizing gas mixtures (oxygen, steam, and carbon oxides) have been observed to cause metallic membranes to rearrange their atomic structure at temperatures greater than 450 ºC. This results in the formation of defects that reduce membrane selectivity for hydrogen. High-temperature and high-pressure seals are difficult to make using ceramic substrates. Seals and joints are a weak link in membrane module construction and one of the most common points of membrane system failure. Large-scale (high-yield, low-cost) manufacturing methods for defect-free thin films and membranes and modules in mass production must be developed and demonstrated. Fabrication of defect-free membranes requires a reduction in membrane deposition cycles. The chemical deposition of thin palladium or palladium-alloy membranes onto support structures is also an important technical challenge. Vapor deposition and solution plating offer the ability to rapidly produce very thin films, but current technologies are defect prone and susceptible to contamination.

O. **Selectivity.** The hydrogen selectivity of microporous membranes is lower than desired for cost-effective use, especially for zeolite-supported membranes where selectivity decreases with increasing temperature (inadequate above 150 ºC). However, temperatures typically need to be greater than 300 ºC in various applications.

P. **Operating Temperature.** Processes that can be designed to operate at or near system conditions, without the need for cooling and/or re-heating, will be more efficient. For example, dense ceramic proton hydrogen separation membranes currently operate only at high temperatures (~900 ºC). Separation systems suitable for distributed reforming of natural gas and renewable liquids are needed. Low temperature systems (< 50 °C) are needed for biological and photoelectrochemical systems.

Q. **Flux.** Flux rates for membranes need to be improved to reduce the membrane size and lower overall cost of hydrogen separation and purification systems.

R. **Testing and Analysis.** Better information is needed to guide researchers and membrane technology developers towards performance targets that are application specific. Standard methods for evaluating and screening membrane materials and modules are needed to provide a solid basis for comparison of alternatives and to conduct needed tests such as accelerated durability tests. Testing under real-world operating conditions is needed to demonstrate durability and robust, reliable performance. Additionally, there is currently a lack of understanding of tradeoffs between different system configurations and operating parameters. Operation at higher temperatures and partial pressure differentials can increase flux rates but results in more expensive membrane modules. Very thin membranes increase flux but they are harder to fabricate defect-free. Analysis is also needed to understand options and tradeoffs for process intensification in different applications.

S. **Cost.** In addition to precious metals, membrane materials and support structures are costly. Even metallic membranes, where small amounts of precious metals are used, are more costly than non-metallic membranes.

T. **Oxygen Separation Technology**. Commercial oxygen separation technology relies on expensive and energy-intensive cryogenic separation. Low-cost oxygen membrane technology needs to be developed for potential use in distributed reforming, biomass gasification/pyrolysis and other hydrogen production technologies.

U. **High-Purity Water Availability**. Impacts on water supplies are not understood. Further analysis is needed.

3.1.4.2.4 Biomass Gasification/Pyrolysis Hydrogen Production

V. **Feedstock Cost and Availability**. Feedstock costs are high. Improved feedstock/agriculture technology (higher yields per acre, etc.), lower cost feedstock collection, and improved feedstock preparation are needed. Because biomass feedstocks are often seasonal in nature, feedstock-flexible processes and/or cost-effective feedstock storage are needed (Tasks to overcome these barriers will be developed by the DOE Biomass Program and the U.S. Department of Agriculture).

W. **Capital Cost and Efficiency of Biomass Gasification/Pyrolysis Technology**. The capital cost for biomass gasification/pyrolysis needs to be reduced. Process intensification by combining steps can significantly reduce capital costs. This could range from combining the current two step shift and PSA separation to a one step shift with integrated separation, to integrating gasification, reforming, shift and separation all in one unit. Improved process efficiency and higher hydrogen yields and selectivities through catalyst research, better heat integration, and alternative gas clean-up approaches are needed. Improved catalysts or engineering approaches for tar cracking are also needed.

3.1.4.2.5 Biological Hydrogen Production

A number of technologies for biological H_2 production are available, but they are not mature at present. Technical barriers related to each individual technology must be overcome, integrated models must be developed, and barriers related to an integrated system must be identified before economic barriers can be meaningfully considered. Methods for engineering and manufacturing these systems have not been fully evaluated. Barriers are listed below for each technology, followed by a model for how these different technologies could be integrated and a list of barriers for the integrated process.

Photolytic H_2 Production from Water (green algae or cyanobacteria):

X. **Light Utilization Efficiency.** The microorganisms used for photobiological H_2 production possess large arrays of light-capturing antenna pigment molecules. Under bright sunlight, pigment antennae absorb much more light than can be utilized by the photosynthetic electron transport apparatus, resulting in heat dissipation and loss of up to 80% of the absorbed sunlight. Research is needed to identify ways to increase the light conversion efficiency, including the identification of better and/or modified photosynthetic organisms for H_2 production.

Y. **Rate of Hydrogen Production.** The current H_2 production rate from photosynthetic microorganisms is too low for commercial viability. The low rates have been attributed to (a) the non-dissipation of a proton gradient across the photosynthetic membrane, which is established during electron transport from water to the hydrogenase (the H_2-producing enzyme) under anaerobic conditions, and (b) the existence of competing metabolic flux pathways for reductant. Genetic means to overcome the restricting metabolic pathways, such as the insertion of a proton channel across the thylakoid membrane, must be used to significantly increase the rate of H_2 production. Under aerobic conditions, with an O_2-tolerant hydrogenase catalyzing H_2 production, the competition between CO_2 fixation and hydrogenase will have to be addressed.

Z. Continuity of Photoproduction. Hydrogen-producing algae co-produce oxygen, which inhibits the hydrogenase enzyme activity. This inhibition needs to be alleviated, possibly by (a) identifying or engineering a less O_2-sensitive enzyme; (b) separating the oxygen and hydrogen production cycles; or (c) affecting the ratio of photosynthesis to respiration (P/R) by a variety of means, such that O_2 does not accumulate in the medium, the quantum yield of photosynthesis is maintained, and full hydrogenase activity is achieved (see details under Integrated System).

AA. Systems Engineering. System requirements for cost-effective implementation of photolytic hydrogen-production technologies have not been adequately evaluated. Analysis and research are needed on inexpensive/transparent materials for H_2 containment, H_2 collection systems, prevention of the build-up of H_2/O_2 gas mixtures, separation of co-produced H_2 and O_2 gases, continuous bioreactor operation, monoculture maintenance, land area requirements and capital costs.

AB. Diurnal Operation Limitations. Photolytic processes are discontinuous because they depend on sunlight, which is unavailable at night and available only at low intensities on cloudy days. This results in increased capital costs for larger facilities to accommodate higher short-term production rates and larger hydrogen storage needs. Engineering options need to be carefully analyzed to minimize capital requirements.

Photosynthetic Bacterial Hydrogen Production, Required for an Integrated System:

AC. Light Utilization Efficiency. Same issues apply as for photolytic systems (see Barrier X).

AD. Rate of Hydrogen Production. Photosynthetic bacteria can metabolize a variety of organic substrates that are waste by-products of various fermentative processes. However, the metabolism of acetic and lactic acids to H_2 also generates by-products such as polymer polyhydroxyalkanoate (PHA). Synthesis of PHA competes with H_2 production for the same source of electron donors. Genes controlling PHA synthesis and perhaps other pathways must be inactivated to maximize H_2 production. Alternative types of nitrogenase are needed to produce larger stoichiometric amounts of H_2/ammonia.

AE. Hydrogen Re-oxidation. Most photosynthetic bacteria contain an H_2-oxidation pathway catalyzed by an uptake hydrogenase enzyme. This enzyme will recycle the H_2 produced by the nitrogenase to support cell growth. Uptake hydrogenase enzyme(s) must be inactivated to ensure net H_2 accumulation by photosynthetic bacteria.

AF. Carbon/Nitrogen Ratio. To maximize nitrogenase activity, the proper ratio of carbon to nitrogen (C/N) nutrients must be maintained. The C/N nutrient content in the photoreactor (algal and cyanobacteria) and in the dark fermentor needs to be evaluated to assess whether the media composition is suitable for subsequent photosynthetic bacterial hydrogen production. Enzyme engineering approaches may be needed to alleviate inhibition of nitrogenase by elevated levels of nitrogen nutrient.

AG. Systems Engineering. The same issues apply as for photolytic systems (see above), except for the mixture of gases. Photosynthetic bacteria do not co-evolve H_2 and O_2 but release H_2 and CO_2. The cost of H_2 and CO_2 separation must be evaluated.

AH. Diurnal Operation Limitation. The same issues apply as for photolytic systems (see Barrier AB).

Dark Fermentative Hydrogen Production, Required for an Integrated System:

AI. H_2 Molar Yield. Up to 4 moles of H_2 can theoretically be produced per mole of glucose through the known fermentative pathways. However, various biological limitations such as H_2-end-product inhibition and waste-acid and solvent accumulation limit the molar yield to around 2 moles per mole glucose consumed. Hydrogen molar yields must be increased significantly through metabolic engineering efforts. New pathways must be discovered to directly take full advantage of the 12 moles of H_2 available in a mole of glucose.

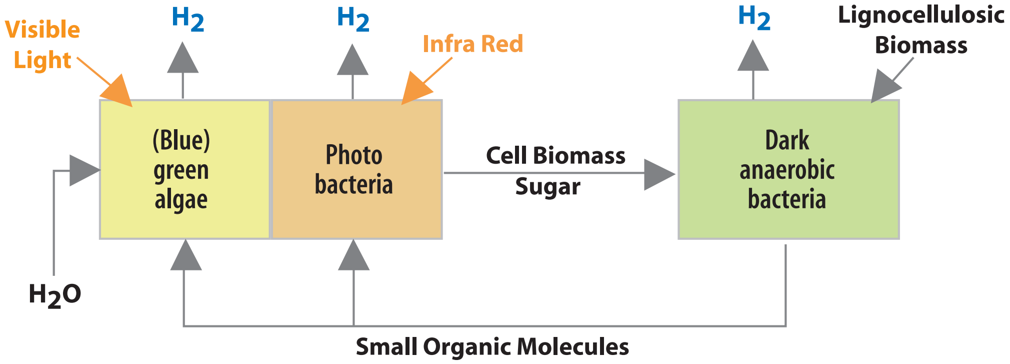
AJ. Waste Acid Accumulation. Organic acids such as acetic and butyric acids are waste by-products of the fermentation process. The production of these acids poses several challenges such as lowering the molar yield of H_2 by diverting the metabolic pathway toward solvent production and requiring subsequent wastewater treatment. Elimination of this pathway or subsequent processing (such as in an integrated biological hydrogen production system) of the organic acids by photosynthetic bacteria is needed to increase hydrogen yields. Potential release of toxins during dark fermentation and their inhibition of the subsequent steps (such as in an integrated system) will need to be evaluated.

AK. Feedstock Cost. The glucose feedstock is the major cost driver for economic H_2 production via fermentation. For renewable H_2 to be cost competitive with traditional transportation fuels, the glucose cost must be around $0.05 per pound and provide a molar yield of H_2 approaching 10 (see Barrier AI and Target Table 3.1.9). Lower-cost methods for producing glucose from whole biomass are needed. Cellulolytic microbes with a high rate of H_2 production are also needed to use the cell biomass of the green algal/cyanobacterial and photosythetic bacterial co-culture (in an integrated biological H_2 production system).

AL. Systems Engineering. The same issues apply as above, plus prevention of methanogen contamination is needed.

Integrated Biological Hydrogen Production System (many configurations are possible, Figure 3.1.2):

Figure 3.1.2. Integrated Biological System



Illustrative Scenario: Anaerobically, co-culture (blue)green algae and photosynthetic bacteria in a photoreactor, and dark anaerobic bacteria in a fermentor. Feedstock for the dark anaerobic bacteria is derived from the cell biomass/sugars of the (blue)green algae and the photosynthetic bacteria. Additional feedstock for the dark anaerobic bacteria is derived from lignocellulosic products. The small organic molecule by-products of the dark anaerobic bacterial fermentation are subsequently utilized as feedstock for the (blue)green algae and photosynthetic bacteria.

AM. Photosynthesis/Respiration Capacity Ratio: Green algae and cyanobacteria become anaerobic when their P/R (photosynthesis/respiration) capacity ratio is 1 or less. Under such anaerobic conditions, photosynthetic water oxidation produces H_2 (instead of starch), and the O_2 evolved by photosynthesis is consumed by respiration, producing CO_2. Currently, this process is achieved by nutrient deprivation, with the drawback that the resulting $P/R \leq 1$ ratio is achieved by partially decreasing the quantum yield of photosynthesis. Alternative mechanisms to bring the P/R ratio to 1 need to be investigated, particularly those methods that focus on achieving a P/R ratio of 1 without changing the quantum yield of photosynthesis. Two further issues will need to be investigated under these conditions: (a) rate limitations due to the non-dissipation of the proton gradient and (b) the ability of the culture to take up a variety of exogenous carbon sources under the resulting anaerobic conditions.

AN. Co-Culture Balance: To extend the absorption spectrum of the H_2-photoproducing cultures to the infrared (700-900 nm), the possibility of co-cultivating oxygenic photosynthetic organisms with anoxygenic photosynthetic bacteria should be investigated. However, in addition to light in the infrared region, photosynthetic bacteria also absorb light in the visible (400 to 600 nm), thus potentially competing with green algae for these latter wavelengths. Strategies need to be devised to either maintain the appropriate biomass ratio of the two organisms as suspensions in the same reactor, or to physically separate them in the same photoreactor via immobilization of one or both cultures. The competition for organic carbon substrates between two organisms in the same medium also needs to be investigated.

AO. Concentration/Processing of Cell Biomass. In an integrated system, cell biomass from either green algae/cyanobacteria or photosynthetic bacteria can serve as the substrate for dark fermentation. The green algal and cyanobacterial cell walls are made mostly of glycoproteins, which are rich in arabinose, mannose, galactose and glucose. Purple photosynthetic bacterial cell walls contain peptidoglycans (carbohydrate polymers cross-linked by protein, and other polymers made of carbohydrate protein and lipid). Pretreatment of cell biomass may be necessary to render it more suitable for dark fermentation. Methods for cell concentration and processing will depend on the type of organism used and how the biological system is integrated.

3.1.4.2.6 Photoelectrochemical Hydrogen Production

Photoelectrochemical hydrogen production, in an early stage of development, depends on a breakthrough in materials development. The primary research in this area is progressing on three fronts: 1) the study of high-efficiency materials to attain the basic science understanding needed for improving lower-efficiency, low-cost materials; 2) the study of low-cost durable materials to attain the basic science understanding needed for modifying higher-efficiency, lower-durability materials; and 3) the development of multijunction devices incorporating multiple material layers to achieve efficient water splitting. Methods of engineering and manufacturing these systems need to be developed in conjunction with the materials and device research.

Current material systems for photoelectrochemical hydrogen production can broadly be divided into three categories, each with its own characteristics and research challenges. These groupings are: (i) stable materials with low visible light absorption efficiency (e.g. oxides), (ii) highly efficient light absorbers with low lifetimes (e.g. III-Vs) and (iii) hybrid and multijunction systems which combine multiple materials in multi-photon devices. The group (i) materials are characterized by high bandgaps and low integrated incident-photon-to-electron conversion (IPEC) over the solar spectrum; the group (ii) materials have very high IPEC (better than 90% throughout the visible spectra), but have low corrosion resistance and poor energetics; and the group (iii) systems can have very high efficiency and long lifetime, depending on the material set, but can be complicated and expensive to build. Research in all three categories is necessary for developing systems that meet the targets reflected in the PEC target table. To date, a range of materials and material systems have met individual 2010 targets of chemical efficiency or durability, but no single material/system has simultaneously met efficiency, durability and cost targets. This is the primary research challenge for photoelectrochemical hydrogen production.

AP. **Materials Efficiency.** Materials with smaller bandgaps more efficiently utilize the solar spectrum, but are often less energetically favorable for hydrogen production because of the bandedge mismatch with respect to either hydrogen or oxygen redox potentials. Materials with appropriate bandedge and bandgap for hydrogen production must be developed.

AQ. **Materials Durability**. Durable materials with the appropriate characteristics for photoelectrochemical hydrogen production that meet the Hydrogen Production Program element goals have not been identified. The high-efficiency materials currently available corrode quickly during operation, and the most durable materials are very inefficient for hydrogen production.

AR. **Bulk Materials Synthesis.** Fabrication techniques for materials identified to have potential for high efficiency, durability and low cost need to be developed on scales consistent with implementation in commercial reactors.

AS. **Device Configuration Designs**. Hybrid and other device designs that combine multiple layers of materials could address issues of durability and efficiency. Techniques are needed for manufacturing appropriate photoelectrochemical materials in these device configurations at commercial scales.

AT. **Systems Design and Evaluation.** System designs incorporating the most promising device configurations, and using cost-effective, hydrogen-impermeable, transparent materials are also needed to implement photolytic production routes. The complete systems evaluation will need to consider a range of important operational constraints and parameters, including the diurnal operation limitations and the effects of water purity on performance and lifetime. Engineering options need to be carefully analyzed to minimize capital requirements.

3.1.4.2.7 High-Temperature Thermochemical, Solar-Driven Production of Hydrogen[6]

AU. **High-Temperature Thermochemical Technology**. There are over 150 possible thermochemical cycles for solar driven water splitting. These cycles need to be evaluated and ranked for their suitability. The most promising cycles need to be more fully explored and verified to down select to a few cycles for research and development. Many of these cycles require the development of technology to either very rapidly quench high temperature reactions and/or separate hydrogen or other materials at high temperatures.

AV. **High-Temperature Robust Materials**. High temperatures are employed in these thermochemical systems. Cost-effective, durable materials are needed that can withstand these high temperatures and the thermal duty cycles present in solar concentrator systems.

AW. **Concentrated Solar Energy Capital Cost**. Concentrated solar energy collection is currently expensive and requires large areas of land. Improved, lower-cost solar concentrator/collection technology, including materials, is needed.[7]

---

[6] DOE's Office of Nuclear Energy, Science and Technology has the lead responsibility for hydrogen production utilizing nuclear energy for high temperature (700°-1000°C) thermochemical water splitting chemical cycles. The Office of Hydrogen, Fuel Cells & Infrastructure Technologies will collaborate with Nuclear Energy, Science and Technology on the thermochemical hydrogen production R&D activities.

[7] The Hydrogen Program will rely on and collaborate with the DOE EERE Solar Program for the advancement of concentrated solar energy technology.

AX. Coupling Concentrated Solar Energy and Thermochemical Cycles. Coupling concentrated solar energy with thermochemical cycles presents many challenges. Receivers and reactors need to be developed and engineered. Cost effective approaches and systems to deal effectively with the diurnal nature of sunlight need to be researched and developed.

3.1.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.1.10. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate Program element.

Table 3.1.10. Technical Task Descriptions

Task	Description	Barriers
1	**Low-Cost, Distributed Production of Hydrogen from Natural Gas** • Develop advanced, small-scale reformer technology for greater efficiency, selectivity, and durability. • Develop advanced shift catalysts that are more efficient and impurity tolerant. Evaluate pathways for improving conventional water-gas-shift catalysts and reactors, including single-stage shift. • Develop advanced technology that integrates process steps and energy to minimize capital, unit size, and energy use in an intensified process. • Utilize Design for Manufacture and Assembly (DFMA) to design appliance type units for high-thoughput low-cost manufacture. • Design for robust operations that minimize maintenance and process monitoring needs.	A, B, C, D, E, F
2	**Distributed Reforming of Renewable Liquid Feedstocks** • Analyze and research options for alternative renewable feedstocks (e.g., ethanol, methanol, sugar alcohols, bio-oils, bio-based Fischer Tropsch liquids) for distributed production. • Utilizing the technology concepts developed for distributed natural gas reforming, develop efficient, integrated, compact, robust process technology for bio-derived liquid feedstocks. • Explore novel technology for reforming bio-derived renewable liquid feedstocks that could result in a cost breakthrough.	A, B, C, D, E, F
3	**Advanced Electrolysis Technologies to Reduce Cost and Increase Efficiency** • Reduce cell stack cost by developing lower cost durable materials with improved manufacturing capability optimized for efficiency, durability, and stack compression. • Develop electrochemical and other novel compression technologies, integral to cell stacks, to reach hydrogen output pressures greater than 500 psi using low-cost materials. • Optimize electrolysis with renewable energy systems to lower cost of power conversion and other system components. • Develop utility-scale electrolysis system suitable for renewable and grid electricity integration. • Develop system components for lower system O&M costs including cell stack durability and compression. • Evaluate steam electrolysis for reducing electricity costs associated with hydrogen production and improving system durability. • Continue development of reversible solid oxide electrolyzer materials and system design.	G, H, I, J, K, U

4	**Separation and Purification Systems (Cross-Cutting Research)** • Develop a membrane reactor system that combines water-gas-shift reaction for hydrogen production with a membrane for hydrogen separation and purification in a single step to achieve reductions in system operations and maintenance costs as well as reductions in overall system capital costs. • Investigate new lower-cost alloys to achieve fundamental improvements in metallic membrane technology to achieve necessary hydrogen purity levels. • Overcome embrittlement and fracture issues associated with producing high-purity hydrogen at high concentrations to promote system durability. • Verify that inorganic, metallic, and ion transport membrane systems can meet or exceed separation targets under realistic commercial operating conditions. • Develop membranes that optimize hydrogen and carbon dioxide selectivity. • Improve existing air separation technologies and identify novel technologies for separating oxygen for gasification and reforming. • Develop integrated membrane/reactor systems for reforming.	A, B, C, E, L, M, N, O, P, Q, R, S, T, V, W, AA, AG, AL, AS, AU, AV
5	**Cost Reduction of Biomass Reforming for Gasification/Pyrolysis** • Identify all opportunities for reducing the cost of biomass gasification/pyrolysis technologies. • Reduce the cost and increase the feedstock flexibility of biomass feedstock preparation (e.g. handling, size reduction, etc.) • Research and develop more cost-effective, efficient, and durable biomass product gas clean up technologies for feed into reforming operations, including hot-gas clean-up, tar cracking, and other related technologies. (This will be coordinated with the Office of Fossil Energy for coal-gasifier product gas clean up technologies and with the EERE Biomass Program.) • Investigate opportunities for catalyst and reactor improvement for reforming and conditioning of biomass producer gases. • Improve process overall heat integration and improve hydrogen yields and selectivities to improve energy efficiency and reduce cost. • Intensify and reduce the capital cost by combining/integrating process steps and operations. This could include single step shift with an integrated membrane, combining shift and reforming in one operation, combining gasification and reforming in one operation, etc. • Develop other gasification/pyrolysis improvements, including further heat integration, reactor configurations, etc.	V, W
6	**Molecular and Physiological Engineering of Organisms for Photolytic Hydrogen Production from Water** • Generate organisms that are O_2-tolerant, have increased light conversion efficiency, allow more efficient photosynthetic electron transport toward H_2, and eliminate competing pathways for enhanced H_2 production. Eliminate H_2 uptake pathways in cyanobacteria. • Research and develop systems in which water photolysis occurs under anaerobic conditions (i.e., in which the P/R ratio is ≤ 1). Test different methods to achieve that ratio without affecting H_2 production (priority for the development of an integrated system). Incorporate elements from the first bullet, if necessary.	X,Y, Z
7	**Systems Engineering for Photolytic Hydrogen Production from Water** • Optimize photoreactor material and system designs. • Discover and develop cost effective, transparent, H_2-impermeable materials for photolytic production of H_2. • Develop hydrogen collection and gas separation technologies. • Verify economic and technical viability of continuous hydrogen production.	AA, AB

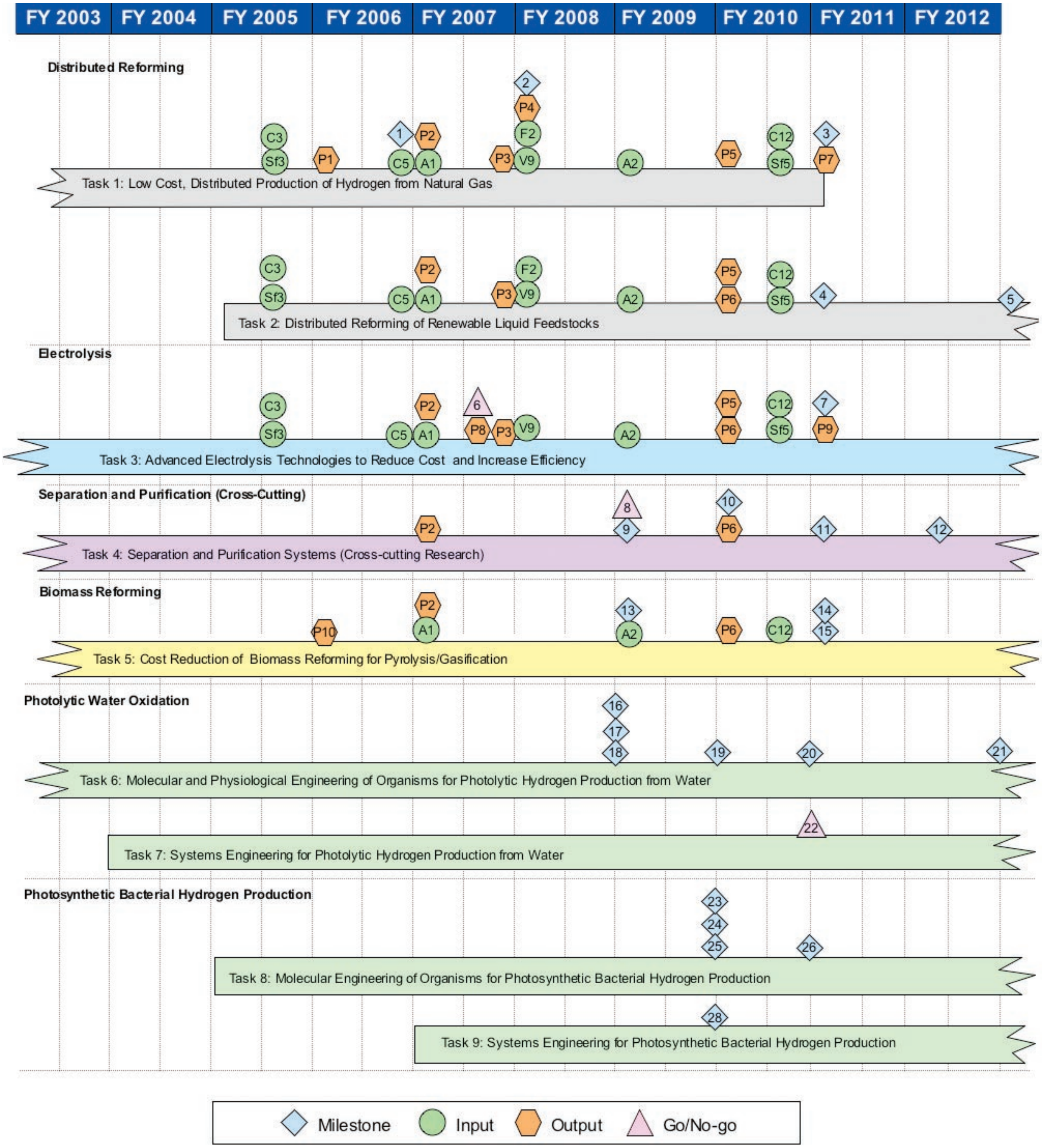
8	**Molecular Engineering of Organisms for Photosynthetic Bacterial Hydrogen Production** • Increase the useful portion of the solar spectrum beyond the visible and into the infrared by co-cultivating green algae/cyanobacteria and photosynthetic bacterial (priority for the development of an integrated system). • Generate photosynthetic bacteria that have increased sunlight conversion efficiency and display more efficient photosynthetic electron transport. Eliminate competitive pathways such as H_2 oxidation and polymer accumulation. Engineer organisms that have a functional nitrogenase at elevated nitrogen-nutrient concentration. Investigate the H_2-production activity and solar efficiency of organisms containing alternative nitrogenases.	AC, AD, AE, AF
9	**Systems Engineering for Photosynthetic Bacterial Hydrogen Production** • Optimize photoreactor material and system designs. • Discover and develop cost effective, transparent, H_2-impermeable materials for photosynthetic bacterial H_2 production. • Develop H_2-collection and gas-separation technologies. • Verify economic and technical viability of continuous H_2 production.	AG, AH
10	**Molecular Engineering of Organisms for Dark Fermentative Hydrogen Production** • Eliminate competing pathways for H_2 production. • Bioprospect for cellulolytic microbes that can ferment cellulose along with mixed sugars, and for organisms with pathways that allow for higher H_2 molar yield. Investigate fermentation of green alga/photosynthetic bacteria cell biomass from the co-culture for H_2 production. Investigate the potential production of toxins by different fermentative organisms that could prevent integration with other components of the overall system.	AI, AJ, AK
11	**Systems Engineering for Dark Fermentative Hydrogen Production** • Develop catalytic degradation processes of cell biomass to be more suitable for the subsequent dark fermentation. Industrial-scale enzymes, or chemical processes, need to be defined that can be applied in large scale for the catalytic breakdown of these cell wall biopolymers to their monomeric constituents. Dark anaerobic fermentations for the production of H_2 can then utilize the resulting sugars as a suitable feedstock. • Develop H_2-collection and gas-separation technologies. • Develop methanogen management approaches.	AL
12	**Integrated Biological Hydrogen Production (dependent on configuration used) (see Figure 3.1.2)** • Investigate the best way to integrate anaerobic water photolysis (green algal and/or cyanobacterial H_2 production) with photosynthetic bacterial H_2 production. This could involve co-cultivation of organisms or immobilized cultures. • Determine the efficacy of green algae/cyanobacteria and photosynthetic bacteria to metabolize different exogenous organic carbon substrates. • Regulate competition (for sunlight and/or nutrients) between different organisms in the case of co-cultivation, and eliminate transfer of potential cell-growth inhibitors from the fermentor to the photoreactors. • Investigate low-cost methods to concentrate/process organisms in suspension, as necessary.	AM, AN, AO

13	**Development of Semiconductor Materials for Photoelectrochemical Hydrogen Production** • Develop and optimize the current state of the art materials for meeting near term efficiency and durability targets. • Discover, utilizing combinatorial or other screening methods, new materials for meeting long-term efficiency, durability, and cost targets. • Develop cost-effective synthesis techniques for fabricating the most promising semiconductor materials. • Develop accelerated screening protocols to evaluate and validate long-term material efficiencies and durability.	AP, AQ, AR
14	**Material Configurations and Device Engineering for Photoelectrochemical Hydrogen Production** • Evaluate device configurations, including multi-junction configurations and other advanced designs, for improved efficiency and durability and lower device cost. • Develop and optimize the most promising device configurations. • Develop cost-effective fabricating synthesis techniques that are scalable and manufactureable for the most promising materials systems, devices, and configurations.	AP, AQ, AR, AS
15	**Systems Development for Photoelectrochemical Hydrogen Production** • Design reactor systems to optimize light-capture efficiency, hydrogen production, gas collection and reactor life – including utilization of novel geometries and electrolyte options. • Identify or develop auxiliary materials and components necessary for photoelectrochemical hydrogen production systems, including cost effective transparent, hydrogen-impermeable materials for reactors. • Develop accelerated testing protocols to evaluate and validate long-term system efficiencies and durability. • Apply economic modeling tools for predicting cost potentials for photolytic production technologies.	AT
16	**High-Temperature, Solar-Driven, Thermochemical Processes** • Evaluate potential high-temperature, solar driven thermochemical water-splitting cycles and down-select to the most promising cycles. • Develop a cost effective integration of concentrated solar power with high-temperature thermochemical water splitting cycles. • Develop a viable integrated, solar-driven high-temperature thermochemical water-splitting process. • Develop cost-effective, high-temperature materials compatible with thermochemical processes. • Verify an integrated, solar-driven high-temperature thermochemical water-splitting cycle with targeted costs.	AU, AV, AW, AX

3.1.6 Milestones

Figure 3.1.3 shows the interrelationship of milestones, tasks, supporting inputs from other Program elements, and technology outputs for the Hydrogen Production Program element from FY 2004 through FY 2012. This information is also summarized in Table B.1 in Appendix B.

Figure 3.1.3. Hydrogen Production R&D Milestone Chart



For chart details see next page.

Milestones

1 Down-select research for distributed natural gas-to-hydrogen production.
2 Select advanced shift catalysts that are more efficient and impurity tolerant.
3 Verify feasibility of achieving $1.50/gge (delivered) from distributed natural gas.
4 Verify feasibility of achieving $3.60/gge for renewable liquids distributed reforming.
5 Down-select research for distributed production from bio-derived renewable liquids.
6 Go/No-Go: Decision on continued high-temperature steam electrolysis R&D based on a complete technoeconomic analysis and laboratory-scale research results.
7 Verify feasibility of achieving $2.85/gge (delivered) from electrolysis.
8 Go/No-Go: Determine if membrane separation technology can be applied to natural gas distributed reforming during the transition to a hydrogen economy.
9 Down-select separation technology for development in distributed natural gas reforming.
10 Demonstrate pilot-scale use of integrated separation (membrane) reactor system for natural gas.
11 Down-select separation technology for distributed bio-derived renewable liquid feedstocks reforming.
12 Demonstrate pilot-scale use of integrated separation (membrane) reactor system for renewable feedstocks.
13 Down-select to a primary technology and configuration for biomass gasification/pyrolysis clean–up, reforming, shift, separation and purification.
14 Verify a projected cost for biomass gasification/pyrolysis of $1.75/gge at plant gate.
15 Down-select to 1-2 primary novel technologies for biomass gasification/pyrolysis clean up, reforming, shift, separation and purification.
16 Identify or generate an Fe-hydrogenase with a half-life of 5 min in air for photolytic hydrogen production.
17 Produce one cyanobacterial recombinant evolving H_2 through an O_2-tolerant NiFe-hydrogenase.
18 Increase the duration of H_2 production by immobilized, sulfur-deprived algal cultures to 40 days.
19 Complete research to develop a photosynthetically efficient green alga/cyanobacterial system in which the P/R ratio is ≤ 2.
20 For photolytic hydrogen production, achieve 15% primary utilization efficiency of incident solar light energy (E0*E1), 2% efficiency of incident light energy to H_2 from water (E0*E1*E2), and 30 min (O_2 tolerant system) duration of continuous photoproduction.
21 Identify or generate an Fe-hydrogenase with a half life of 30 min in air for photolytic hydrogen production.
22 Go/No-Go: Identify cost-effective (based on analysis) transparent H_2 -impermeable material for use in photobiological H_2 -production system.
23 Complete research to generate photosynthetic bacteria that have 50% smaller (compared to wild-type) Bchl antenna size and display increased sunlight conversion efficiency.
24 Complete research to engineer photosynthetic bacteria with a 30% expression level of a functional nitrogenase/hydrogenase at elevated nitrogen-carbon ratios (expression level is defined relative to that detected at low N:C ratios).
25 Complete research to inactivate competitive uptake of H_2 by hydrogenase.
26 For photosynthetic bacterial hydrogen production, achieve 3% efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, and 50% of maximum molar yield of carbon conversion to H_2 (depends on nature of organic substrate).

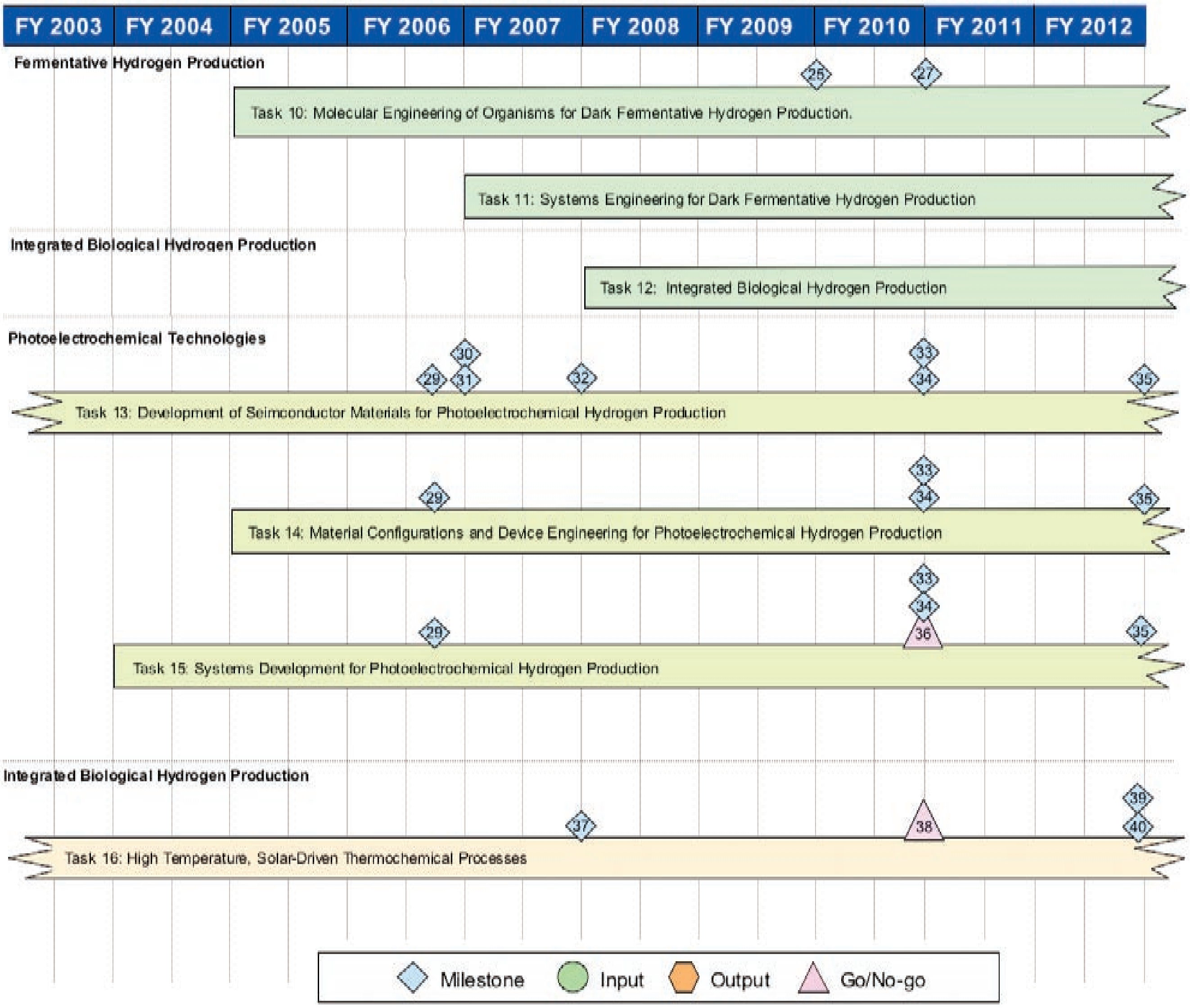
Outputs

P1 Output to Fuel Cells and Technology Validation: Hydrogen production technology for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P2 Output to Delivery, Storage and Fuel Cells: Assessment of fuel contaminant composition.
P3 Output to Systems Analysis and Systems Integration: Impact of hydrogen purity on cost and performance.
P4 Output to Fuel Cells and Technology Validation: Hydrogen production technology for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P5 Output to Systems Analysis and Systems Integration: Impact of hydrogen purity on cost and performance.
P6 Output to Delivery, Storage and Fuel Cells: Assessment of fuel contaminant composition.
P7 Output to Fuel Cells and Technology Validation: Hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P8 Output to Technology Validation: Down-select of high-temperature electrolysis technology based on research results.
P9 Output to Technology Validation: Electrolysis system making hydrogen for $2.85/gge delivered.
P10 Output to Technology Validation: Hydrogen production system making hydrogen for $1.90/gge from biomass at the plant gate.

Inputs

C3 Input from Codes and Standards: Preliminary Assessment of Safety, Codes and Standards requirements for the hydrogen delivery infrastructure.
Sf3 Input from Safety: Safety requirements and protocols for refueling.
C5 Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
A1 Input from Systems Analysis: Complete technoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.
F2 Input from Fuel Cells: Research results of advanced reformer development.
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.
Sf5 Input from Safety: Safety requirements and protocols for refueling.

Figure 3.1.3. Hydrogen Production R&D Milestone Chart



For chart details see next page.

Milestones

27 For dark fermentative hydrogen production, achieve 4 molar yield of H_2 production from glucose.

28 Complete research to determine the efficacy of green algae/cyanobacteria and photosynthetic bacteria to metabolize carbon substrates ($C \leq 4$) and produce H_2 in co-cultivation.

29 Update technoeconomic analysis on the projected technology.

30 Complete structure and initial data population of a photoelectrochemical materials database.

31 Establish standard cell and testing protocols for PEC materials for validation efficiencies.

32 Install testing laboratory for the standard cell and testing protocol for PEC materials.

33 Update technoeconomic analysis on the projected technology.

34 Identify materials/systems with a 2.3 eV useable semiconductor bandgap, 8% plant solar-to-hydrogen efficiency, and projected durability of 1,000 hours.

35 Build a consensus, lab-scale PEC panel based on best available 2010 technology to validate technoeconomic analysis.

36 Go/No-Go: Identify cost-effective (based on analysis) transparent hydrogen-impermeable material for use in photoelectrochemical hydrogen production system.

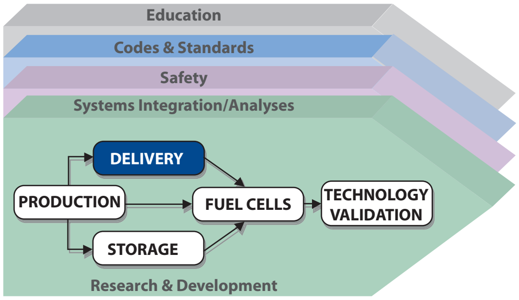
37 Down-select to 2-4 promising high temperature solar-driven thermochemical cylcles for R&D based on analysis and initial laboratory work of potential cycles.

38 Go/No-Go: Verify the feasibility of an effective integrated high-temperature solar-driven thermochemical cycle for hydrogen projected to meet the 2010 cost goal of $4/gge.

39 Verify the successful continuous operation of a promising integrated high temperature solar-driven thermochemical cycle at a scale of >10 kg/hr. of hydrogen production.

40 Down-select to 1-2 promising high-temperature solar-driven thermochemical cycles for development.

3.2 Hydrogen Delivery



Hydrogen must be transported from the point of production to the point of use. It also must be compressed, stored and dispensed at refueling stations or stationary power facilities. Due to its relatively low volumetric energy density, transportation, storage and final delivery to the point of use can be one of the significant cost and energy inefficiencies associated with using hydrogen as an energy carrier.

3.2.1 Technical Goal and Objectives

Goal

Develop hydrogen delivery technologies that enable the introduction and long-term viability of hydrogen as an energy carrier for transportation and stationary power.

Objectives

- By 2006, define criteria for a cost-effective and energy-efficient hydrogen delivery infrastructure for the transition and long-term use of hydrogen for transportation and stationary power.
- By 2010, reduce the cost of hydrogen transport from central and semi-central production facilities to the gate of refueling stations and other end users to <$0.90/gge of hydrogen.[1]
- By 2010, reduce the cost of compression, storage and dispensing at refueling stations and stationary power facilities to <$0.80/gge of hydrogen (independent of transport).[1]
- By 2015, reduce the cost of hydrogen delivery from the point of production to the point of use in vehicles or stationary power units to <$1.00/gge of hydrogen in total.[1]

3.2.2 Technical Approach

The Hydrogen Delivery Program element is focused on meeting the hydrogen delivery objectives outlined in Section 3.2.1 by conducting R&D through industry, national laboratory and university projects. Projects will address the barriers outlined in Section 3.2.4.2, and progress toward meeting the objectives will be measured against the technical targets outlined in Section 3.2.4.1. Delivery efforts will be coordinated with any related activities in the DOE Office of Fossil Energy and the Department of Transportation.

Infrastructure Options

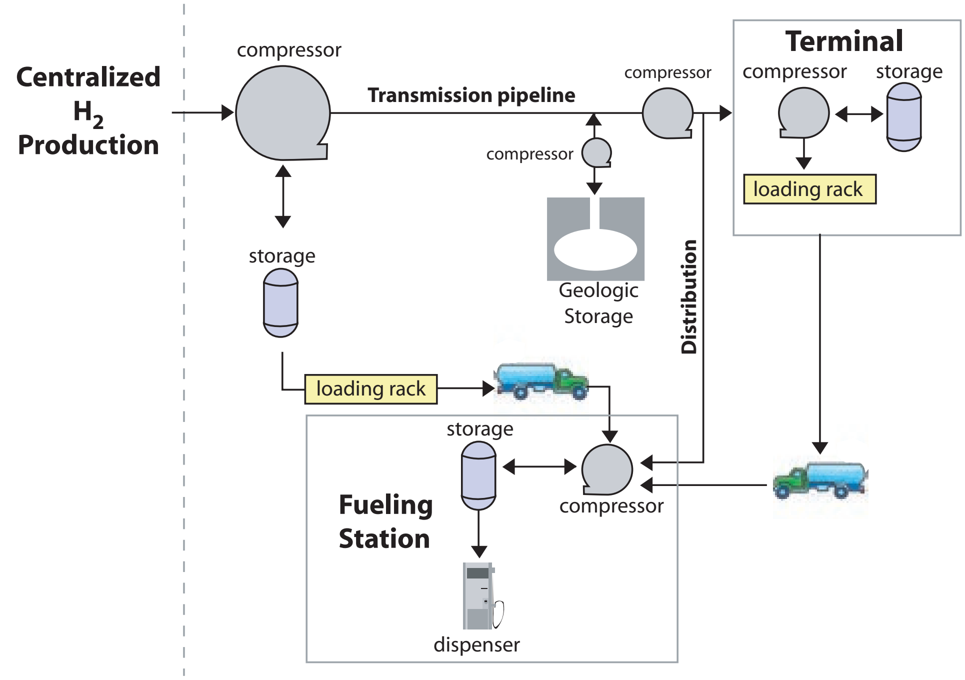
The hydrogen production strategy greatly affects the cost and method of delivery. If the hydrogen is produced centrally, the longer transport distances can increase delivery costs. It can be produced semi-centrally (within 50-100 miles of the point of use) to reduce this transport distance. Distributed production at the point of use eliminates the transportation costs but results in higher production costs because the economy of larger scale production is lost. In all cases, the delivery costs associated with compression, storage and dispensing at the refueling station or stationary power site are significant and need to be minimized.

---

[1] These targets are based on a well-established hydrogen market demand for transportation. The specific scenario examined assumed central and semi-central production of hydrogen servicing small (~100,000 people) and large (~1,000,000 people) cities.

There are three primary options for hydrogen delivery. One option is that it can be delivered as a gas in pipelines or high-pressure tube trailers. This is illustrated in Figure 3.2.1. This option offers the possibility of transporting a mixture of hydrogen and natural gas in the existing natural gas pipeline infrastructure followed by separation and purification of the hydrogen. Hydrogen can also be liquefied and delivered in cryogenic tank trucks. This is illustrated in Figure 3.2.2. Gaseous and liquid delivery are used today but there is only a very limited hydrogen pipeline infrastructure for gaseous service.

Figure 3.2.1. Gaseous Hydrogen Delivery Pathway

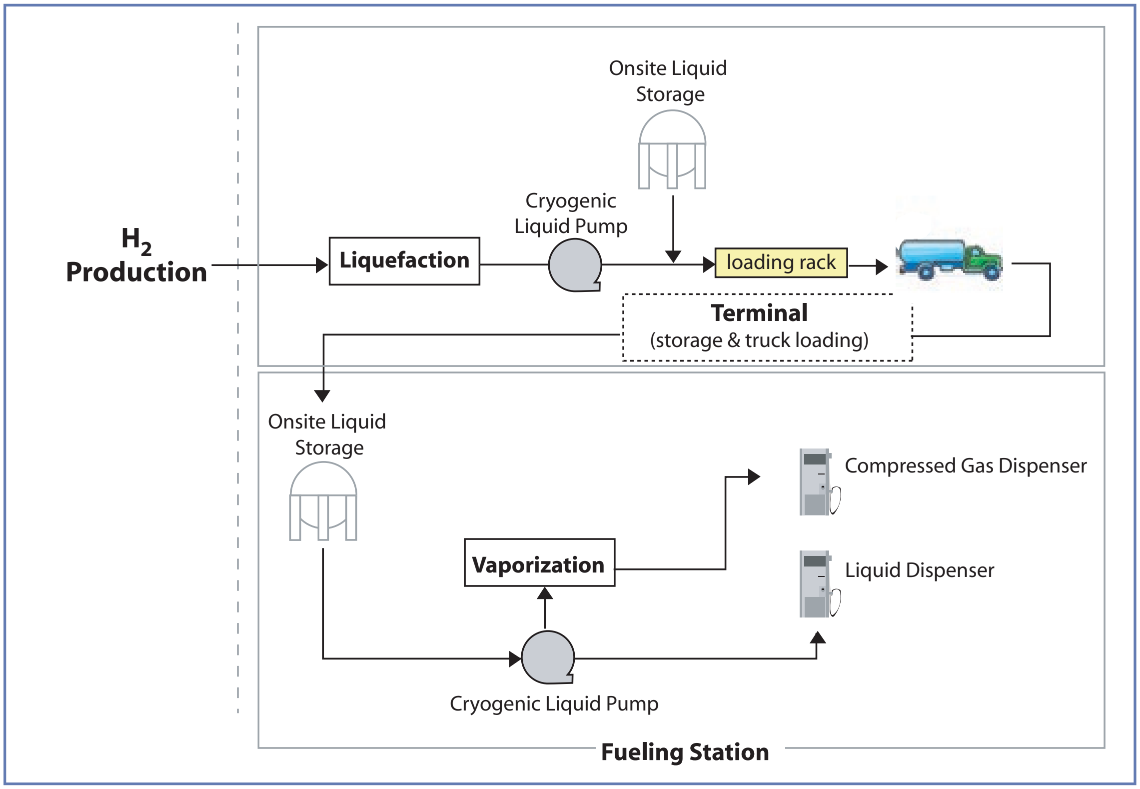


NOTE 1: sensors for leak detection, purity, and flow rate will be required at multiple locations

NOTE 2: rail and barge transportation is possible for large volume shipments between central production and a terminal facility

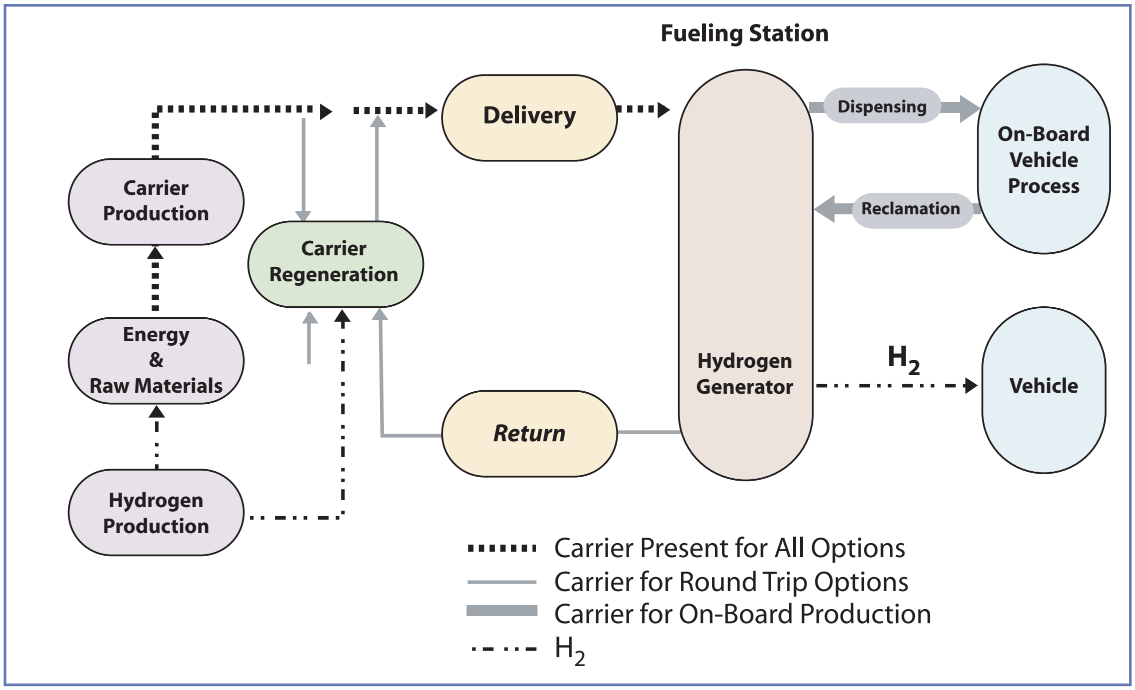
NOTE 3: intermediate storage possible at a variety of locations

Figure 3.2.2. Cryogenic Liquid Hydrogen Delivery



A third option is higher volumetric energy density carriers such as natural gas, methanol, ethanol or other liquids derived from renewable biomass that can be produced, transported to the point of use, and reformed to hydrogen. Novel carriers such as metal hydrides or other hydrogen containing solids or liquids that can be treated to release hydrogen at a refueling station or stationary power location or possibly even directly on-board a vehicle are other promising alternatives. This carrier approach is illustrated in Figure 3.2.3.

Figure 3.2.3. Novel Carrier Pathway



These primary delivery pathways can also be used in combination. For example, gaseous hydrogen could be delivered by pipeline to a terminal where it could be liquefied and then delivered by cryogenic tank truck or transformed to a novel carrier system for delivery. There are many potential components to a complete hydrogen delivery infrastructure:

- Pipelines
- Compression
- Liquefaction
- Tube Trailers, Cryogenic Liquid Trucks, Rail, Barges, Ships (liquid and gaseous H_2)
- Liquid and Gaseous Tanks
- Geologic Storage
- Terminals
- Separation/Purification
- Dispensers
- Carriers

One advantage of hydrogen is that it can be produced from a variety of feedstocks in a variety of ways. It will be produced from a spectrum of feedstocks and production technologies over the course of its introduction and long-term use as a primary energy carrier. Similarly, the delivery technology may well encompass several options over the short and long terms. The transportation methods used at the early stages, when hydrogen volumes are relatively low, may be different than those used when hydrogen is used in large quantities as a primary energy carrier. At very large volumes, an extensive pipeline infrastructure is currently the most cost-effective and energy efficient manner to transport hydrogen to much of the market as is done with natural gas today. However, other methods, such as, cryogenic liquid truck delivery or distributed natural gas or liquid reforming, will be needed for the transition period. In any event, lower cost and more energy-efficient technologies are needed for hydrogen transportation and handling for hydrogen to become a major energy carrier.

Terminals, Trucks, Rail Barges, and Ships

The current petroleum delivery infrastructure includes terminals, trucks, rail, barges and ships for delivery. Other than truck delivery, none of these delivery infrastructure modes are used today for hydrogen delivery. For the delivery infrastructure for hydrogen as a major energy carrier, some of these other delivery infrastructure elements may be needed.

Bulk Storage

Storage within the hydrogen delivery infrastructure will be important to provide surge capacity for daily and seasonal demand variations. The most common pressure vessels for gaseous hydrogen are steel tubes. They can be used to store hydrogen at 6,000 psi or higher. They are often manifolded together allowing for larger storage capacity. Hydrogen is also stored as a cryogenic liquid due to its higher volumetric energy density and thus smaller footprint. This approach is not a low cost option due to the high cost of hydrogen liquefaction.

Geologic storage is routinely used to provide seasonal surge capacity in the natural gas delivery infrastructure. Very large volumes of natural gas are stored in natural geologic formations such as salt caverns under modest pressure (typically about 2000 psi or less). The hydrogen infrastructure will likely require similar bulk storage capability. Besides naturally-occurring geologic formations, storing hydrogen in specially engineered rock caverns, referred to as lined rock caverns (LRC), offers another possibility. Research into the suitability of geologic storage is needed. Hydrogen is a much smaller molecule than natural gas and has a much higher diffusivity. Containment within geologic storage may be more challenging and potential environmental impacts need to be investigated.

Novel hydrogen carriers could be very useful for off-board hydrogen storage. For example, a solid that could reversibly adsorb and desorb significant amounts of hydrogen and store it at low pressures could significantly reduce the compression costs associated with gaseous storage and might prove to have lower capital cost requirements as well.

Interface with On Board Vehicular Storage of Hydrogen

The technology selected for storing hydrogen on board vehicles may affect the hydrogen delivery system and infrastructure. Delivery and on-board storage need to be integrated at some junction in the system. For example, the on-board storage system could be a solid carrier that receives hydrogen gas directly from a dispenser at a refueling station. On the other hand, if an on-board carrier system requiring off-board regeneration is selected, the hydrogen delivery system will need to cost-effectively accommodate this approach. In addition, vehicle interface technologies will need to be jointly addressed by both the Delivery and Storage Program elements, as promising options are selected. The Hydrogen Delivery milestone chart in Section 3.2.6 and the Hydrogen Storage milestone chart in Section 3.3.6 show inputs and outputs between the Delivery and the Storage Program elements that address these interactions.

Research Strategy

To enable the introduction of hydrogen as an energy carrier, a key initial focus of the Hydrogen Delivery Program element will be on hydrogen delivery research challenges at refueling stations and stationary power sites with respect to compression and storage technology. The improved technologies necessary for transport of hydrogen from more central production facilities will be researched in a parallel effort but with greater emphasis later in the program. After 2015, the remaining federal effort will likely be selective and only fund new concepts that could make further significant impacts on delivery costs or energy efficiencies.

3.2.3 Programmatic Status

Specific focus on hydrogen transportation and delivery in the Program is now underway. The importance of this part of the value chain was highlighted in the National Hydrogen Energy Roadmap published in the fall of 2002 and more recently by the National Academies[2]. The Hydrogen Delivery Program element is now being initiated.

---

[2] *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs.* National Research Council and National Academy of Engineering of the National Academies. National Academies Press, Washington, c2004.

The current projects that pertain to this Program element are shown in Table 3.2.1.

Table 3.2.1. Current Hydrogen Delivery Projects

Challenge	Approach	Activities
Pipelines: Reduce the capital costs and ensure safety and reliability	• Develop new and improved materials for pipeline delivery of hydrogen	• **Oak Ridge National Laboratory (ORNL):** Improved steel materials and welds. • **ORNL:** Low-cost fiber reinforced polymer (FRP) composite pipelines. • **Savannah River National Laboratory (SRNL):** Natural Gas pipelines for hydrogen use. • **Secat, Inc. ORNL, ASME, U. of Illinois, Applied Thin Films, Columbia Gas, CCC Coatings, ATC, and Oregon Steel Mills:** Pipeline and weld materials, and coatings testing and modeling. • **U. of Illinois:** Lifetime prediction model for pipeline steels in hydrogen service.
Carriers: Develop carriers that can enable low cost hydrogen delivery	• Explore novel liquid and solid carrier technology for use in hydrogen delivery.	• **Air Products & Chemicals, Inc., UTRC, and Pennsylvania State University:** Reversible liquid carrier for integrated hydrogen, storage, and delivery.
Compression: Increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compression	• Develop improved compression technologies for hydrogen	• **Argonne National Laboratory (ANL):** Novel screw compression technology for hydrogen service. • **HERA:** Novel hydride compression and purification
Analysis: Identify the better options for cost-effective and energy-efficient hydrogen delivery infrastructure for the introduction and long-term use of hydrogen	• Analyze systems and infrastructures for delivery of gaseous and liquid hydrogen and novel solid/liquid hydrogen carriers	• **National Renewable Energy Laboratory (NREL), ANL and Pacific Northwest National Laboratory (PNNL):** Components modeling; compression technology and issues; ethanol delivery infrastructure characterization; and hydrogen delivery scenario modeling. • **Nexant, Inc., Air Liquide, ChevronTexaco, NREL, Gas Technologies Institute, Pinnacle West, and TIAX:** Cost/environmental analyses for delivery scenarios as a function of time and demand.
Off-Board Storage: Reduce the cost and footprint of hydrogen storage at refueling stations.	• Analyze available technology options for bulk storage of hydrogen at a refueling station. Address capital cost, operating costs, footprint, fuel capacity and safety.	• **Gas Technology Institute:** Options for off-board storage at refueling stations with emphasis on the suitability of underground liquid hydrogen storage. • **Lawrence Livermore National Laboratory:** Composite materials and structures for high-pressure off-board storage and tube trailers.
Liquefaction: Reduce the cost and improve the energy efficiency of hydrogen liquefaction.	• Explore new approaches to hydrogen liquefaction.	• **NCRC Corporation, Promethius Energy Inc., and H2 Storage Solutions:** Efficient and inexpensive magnetic liquefaction technology. • **Gas Equipment Engineering Corporation and R&D Dynamics:** Turbocompressor/expander technology for liquefaction.

Research and development of metal hydrides and other novel solid or liquid carriers of hydrogen useful for storage (see section 3.3) may also find use for hydrogen delivery.

3.2.4 Technical Challenges

Cost and Energy Efficiency

The overarching technical challenge for hydrogen delivery is reducing the cost of the technology so that stakeholders can achieve a return on the investment required for this infrastructure. The energy efficiency of delivery also needs to be improved.

Current costs for the transport of hydrogen, with the exception of that transported through the very limited amount of hydrogen pipelines, is \$4-\$9/gge of hydrogen.[3] This is based on transport by gaseous tube trailers or cryogenic liquid trucks and is very dependent on amounts and distances. Pipeline transport costs are dependent on transport distance and the amount of hydrogen delivered. These transport costs do not include the delivery costs associated with compression, storage and dispensing at the point of use.

Hydrogen Purity Requirements

PEM fuel cells for automotive and other uses require very pure hydrogen (see Table 3.2.2). There also might be purity specifications for the final technology developed and adopted for on–board vehicle storage (see section 3.3). If the hydrogen is produced to these purity specifications, then the delivery infrastructure must ensure it does not contaminate the hydrogen. Alternatively, the hydrogen could be produced to somewhat lower purity levels and then be purified to specifications just 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 as depicted in Figure 3.2.5 has several inputs and outputs among Hydrogen Production, Delivery, Storage, Fuel Cells and Systems Analysis to help optimize this purification strategy.

Hydrogen Leakage

The hydrogen molecule is very small and diffuses more rapidly compared with other gases such as natural gas. This makes it more challenging to design equipment, materials, seals, valves and fittings to avoid hydrogen leakage. Currently hydrogen is used and handled in significant quantities in industrial settings in petroleum refining, ammonia production, and specialty chemicals production without significant leakage issues. Industrial hydrogen operations are monitored and maintained by skilled people. The delivery infrastructure for hydrogen use as a major energy carrier will need to rely heavily on sensors and robust designs and engineering.

Infrastructure Trade-Offs

Options and trade-offs for hydrogen delivery from central, semi-central and distributed production to the point of use are not well understood. Analysis is needed to understand the advantages and disadvantages of the various energy sources and production and delivery technology options to guide research and investment efforts for the ultimate hydrogen infrastructure and for the most appropriate infrastructure to be used during the introduction of hydrogen as a primary energy carrier. Examples of some of these trade-offs include:

---

[3] Chemical and Market Reporter, February 24, 2003, p. 43.

- Centrally producing a liquid fuel, such as ethanol from biomass, and then transporting this relatively high volumetric energy density fuel to a refueling station for reforming into hydrogen versus centrally producing hydrogen from biomass and then transporting the lower volumetric energy density hydrogen to the refueling station.
- Utilizing liquefaction and liquid truck delivery during the early transition period at low hydrogen demand rates versus installing some hydrogen delivery pipelines early. The former involves potentially less capital risk while the latter sets the stage for the longer term, lower cost delivery option when hydrogen is in high demand.
- Purifying hydrogen at the central production point to required final use specifications and designing the delivery infrastructure to avoid any contamination versus basic purification at the point of manufacture and final polishing purification just prior to the point of use.
- The cost of a novel solid or liquid hydrogen carrier delivery system without the need for compression versus the cost of gaseous delivery with compression.

3.2.4.1 Technical Targets

Table 3.2.2 lists the technical targets for the Hydrogen Delivery Program element.

The key to achieving the goal and objectives of the Hydrogen Delivery Program element is to bring down the costs, improve the energy efficiency and ensure reliable performance of the key delivery technologies; compression, liquefaction, pipelines and off-board bulk storage. The targets shown in Table 3.2.2 are based on an analysis of current technology and costs, estimates of what might be possible with technology advances, and the market-driven requirements for the total delivery system costs. Delivery system costs are a complex function of the technology, delivery distances, system architecture and hydrogen demand. The 2015 cost targets in the table are the estimated costs needed for these technologies to achieve the objective of the overall delivery system cost contribution to be < $1.00/gge of hydrogen in 2015.

Initial targets are also given for hydrogen solid- or liquid-carrier technologies that could prove useful for hydrogen delivery. There are many possible options for use of hydrogen carriers within the delivery system.

An important emphasis of the Program is the transition period when hydrogen will start to become utilized in the transportation market. In the Production area, this results in an initial focus on distributed production at refueling stations. Delivery research will support this through an emphasis on the cost of compression and storage at refueling stations. This is also reflected in the targets.

All targets must be acheived simultaneously; however, status is not necessarily reported from a single system.

Table 3.2.2 Hydrogen Delivery Targets[a]

Category	2003 Status	2005	2010	2015
Pipelines: Transmission				
Total Capital Cost ($M/mile)[b]	$1.20	$1.20	$1.00	$0.80
Pipelines: Distribution				
Total Capital Cost ($M/mile)[b]	$0.30	$0.30	$0.25	$0.20
Pipelines: Transmission and Distribution				
Reliability (relative to H_2 embrittlement concerns and integrity)[c]	Undefined	Undefined	Understood	High (Metrics TBD)
H_2 Leakage[d]	Undefined	Undefined	<2%	<0.5%
Compression: Transmission				
Reliability[e]	92%	92%	95%	>99%
Hydrogen Energy Efficiency (%)[f]	99%	99%	99%	99%
Capital Cost ($M/compressor)[g]	$18	$18	$15	$12
Compression: At Refueling Sites				
Reliability[e]	Unknown	Unknown	90%	99%
Hydrogen Energy Efficiency (%)[f]	94%	94%	95%	96%
Contamination[h]	Varies by Design	Varies by Design	Reduced	None
Cost Contribution ($/gge of H_2)[i,j]	$0.60	$0.60	$0.40	$0.25
Liquefaction				
Small-Scale (30,000 kg H_2/day) Cost Contribution ($/gge of H_2)[k]	$1.80	$1.80	$1.60	$1.50
Large-Scale (300,000 kg H_2/day) Cost Contribution ($/gge of H_2)[k]	$0.75	$0.75	$0.65	$0.55
Small-Scale (30,000 kg H_2/day) Electrical Energy Efficiency (%)[k, l]	25%	25%	30%	35%
Large-Scale (300,000 kg H_2/day) Electrical Energy Efficiency (%)[k,l]	40%	40%	45%	50%
Carriers				
H_2 Content (% by weight)[m]	3%	3%	6.6%	13.2%
H_2 Content (kg H_2/liter)	Undefined	Undefined	0.013	0.027
H_2 Energy Efficiency (From the point of H_2 production through dispensing at the refueling site)[f]	Undefined	Undefined	70%	85%
Total Cost Contribution (From the point of H_2Production through dispensing at the reueling site) ($/gge of H_2)	Undefined	Undefined	$1.70	$1.00
Storage				
Refueling Site Storage Cost Contribution ($/gge of H_2)[j, n]	$0.70	$0.70	$0.30	$0.20
Geologic Storage	Feasibility Unknown	Feasibility Unknown	Verify Feasibility for H2	Capital and operating cost <1.5X that for natural gas on a per kg basis
Hydrogen Quality[o]	**>98% (dry basis)**			

[a] All dollar values are in 2003 U.S. dollars

[b] The 2003 status is based on data from True, W.R.,"Special Report: Pipeline Economics," Oil and Gas Journal, Sept. 16, 2002, pp 52-57. This article reports data on the cost of natural gas pipelines as a function of pipe diameter. It breaks the costs down by materials, labor, misc. and right of way. It is based on a U.S. average cost. A 15 inch pipe diameter was used for transmission and 2.5 inch for distribution. It was assumed that hydrogen pipelines will cost 30% more than natural gas pipelines based on advice from energy and industrial gas companies and organizations. The targeted cost reductions for 2010 and 2015 assume the right of way costs do not change.

[c] Pipeline reliability used here refers to maintaining integrity of the pipeline relative to potential hydrogen embrittlement or other issues causing cracks or failures. The 2015 target is intended to be at least equivalent to that of today's natural gas pipeline infrastructure.

[d] Hydrogen leakage based on the hydrogen that permeates or leaks from the pipeline as a percent of the amount of hydrogen put through the pipeline. The 2015 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, pp1365-1390, 1997.

[e] Compression reliability is defined as the percent of time that the compressor can be reliably counted on as being fully operational. The 2003 value for transmission compressors is based on information from energy companies that use these types and sizes of compressors on hydrogen in their own operations.

[f] Hydrogen energy efficiency is defined as the hydrogen energy (LHV) out divided by the sum of the hydrogen energy in (LHV) plus all other energy needed for the operation of the process.

[g] The 2003 value is based on data from "Special Report: Pipeline Economics," Oil and Gas Journal, Sept. 4, 2000, p 78. The compressor capital cost data was plotted vs. the power required for the compressor using the natural gas transmission compressor data provided. The capital cost was increased by 30% as an assumption for higher costs for hydrogen compressors. The power required was calculated assuming 1,000,000 kg/day of hydrogen flow with an inlet pressure of 700 psi and an outlet pressure of 1,000 psi.

[h] Some gas compressor designs require oil lubrication that results in some oil contamination of the gas compressed. Due to the stringent hydrogen purity specifications for PEM fuel cells, the 2015 target is to ensure no possibility of lubricant contamination of the hydrogen from the compression needed at refueling stations or stationary power sites since this compression is just prior to use on a vehicle or stationary power fuel cell.

[i] The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas hydrogen production case (www.eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that two compressors would be needed due to the currently unknown reliability of forecourt compressors, at a total installed capital cost of $600K. The electricity required assumed an isentropic energy efficiency of 70% and an electricity price of $.07/kWhr. The compression operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

[j] For 2003 and 2005, it is assumed that the hydrogen delivery pressure to the vehicle is 5000 psi. For 2010 and 2015, it is assumed that the hydrogen delivery pressure to the vehicle is 1500 psi or less based on the on-board vehicle storage program (Section 3.3) being successful in meeting its targets.

[k] The 2003 cost contribution and electrical energy efficiency was determined using the H2A Delivery Component Model spreadsheet using standard H2A financial input assumptions and the liquefaction spreadsheet tab (www.eere.energy.doe/hydrogenandfuelcells). The H2A spreadsheet information is based on data from other references sited in the H2A Delivery Component Model. References and a plot of liquefier capital cost as a function of capacity and a plot of actual energy used as a function of liquefier capacity are provided in the H2A Delivery Component model.

[l] Electrical energy efficiency is defined as the theoretical energy needed to liquefy the hydrogen divided by the energy actually needed in a hydrogen liquefaction plant. The theoretical energy is that energy needed to cool the gas to the liquefaction temperature and the energy needed for the ortho/para transition. The H2A Delivery Component Model (www.eere.energy.doe/hydrogenandfuelcells) provides the references and a plot of actual energy needed for current hydrogen liquefiers as a function of capacity.

[m] The 2010 hydrogen content targets are based on transporting 1500 kg of hydrogen in a truck. Although regulations vary to some degree by state, a typical truck is limited to carrying 25,000 kg of load and/or 113,000 liters of volume. The minimum hydrogen content (% by weight and kg H_2/liter) to achieve 1500 kg of hydrogen on the truck is determined by the maximum loads allowable. Trucking costs with this hydrogen payload are such that this transport option would seem attractive relative to the delivery cost objectives. A typical refueling station of 1500 kg/day of hydrogen servicing hydrogen fuel cell vehicles would service the same number of vehicles as typical gasoline stations serve today. This delivery option would require one truck delivery per day which is also typical of today's gasoline stations. The 2015 targets are calculated in the same way but assuming 3000 kg per truck load so that the one truck could service two refueling stations. The total cost and attractiveness of this delivery option would depend on the cost of the total carrier delivery system including the cost of discharging the hydrogen at the refueling station and any carrier regeneration costs.

[n] The 2003 value is based on utilizing the H2A Forecourt (refueling station) Model spreadsheet tool for a 1500 kg/day distributed natural gas case (www.eere.energy.gov/hydrogenandfuelcells). The standard H2A financial input assumptions were used. It was assumed that the hydrogen storage installed capital cost is $1.1M based on current technology and 1,100 kg of hydrogen storage. The storage operation was assumed to have a fractional share of the forecourt fixed costs based proportional to its capital and the total capital cost of the forecourt.

[o] Based on current available PEM fuel cell information, the tentative contaminant targets are: <10ppb sulfur, <1 ppm carbon monoxide, <100 ppm carbon dioxide, < 1 ppm ammonia, < 100 ppm non-methane hydrocarbons on a C-1 basis, oxygen, nitrogen and argon can not exceed 2% in total, particulate levels must meet ISO standard 14787. Future information on contaminant limits for on-board storage may add additional constraints.

3.2.4.2 Barriers

A. Lack of Hydrogen/Carrier and Infrastructure Options Analysis. Options and trade-offs for hydrogen/carrier delivery from central and semi-central production to the point of use are not well understood. Distributed production is another option. Analysis is needed to understand the advantages and disadvantages of these various approaches. Many site-specific and regional issues are associated with integrating production and use of hydrogen. Production and delivery systems need to be integrated to minimize cost and take full advantage of local resources and situations.

B. Reliability and Costs of Hydrogen Compression. Compression of natural gas is a well-developed technology. The hydrogen molecule is much smaller than methane, which creates significant challenges for compression. Current compression technology used for hydrogen is unreliable, resulting in the need for redundant compressors and thus higher cost. Centrifugal compression is the lowest cost approach for pipeline compression needs but the current technology does not work with hydrogen. Lubricants used in normal compression applications result in unacceptable contamination of hydrogen for PEM fuel cell use. If high-pressure (5,000 -10,000 psi) on-board hydrogen storage is used for vehicles, this also adds to the compression technology needs for hydrogen. Reliable, lower-cost, more efficient compression technologies are needed.

C. High Cost and Low Energy Efficiency of Hydrogen Liquefaction. Cryogenic liquid hydrogen has a much higher volumetric energy density than gaseous hydrogen. As a result, in the absence of a hydrogen pipeline infrastructure, transporting liquid hydrogen by cryogenic truck is significantly less costly than transporting compressed hydrogen by gaseous tube trailer. However, the cost of the liquefaction step adds very significantly to the cost of delivered hydrogen. In addition, this process is very energy intensive and inefficient (see Table 3.2.2). Improved liquefaction technology is needed. Possibilities include increasing the scale of these operations and improving heat integration, integrating these operations with hydrogen production or power production for improved heat integration and energy efficiency, and completely new liquefaction technologies such as magnetic or acoustic liquefaction or other approaches. In addition, hydrogen boil-off from cryogenic liquid storage tanks and tank trucks needs to be addressed and minimized or eliminated for improved cost and energy efficiency.

D. High Capital Cost and Hydrogen Embrittlement of Pipelines. Existing hydrogen pipelines are very limited and not adequate to broadly distribute hydrogen. Materials, labor 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. 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. Hydrogen leakage through the pipe itself, as well as through valves, fittings and seals is much more problematic than for natural gas due to the very small size of hydrogen molecules. Research is needed to determine suitable steels, and/or coatings, or other materials of construction to provide safe and reliable transport of hydrogen in pipelines while reducing the capital costs for materials and labor. Development of innovative materials and technologies (seals, components, sensors, and safety and control systems) is needed. Approaches for using existing natural gas pipelines to transport mixtures of natural gas and hydrogen without hydrogen embrittlement and leakage will be explored. Technologies for low cost separation and purification of hydrogen from natural gas would need to be developed for this approach to hydrogen delivery. The possibility of utilizing or upgrading natural gas or petroleum pipelines for pure hydrogen use also needs to be examined.

E. Solid and Liquid Hydrogen Carrier Transport. Novel solid or liquid carriers that can release hydrogen without significant processing operations are possible options for hydrogen transport and off-board 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.

F. Hydrogen Delivery Infrastructure Storage Costs. Hydrogen storage at production facilities, refueling stations, and other points of end use, and for system surge capacity for pipelines, trucks and rail at terminals, adds cost to the delivery infrastructure. Understanding and minimizing the need for this storage, while not adversely impacting the market daily and seasonal hydrogen demand cycles, will be important to minimizing these costs. Lower cost technologies to satisfy these storage requirements will also reduce overall delivery costs.

G. Geologic Storage. The feasibility of geologic hydrogen storage needs to be addressed. Geologic storage is routinely used to provide seasonal surge capacity for natural gas and could be equally important for a hydrogen delivery infrastructure. Novel approaches may be needed to deal with the higher diffusivity and potentially higher reactivity of hydrogen as compared to natural gas. Options such as alternative cushion gases coupled with membrane-separation of recovered hydrogen and identification of geologic structures with particularly promising permeability characteristics may need to be examined. Potential environmental impacts need to be investigated.

H. Storage Tank Materials and Costs. Off-board storage tanks required at refueling stations and at other points in the delivery infrastructure add costs to the delivery system not only for the cost of the tanks themselves but also for the cost of the valuable real estate space they consume. They can be impacted by hydrogen embrittlement, as discussed in Barrier D. This can be exacerbated by pressure cycling. Materials research is needed to help resolve hydrogen embrittlement issues. Higher pressures could reduce storage footprint requirements. Research into new materials such as metal ceramic composites, improved resins, and engineered fiber composites is needed. Costs might also be reduced through the use of Design for Manufacture Analysis (DFMA) and mass production of many identical storage units.

I. Hydrogen Leakage. The hydrogen molecule is very small and diffuses more rapidly compared with other gases such as natural gas. This makes it more challenging to design equipment, materials, seals, valves and fittings to avoid hydrogen leakage. Current industrial hydrogen operations are monitored and maintained by skilled people. The delivery infrastructure for hydrogen use as a major energy carrier will need to rely heavily on sensors and robust designs and engineering.

J. Safety, Codes and Standards, Permitting and Sensors. 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. Others are not, such as an extensive pipeline infrastructure for transmission and distribution and terminal operations. Applicable codes and standards are needed to facilitate provision for off-board storage at refueling stations and upstream in the hydrogen supply chain. More cost-effective sensors for leak detection and other purposes need to be developed. Sighting and permitting hurdles need to be overcome. The plan to address these issues is in the Codes and Standards section (Section 3.6).

3.2.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.2.3. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate Program element.

Table 3.2.3. Technical Task Descriptions

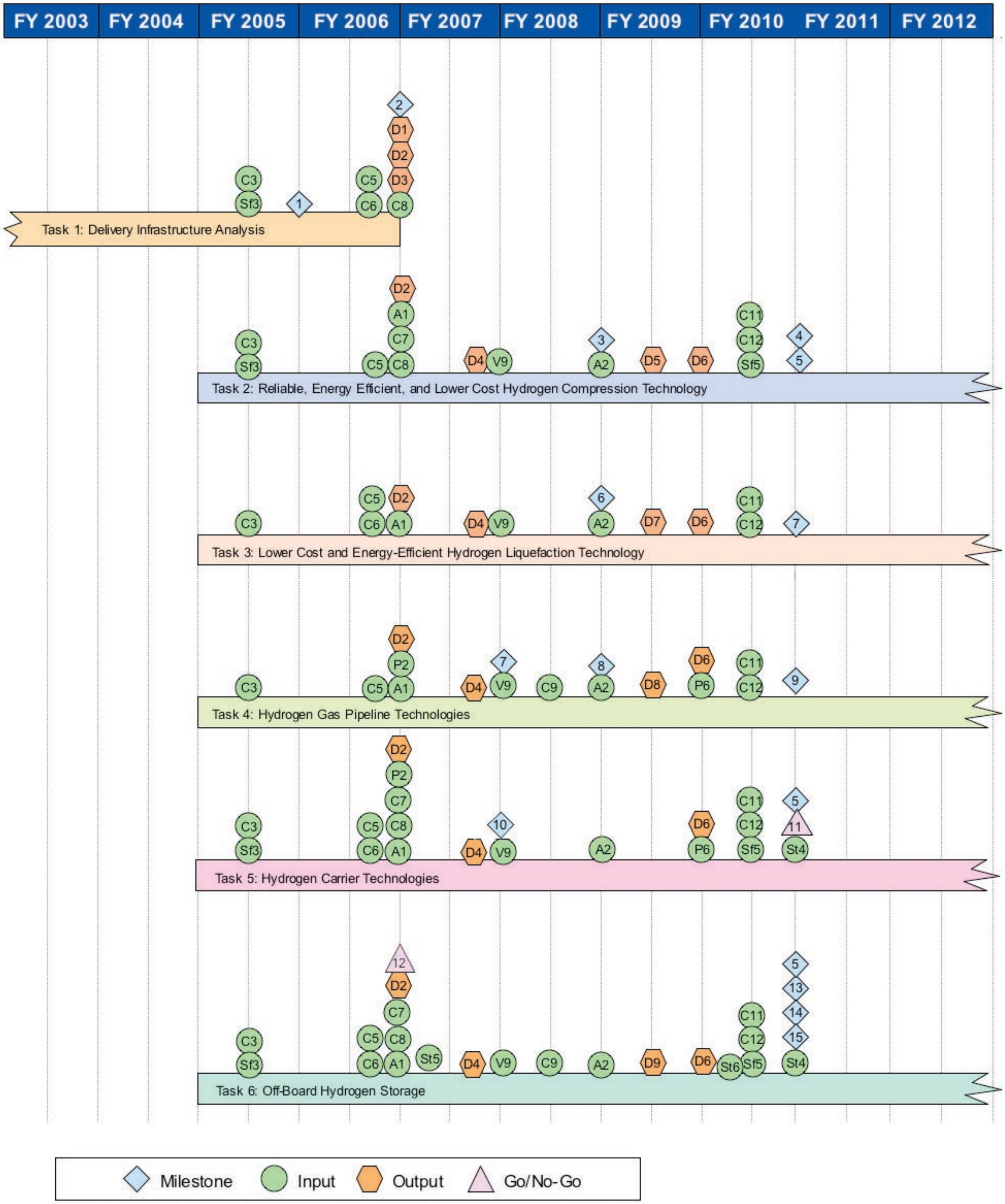
Task	Description	Barriers
1	**Delivery Infrastructure Analysis** • Characterize the current cost and energy efficiency of the components and complete pathways for gaseous and liquid hydrogen and identify the key cost reductions and energy efficiency improvements needed. • Characterize the cost boundaries of novel solid and liquid hydrogen carrier systems for delivery. • Perform analysis to examine the options and trade-offs of hydrogen/carrier delivery infrastructures and identify cost-effective, energy-efficient and safe hydrogen delivery infrastructure for the introduction and long-term use of hydrogen for transportation and stationary power. • Analyze and optimize the trade-offs and costs at refueling stations relative to the amount and pressure of hydrogen storage, compression needs, and the utilization factor for distributed hydrogen production.	A, B, C, D, E, F, G, H, I, J
2	**Reliable, Energy-Efficient, and Lower Cost Hydrogen Compression Technology** • Research existing and novel hydrogen compression technologies that can improve reliability, eliminate contamination, and reduce cost. • Develop reliable, low cost, energy efficient compression technology for hydrogen pipeline transmission service. • Develop reliable, low cost, energy efficient compression technology for hydrogen refueling station needs.	B, I
3	**Lower Cost and Energy-Efficient Hydrogen Liquefaction Technology** • Investigate cost and energy efficiency gains for larger scale operations, achieving additional energy integration, and improving refrigeration schemes. • Explore new and novel breakthrough technologies such as magnetic-caloric liquefaction.	C
4	**Hydrogen Gas Pipeline Technologies** • Research and identify preventative measures for hydrogen embrittlement and permeability in steel pipelines, including in the delivery of mixtures of hydrogen and natural gas. • Research improved steel pipe joining methods and other approaches to reduce capital cost and hydrogen embrittlement concerns. • Research and develop coating technology for steel or other possible pipeline materials to resolve hydrogen embrittlement and permeation issues. • Research and develop alternative materials to steel for hydrogen pipelines that could reduce capital cost while providing safe and reliable operations. • Develop improved and lower cost valves, fittings and seals to reduce hydrogen leakage. • Define available right of way and probable right of way costs for a complete hydrogen pipeline infrastructure. • Analyze, investigate, and develop technologies for existing natural gas pipelines for transporting hydrogen and natural gas mixtures (including technology to cost-effectively separate and purify the hydrogen) and for upgrading natural gas pipelines for pure hydrogen.	D, I

5	**Hydrogen Carrier Technologies** • Develop novel solid or liquid hydrogen carrier technologies for high volumetric energy density, low-cost transport and/or storage of hydrogen.	B, C, D, E, F, G, H. I, J
6	**Off-Board Hydrogen Storage** • From the outputs of Task 1, characterize the R&D requirements for off-board storage including storage options at refueling stations and throughout the delivery infrastructure. • Research the feasibility of geologic storage as a low cost storage option. • Develop more cost effective hydrogen storage technology by researching areas including: tank materials, novel carriers, and the use of DFMA and high throughput production methods. • Identify the needs and initiate any appropriate research for the interface requirements, including thermal management, between the refueling station compression, storage and dispensing and the on-board vehicle storage system, during refueling.	B, E, F, G, H, I, J

3.2.6 Milestones

Figure 3.2.4 shows the interrelationship of milestones, tasks, supporting inputs from other program elements, and technology program outputs for the Hydrogen Delivery program element from FY 2004 through FY 2010. This information is also summarized in Table B.2 in Appendix B.

Figure 3.2.4. Hydrogen Delivery R&D Milestone Chart



For chart details see next page.

Milestones

1 Characterize the current cost and energy efficiency of the components and complete pathways for gaseous and liquid hydrogen delivery and the cost boundaries of potential novel solid and liquid carrier systems.
2 Identify cost-effective options for hydrogen delivery infrastructure to support the introduction and long-term use of hydrogen for transportation and stationary power.
3 Down select to 2-3 most promising compression technologies for hydrogen transmission, refueling, and other needs in delivery.
4 Verify 2010 targeted costs and performance for hydrogen compression (transmission and forecourt).
5 Verify achieving a refueling station cost contribution for compression, storage and dispensing of $0.80/gge of hydrogen
6 Down-select to most promising 1-2 liquefaction technologies.
7 Verify 2010 targeted cost and performance for hydrogen liquefaction.
8 Research identifies fundamental mechanism of hydrogen embrittlement and permeation in steel pipelines and identifies promising cost effective measures to mitigate these issues.
9 Down-select on materials and/or coatings for pipelines including the potential use of natural gas pipelines for mixtures of natural gas and hydrogen, or hydrogen alone.
10 Verify 2010 targeted cost and performance for hydrogen pipelines.
11 Go/No-Go: Initial down-select for potential solid or liquid carrier systems for hydrogen delivery based on cost boundary analysis and initial research efforts.
12 Go/No-Go: Verify the feasibility of a hydrogen carrier system to meet the 2010 carrier targets.
13 Complete baseline analyses of off-board storage options at refueling stations and throughout the delivery infrastructure.
14 Complete the research to establish the feasibility and define the cost for geologic hydrogen storage.
15 Down-select to the most promising 1-2 technologies for off-board storage.
16 Verify the feasibility of achieving the 2010 refueling station storage cost targets.

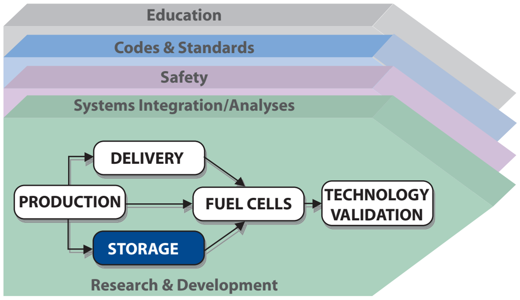
Outputs

D1 Output to Storage, Systems Analysis and Systems Integration: Assessment of cost and performance requirements for off-board storage systems.
D2 Output to Storage and Fuel Cells: Hydrogen contaminant composition and issues.
D3 Output to Technology Validation, Systems Analysis and Systems Integration: Hydrogen delivery infrastructure analysis results.
D4 Output to Systems Analysis and Systems Integration: Assessment of impact of hydrogen purity requirements on cost and performance of hydrogen delivery.
D5 Output to Technology Validation: Compression technology recommended for validation.
D6 Output to Systems Analysis and Systems Integration : Update of hydrogen purity/impurity requirements.
D7 Output to Technology Validation: Recommended liquefaction technology for potential validation.
D8 Output to Technology Validation: Recommended pipeline technology for validation.
D9 Output to Storage and Technology Validation: Recommended off-board storage technology for validation.

Inputs

C3 Input from Codes and Standards: Preliminary assessment of Safety, Codes and Standards for the hydrogen delivery infrastructure.
Sf3 Input from Safety: Safety requirements and protocols for refueling.
C5 Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
C6 Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.
C8 Input from Codes and Standards: Draft standards (balloting) for refueling stations (NFPA).
A1 Input from Systems Analysis: Complete technoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.
C7 Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system
C11 Input from Codes and Standards: Codes and Standards for the delivery infrastructure complete.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.
Sf5 Input from Safety: Safety requirements and protocols for refueling.
P2 Input from Production: Assessment of fuel contaminant composition.
C9 Input from Codes and Standards: Materials compatibility technical reference.
P6 Input from Production: Assessment of fuel contaminant composition.
St4 Input from Storage: Full-cycle, integrated chemical hydrogen system meeting 2010 targets.
St5 Input from Storage: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.
St6 Input from Storage: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc.) and down-select to a primary on-board storage system candidate.

3.3 Hydrogen Storage



Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell power technologies in transportation, stationary, and portable applications. The Hydrogen Storage Program element will focus on the research and development of on-board vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles. In addition, technologies applicable for off-board storage, such as for refueling infrastructure and Power Parks, will be coordinated with the Hydrogen Delivery Program element.

3.3.1 Technical Goal and Objectives

Goal

Develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications.

Objective

- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and $4/kWh.; by 2015, 3 kWh/kg (9 wt%), 2.7 kWh/L, and $2/kWh.

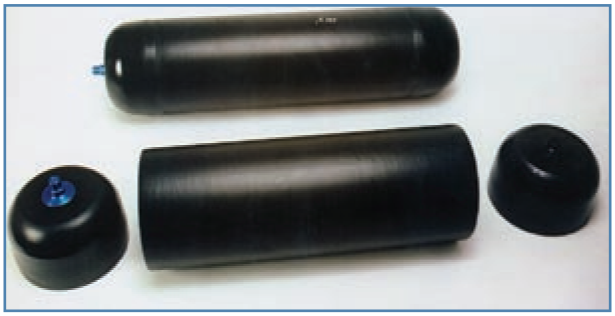
3.3.2 Technical Approach

On-board hydrogen storage to enable a driving range of greater than 300 miles, while meeting vehicular packaging, cost and performance requirements, is the focus of the Hydrogen Storage Program element. Research and development activities for vehicle interface technologies and off-board hydrogen storage will be coordinated with the Hydrogen Delivery Program element—emphasizing that hydrogen delivery entails delivering hydrogen from the point of production to the point of use on-board the vehicle, including storage at the fueling station (see Hydrogen Delivery section 3.2 for complete description of off-board storage).

To lay the strategic foundation for hydrogen storage activities, a series of workshops with scientists and engineers from universities, national laboratories and industry was held to identify R&D priorities. A “Think Tank” meeting, which included Nobel laureates and other award-winning scientists, was held to identify advanced material concepts and to develop an R&D strategy. Interactions with the DOE Office of Science are ongoing to define and coordinate the basic research activities for hydrogen storage materials.

Gravimetric, volumetric and cost targets for hydrogen storage have been developed for 2010 and 2015, as indicated in the objectives. Storage approaches currently being pursued are: 1) advanced concepts, conformability and cost reduction of compressed gas and cryogenic hydrogen tanks for near-term vehicles, and 2) reversible solid-state hydrogen storage materials, chemical hydrogen storage, and new materials and concepts for the longer-term vehicle applications (see Figures 3.3.1 and 3.3.2). The primary focus is on the latter set of technologies and on exploratory research with potential to meet long-term goals, rather than on pre-commercial technology development such as high-pressure tanks. Currently, hydrogen is stored both off-board and on-board prototype vehicles as a high-pressure compressed gas or as a cryogenic liquid. Compressed hydrogen gas tanks will likely be used in early hydrogen-powered vehicles and will need to meet cost and packaging requirements to play a role in the transition to the hydrogen economy. Furthermore, tanks will be required for all future storage approaches (e.g. solid-state or liquid chemical approaches) and will need to conform to space limitations as well as meet performance requirements such as heat management during fueling. Hence, current efforts in tank R&D also include novel concepts that are applicable to multiple forms of storage.

Figure 3.3.1. Hydrogen storage tanks.

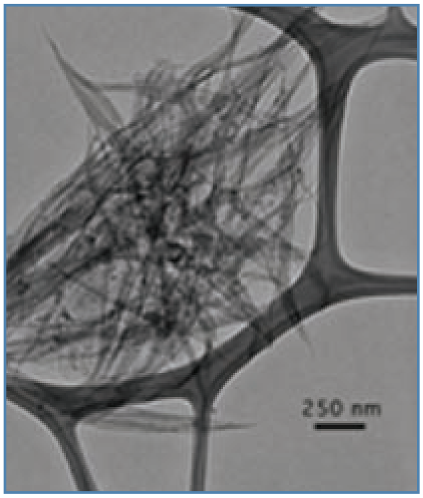


The Hydrogen Storage Program element will include on-going analysis to examine the lifecycle cost, energy efficiency, and environmental impact of the technologies developed, any changes in the system-level requirements that might alter the technical targets, and the progress of each technology development effort toward achieving the technical targets.

As technologies are down-selected with potential for on-board storage, future activities on vehicle interface technologies will be coordinated with the Delivery Program element. Vehicle refueling connection devices will need to be compatible with high pressure and cryogenic storage in the near-term. In the long term, as progress is made on solid-state or liquid-based options, vehicle refueling issues such as thermal management or byproduct reclamation will need to be addressed.

Funding for hydrogen storage R&D will be scaled down according to measurable progress—as technical and cost targets are met or missed, funding for particular technological approaches will be adjusted. When all performance, safety and cost targets are met, hydrogen storage R&D funding will end as appropriate. If specific performance issues remain at that time, R&D could be extended if the risk of the continued effort is justified by the potential benefit.

Figure 3.3.2. Micrograph of carbon nanostructure for hydrogen storage.



3.3.3 Programmatic Status

Current Activities

Table 3.3.1 summarizes the current (FY 2004) activities in the Hydrogen Storage Program element. For compressed hydrogen, lightweight composite tanks with high-pressure ratings and conformability are being developed. Complex metal hydrides, including alanates and other promising materials, are being explored to determine their potential for hydrogen storage and to improve our understanding of hydrogen storage processes. The search for new metal hydrides also includes combinatorial and high-throughput materials development and screening. Similarly, carbon nanotubes and other carbon-based materials are being investigated to explore possible novel hydrogen uptake mechanisms. Projects on chemical hydrogen storage, such as sodium borohydride and magnesium hydride slurries, were initiated in FY 2004, with a focus on the key issue for chemical hydrogen storage—off-board regeneration of the spent fuel. A project was also initiated on off-board hydrogen storage and will be coordinated with the Delivery Program element (see section 3.2). Also shown below are the new awards on novel materials and concepts that were announced in FY 2004. New projects on systems analysis will include performance, cost and life-cycle analyses of on-board storage options. Finally, a test and evaluation facility is being established to develop standard test protocols and provide independent verification of hydrogen storage performance in reversible solid-state materials.

In FY 2005, coordinated activities will be launched with multiple university, industry and national laboratory partners in the key focus areas of metal hydrides, carbon-based materials and chemical hydrogen storage. New materials and concepts will be an emphasis in the FY05 storage portfolio. Future efforts also include collaboration with the DOE Office of Science in FY 2005 on basic science, theory and modeling related to various hydrogen storage technologies.

Table 3.3.1. Current Hydrogen Storage Activities

Approach	Organizations	Project Focus
Compressed Hydrogen Tanks	Quantum	10,000 psi Composite Tanks, Cost Reduction
	Lawrence Livermore National Laboratory	Cryo-compressed Tanks and Advanced Concepts
Complex Metal Hydrides	United Technologies Research Center (2 projects)	Materials discovery of new alanate compositions; study of system prototype using sodium alanate
	United Oil Products (UOP)	Discovery of novel complex hydrides using combinatorial methods
	Center of Excellence on Metal Hydrides (Sandia National Laboratory-Livermore, Brookhaven National Laboratory, California Institute of Technology, General Electric, HRL Laboratories, Intematix Corporation, Jet Propulsion Laboratory, NIST, Oak Ridge National Laboratory, Savannah River National Laboratory, Stanford University, University of Hawaii, University of Illinois-Urbana-Champaign, University of Nevada-Reno, University of Pittsburgh/Carnegie Mellon University, University of Utah)	Light-weight complex hydrides, destabilized binary hydrides, intermetallic hydrides, modified lithium amides, and other on-board reversible hydrides
Carbon	Center of Excellence on Carbon-based Materials (National Renewable Energy Laboratory, Air Products & Chemicals, Inc., California Institute of Technology, Duke University, Lawrence Livermore National Laboratory, NIST, Oak Ridge National Laboratory, Penn State University, Rice University, University of Michigan, University of North Carolina, University of Pennsylvania)	Carbon-based materials and high surface area sorbents; storage capacity, mechanisms, characterization, optimization
Chemical Hydrides	Millennium Cell	Sodium borate regeneration
	Air Products & Chemicals, Inc.	Liquid chemical hydride
	Safe Hydrogen LLC	Magnesium hydride slurry
	Center of Excellence on Chemical Hydrogen Storage (Los Alamos National Laboratory, Pacific Northwest National Laboratory, Intematix, Millennium Cell, Northern Arizona University, Penn State University, Rohm and Haas, University of Alabama, UC-Davis, UCLA, University of Pennsylvania, University of Washington, US Borax)	New chemical hydrogen storage and regeneration processes

New Materials and Concepts	Cleveland State University	Complex metal nanostructured grids
	Alfred University	Hollow glass microspheres and electromagnetic radiation
	Carnegie Institute of Washington	Clathrates
	Gas Technology Institute	Graphite-based materials
	Michigan Technological University	Metal perhydrides
	Research Triangle Institute	Nitrogen/boron hydrides
	SUNY -Syracuse	Novel nanostructured activated carbon materials
	TOFTEC, Inc.	Synthesis of carbon and boron nitride materials by gamma irradiation
	University of California-Berkeley and Lawrence Berkeley National Laboratory	Nanoporous polymers, nanoporous coordination solids, destabilized high-density hydrides, nanostructured boron nitride and magnesium and metal alloy nanocrystals
	University of California-Santa Barbara	Nanoporous nickel phosphates, inorganic and organic framework materials and metal hydrogen complexes
	University of Connecticut	Mechanically activated, nanoscale lithium nitride materials
	University of Michigan	Metal-organic frameworks
	University of Missouri	Organic clathrates
	University of Pennsylvania and Drexel University	Carbide based nanomaterials
Testing and Evaluation	Southwest Research Institute	Standard Test Protocols, Independent Test Facility
Analysis	TIAX LCC	Analysis of performance and life cycle costs of on-board storage options
	Argonne National Laboratory	Analysis of hybrid concepts and systems

Technology Status (Demonstrations)

In the area of on-board hydrogen storage, the state-of-the-art is 5,000- and 10,000-psi compressed tanks, and cryogenic liquid hydrogen tanks. Tanks have been certified worldwide according to ISO 11439 (Europe), NGV2 (U.S.), and Reijikijun Betten (Iceland) standards, and approved by TUV (Germany) and KHK (Japan). They have been demonstrated in several prototype fuel cell vehicles and are commercially available at low production volumes. All-composite 10,000-psi tanks have demonstrated a 2.35 safety factor (23,500-psi burst pressure) as required by the European Integrated Hydrogen Project specifications. Liquid hydrogen tanks have also been demonstrated. A sodium borohydride system has been demonstrated in a concept vehicle. A lithium hydride slurry prototype has been demonstrated in a pick up truck with a hydrogen internal combustion engine.

3.3.4 Technical Challenges

For transportation applications, the overarching technical challenge for hydrogen storage is how to store the necessary amount of hydrogen fuel required for conventional driving range (>300 miles), within the constraints of weight, volume, durability, efficiency and total cost. Clearly, many important technical challenges for hydrogen storage must be resolved to meet the ultimate performance and safety targets. Substantial improvements must be made in the weight, volume and cost of these systems, for vehicular applications. Durability over the performance lifetime of these systems must be verified and validated, and acceptable refueling times must be achieved. Section 3.3.4.1 lists specific technical targets that the hydrogen storage system must achieve to meet customer-driven requirements for vehicle performance. Section 3.3.4.2 lists the specific technical barriers that must be overcome to achieve the performance targets. Section 3.3.5 describes the tasks that will be carried out to resolve the identified technical barriers.

3.3.4.1 Technical Targets

The technical performance targets for hydrogen storage systems are summarized in Table 3.3.2. Figure 3.3.3 shows the status of current technologies relative to performance and cost targets. These targets were established through the FreedomCAR and Fuel Partnership between DOE, the U.S. Council for Automotive Research (USCAR) and the energy companies. The targets are subject to change as more is learned about system-level requirements and as fuel cell technology progresses.

Based on the lower heating value (LHV) of hydrogen and greater than 300-mile vehicle range, the targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. The targets are based on the U.S. weighted average corporate vehicle (WACV) that includes minivans, light trucks, economy cars, and SUV/crossover vehicles, in proportion to their sales. A detailed explanation of each target is provided at www.eere.energy.gov/hydrogenandfuelcells. It should also be noted that unless otherwise indicated in Table 3.3.2, the targets are for both internal combustion engine and fuel cell power plants.

In addition, hydrogen storage systems must be energy efficient in delivering hydrogen to the vehicle power plant. For on-board reversible systems, greater than 90% energy efficiency for the energy delivered to the power plant from the on-board storage system is required. For systems regenerated off-board, the overall efficiency is also important. In this case, the energy content of the hydrogen delivered to the automotive power plant should be greater than 60% of the total energy input to the process, including the input energy of hydrogen and any other fuel streams for generating process heat and electrical energy. This is based on the DOE on-board target of 90% efficiency and the DOE off-board energy efficiency targets of 79% for hydrogen produced from natural gas and 85% for well-to-tank efficiency.

.

Table 3.3.2. Technical Targets: On-Board Hydrogen Storage Systems

Storage Parameter	Units	2007[a]	2010	2015
Usable, specific-energy from H_2 (net useful energy/max system mass)[b] ("Gravimetric Capacity")	kW·h/kg (kg H_2/kg)	1.5 (0.045)	2 (0.06)	3 (0.09)
Usable energy density from H_2 (net useful energy/max system volume) ("Volumetric Capacity")	kW·h/L (kg H_2/L)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost[c]	\$/kW·h net (\$/kg H_2)	6 (200)	4 (133)	2 (67)
Fuel cost[d]	\$ per gallon gasoline equivalent at pump	3	1.5	1.5
Operating ambient temperature[e]	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)
Cycle life (1/4 tank to full)[f]	Cycles	500	1000	1500
Cycle life variation[g]	% of mean (min) @ % confidence	N/A	90/90	99/90
Minimum and Maximum delivery temperature of H_2 from tank	°C	-20/85	-30/85	-40/85
Minimum full-flow rate	(g/s)/kW	0.02	0.02	0.02
Minimum delivery pressure of H_2 from tank; FC=fuel cell, ICE=internal combustion engine	Atm (abs)	8 FC 10 ICE	4 FC 35 ICE	3 FC 35 ICE
Maximum delivery pressure of H_2 from tank[h]	Atm (abs)	100	100	100
Transient response 10%-90% and 90%-0%[i]	s	1.75	0.75	0.5
Start time to full-flow at 20°C[j]	s	4	4	0.5
Start time to full-flow at minimum ambient[j]	s	8	8	2
System Fill Time	min	10	3	2.5
Loss of useable hydrogen[k]	(g/h)/kg H_2 stored	1	0.1	0.05
Quality[l] (H_2 from storage system)	%	98% (dry basis)		
Permeation and leakage[m]	Scc/h	Federal enclosed-area safety-standard		
Toxicity		Meets or exceeds applicable standards		
Safety		Meets or exceeds applicable standards		

Useful constants: 0.2778kWh/MJ, ~33.3kWh/gal gasoline equivalent.

[a] Some near-term targets have been achieved with compressed and liquid tanks. Emphasis is on materials-based technologies.

[b] Generally the 'full' mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.

[c] 2003 US\$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.

[d] 2001 US\$; includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H_2 production cost of \$1.50/gasoline gallon equivalent untaxed (subject to change based on DOE hydrogen production cost target).

[e] Stated ambient temperature plus full solar load. No allowable performance degradation from –20C to 40C. Allowable degradation outside these limits is TBD.

[f] Equivalent to 100,000; 200,000; and 300,000 miles respectively (current gasoline tank spec).

[g] All targets must be achieved at end of life.

[h] In the near term, the forecourt should be capable of delivering 10,000 psi compressed hydrogen, liquid hydrogen, or chilled hydrogen (77 K) at 5,000 psi. In the long term, it is anticipated that delivery pressures will be reduced to between 50 and 150 atm for solid state storage systems, based on today's knowledge of sodium alanates.

[i] At operating temperature.

[j] Flow must initiate within 25% of target time.

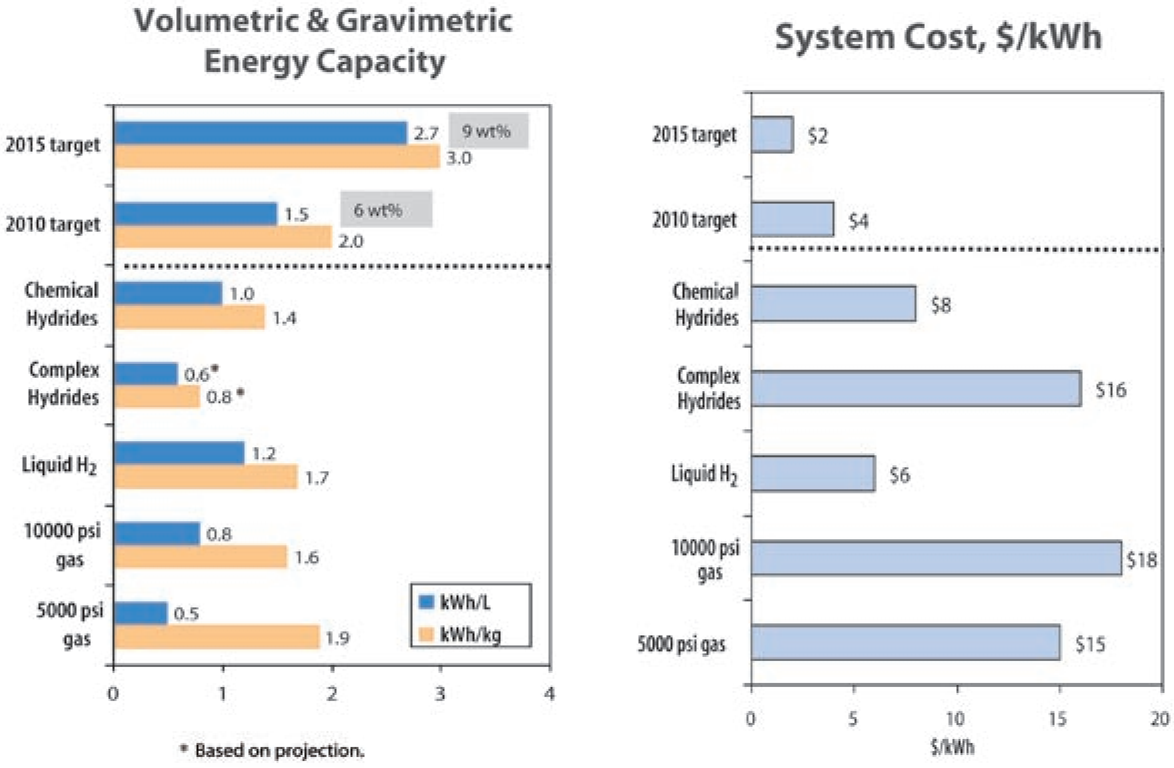
[k] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

[l] For fuel cell systems, steady state levels less than 10 ppb sulfur, 1 ppm carbon monoxide, 100 ppm carbon dioxide, 1 ppm ammonia, 100 ppm non-methane hydrocarbons on a C-1 basis; oxygen, nitrogen and argon can't exceed 2%. Particulate levels must meet ISO standard 14687. Some storage technologies may produce contaminants for which effects are unknown; these will be addressed as more information becomes available.

[m] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/NGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.

The current status for system capacity and cost, as shown in Figure 3.3.3, are estimates provided by technology developers and the R&D community. All targets must be achieved simultaneously; however, status is not neccessarily reported from a single system. Because it is challenging to estimate *system-level* weights and volumes when research is still at the stage of materials development, the current status data will be revisited and updated periodically. However, it is clear that none of the current systems meets the combined gravimetric, volumetric, and system cost targets for either 2010 or 2015. Also note that although recent accomplishments may show materials-based capacities as high as 5 wt%, the targets of 6 wt% by 2010 and 9 wt% by 2015 are *system-level* capacities that include the material, tank and all balance-of-plant components of the storage system. The system-level data also needs to include the first charge of hydrogen as well as any preconditioning such as purification, liquefaction and regeneration of material, particularly for chemical hydrogen storage, for which the cost of regenerating spent fuel will need to be included.

Figure 3.3.3 Status of current technologies relative to the key performance and cost targets.



3.3.4.2 On-Board Hydrogen Storage Technical Barriers

General

A. **Cost.** The cost of on-board hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost materials and components for hydrogen storage systems are needed, as well as low-cost, high-volume manufacturing methods.

B. **Weight and Volume.** The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate vehicle range compared to conventional petroleum fueled vehicles. Materials and components are needed that allow compact, lightweight, hydrogen storage systems while enabling greater than 300-mile range in all light-duty vehicle platforms. Reducing weight and volume of thermal management components is required.

C. **Efficiency.** Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out of the material is an issue for reversible solid-state materials. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent medium and by-products are typically regenerated off-board. In addition, the energy associated with compression and liquefaction must be considered for compressed and liquid hydrogen technologies. Thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency.

D. **Durability.** Durability of hydrogen storage systems is inadequate. Materials and components are needed that allow hydrogen storage systems with a lifetime of 1500 cycles and tolerance to fuel contaminants.

E. **Refueling Time.** Refueling times are too long. There is a need to develop hydrogen storage systems with refueling times of less than three minutes, over the lifetime of the system. Thermal management during refueling is a critical issue that must be addressed.

F. **Codes and Standards.** Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, have not been established. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. **System Life-Cycle Assessments.** Assessments of the full life cycle, cost, efficiency, and environmental impact for hydrogen storage systems are lacking.

Compressed Gas Systems

H. **Sufficient Fuel Storage for Acceptable Vehicle Range.** Compressed hydrogen storage systems that contain enough hydrogen to provide equivalent range to conventional vehicles are too bulky, which compromises passenger and luggage space.

I. **Materials.** High-pressure containment limits the choice of construction materials and fabrication techniques, within the weight, volume, performance, and cost constraints. Research into new materials such as metal ceramic composites, improved resins, and engineered fibers is needed to meet cost targets without compromising performance. Materials to meet performance and cost requirements for hydrogen delivery and off-board storage are also needed (see Hydrogen Delivery section 3.2).

J. **Lack of Tank Performance Data**. An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failure due to accident or to neglect is lacking. Data on tank performance and failure are needed to optimize tank structure for performance and cost. An independent test facility is needed that has the capability to acquire the required data.

K. **Balance of Plant (BOP) Components.** Light-weight, cost-effective, high-pressure balance-of-plant components are lacking. These include tubing, fittings, check valves, regulators, filters, relief and shut-off valves, and sensors.

Cryogenic Liquid Systems

L. **Liquefaction Energy Penalty and Hydrogen Boil-Off**. The boil-off of liquid hydrogen requires venting, reduces driving range and presents a potential safety/environmental hazard, particularly when the vehicle is in an enclosed environment. The energy penalty associated with liquefaction, typically 30% of the lower heating value of hydrogen, is an issue. Materials and methods to reduce boil-off in cryogenic tanks and to reduce the energy requirements for liquefaction are needed.

Reversible Solid-State Material Storage Systems (Regenerated On Board)

M. **Hydrogen Capacity and Reversibility.** Hydrogen capacity and reversibility are inadequate at practical operating temperatures and pressures and within refueling time constraints. Adequate cycle life of these systems has not been demonstrated.

N. **Lack of Understanding of Hydrogen Physisorption and Chemisorption.** Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of absorption/desorption kinetics is needed to optimize hydrogen uptake and release capacity rates.

O. **Test Protocols and Evaluation Facilities.** Standard test protocols and independent facilities for evaluation of hydrogen storage materials are lacking.

P. **Dispensing Technology.** Requirements for dispensing hydrogen to and from the storage system have not been defined. This includes meeting heat rejection requirements during fueling.

Q. **Thermal Management.** Reversible materials typically require heat to release hydrogen on board. Heat must be provided to the storage system at reasonable temperatures to meet the flow rates needed by the vehicle powerplant. Similarly, while charging the material with hydrogen, a significant challenge is removal of the heat generated within the fueling time requirements.

Chemical Hydrogen Storage Systems (Typically Regenerated Off Board)

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

S. **By-Product/Spent Material Removal.** The refueling process is potentially complicated by removal of the byproduct and/or spent material. System designs must be developed to address this issue and the infrastructure requirements for off-board regeneration.

T. **Heat Removal.** Significant heat may be generated or required during formation of hydrogen, requiring substantial thermal management.

3.3.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.3.3. Issues regarding safety will be addressed within each of the tasks. The barriers associated with each task appear after the task title.

Table 3.3.3. Technical Task Descriptions

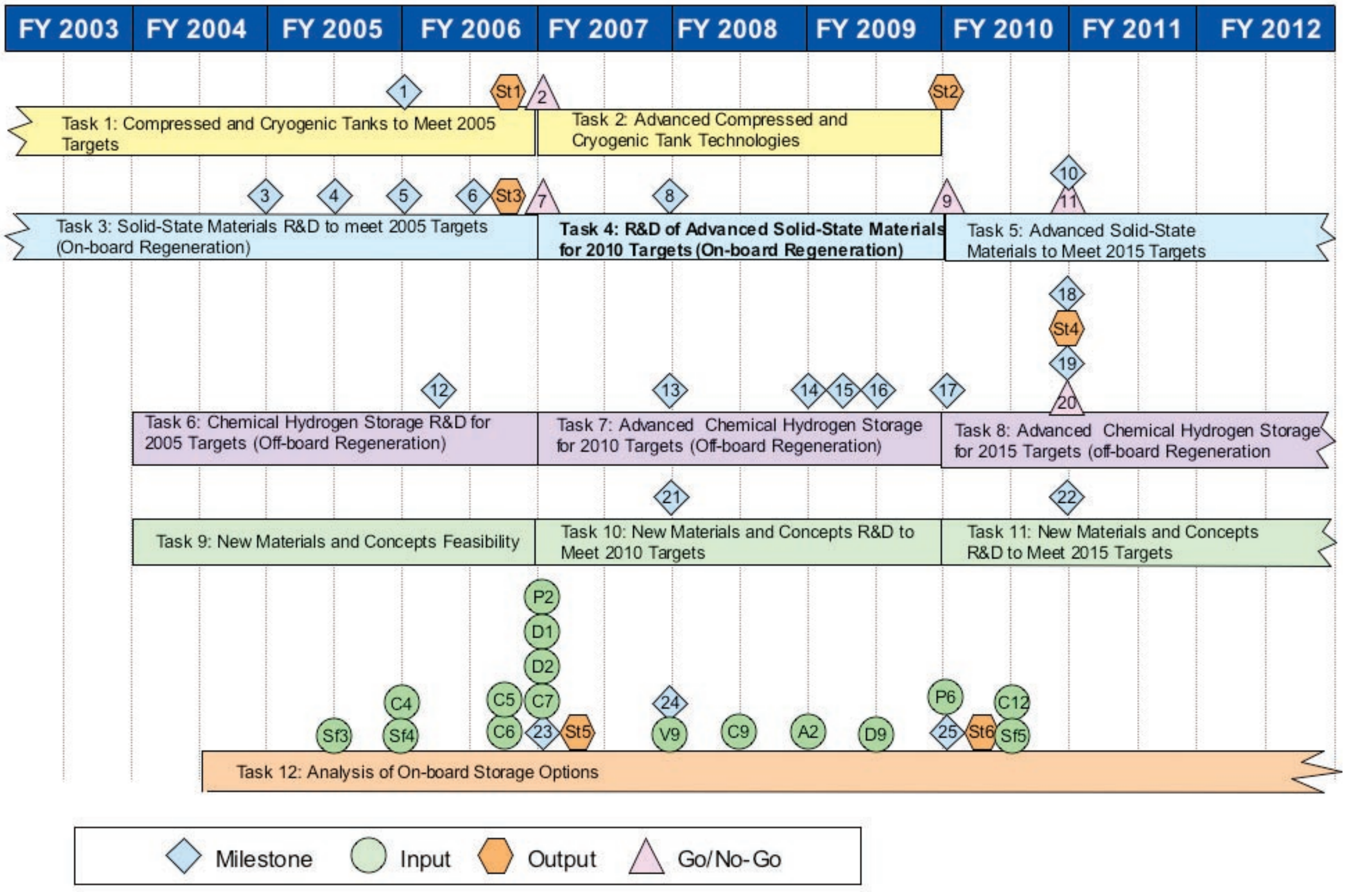
Task	Description	Barriers
1	**Compressed and Cryogenic Tanks to Meet 2005 Targets** • Develop, demonstrate and verify low cost, compact 10,000-psi storage tanks. • Assess the need for liner materials to reduce hydrogen gas permeation. • Develop and optimize carbon fiber/epoxy over-wrap. • Identify alternate designs and materials for advanced, integrated storage systems. • Explore conformable tanks for compressed hydrogen. • Demonstrate safety of hydrogen storage systems. • Explore compressed gas/reversible storage material hybrid systems. • Establish an independent test facility to acquire data on performance and durability of compressed tanks using standardized test methods. • Develop lightweight, low-cost balance of plant components for compressed and cryogenic tanks. • Study requirements and conceptual designs for cost-competitive off-board storage of hydrogen, including underground scenarios.	A-L
2	**Advanced Compressed and Cryogenic Tank Technologies** • Develop advanced compressed and cryogenic tank technologies to meet 2010 targets.	A-L
3	**Solid-State Hydrogen Storage Materials R&D to Meet 2005 Targets (On-board Regenerated)** • Perform theoretical modeling to provide guidance for materials development. • Improve understanding of sodium alanate system to aid development of alanate and other complex hydride materials with higher hydrogen capacities. • Investigate a family of alanate materials with hydrogen capacities of 6 wt% or greater with adequate charge/discharge kinetics and cycling characteristics. • Investigate composite-wall containers compatible with the optimal alanate materials. • Determine the decomposition products and pathways of materials to better understand their mechanisms and kinetics. • Engineer a hydride bed capable of efficiently storing and releasing hydrogen at 90°C. • Determine the hydrogen storage capacity of nanostructured carbon materials; demonstrate reproducibility of synthesis and capacity measurements. • Develop cost-effective fabrication processes for promising nanostructured carbon materials. • Explore combinatorial approaches to rapidly identify promising hydrogen storage materials. • Perform analyses to assess cost effectiveness of reversible hydrogen storage materials including scale-up to high-volume production. • Explore non-thermal discharging methods, including mechanical, chemical and electrical mechanisms. • Establish an independent test facility and standard test protocols to evaluate reversible hydrogen storage materials.	A-G, M-Q
4	**Advanced Solid-State Materials to Meet 2010 Targets (On-board Regeneration)** • Develop and verify most promising reversible storage materials to meet 2010 targets.	A-G, M-Q

5	**Advanced Solid-State Materials** • Develop and verify most promising reversible storage materials to meet 2015 targets.	A-G, M-Q
6	**Chemical Hydrogen Storage (Off-board Regeneration)** • Identify a family of chemical hydrogen storage materials capable of meeting weight and volume goals. Characterize the reaction chemistry and thermodynamics of the most promising candidates. • Rank viable candidates according to hydrogen capacity based on resource availability, full fuel cycle energy efficiency and emissions, and cost of the delivered fuel. • Identify and develop improved processes, chemistry, catalysts and operating conditions for the complete fuel cycle. • Evaluate the safety performance of the complete system. • Verify an entire closed loop, chemical hydrogen storage system, including an efficient regeneration process that meets cost and performance targets. • Ensure compatibility with applicable codes and standards for on-vehicle storage and fueling interface. • Assess the impact of a potentially complicated refueling process (due to spent material or by-product removal) on implementation of hydrogen storage systems that are regenerated off-board.	A-G, R, S
7	**Advanced Chemical Hydrogen Storage (Off-board Regeneration)** • Develop and verify most promising chemical hydrogen storage materials to meet 2010 targets.	A-G, R-T
8	**Advanced Chemical Hydrogen Storage (Off-board Regeneration)** • Develop and verify most promising chemical hydrogen storage materials to meet 2015 targets.	A-G, R-T
9	**New Materials and Concepts Feasibility** • Identify and investigate new materials and storage approaches that have the potential to achieve 2010 targets of 2 kWh/kg (6wt%) or greater, and 1.5 kWh/L or greater.	A-G
10	**New Materials and Concepts R&D** • Develop and characterize new materials and concepts to meet 2010 targets.	A-G
11	**New Materials and Advanced Concepts R&D** • Develop and characterize new materials and advanced concepts to meet 2015 targets.	A-G
12	**Analysis of On-board Storage Options** • Conduct analyses to examine life-cycle cost, energy efficiency, and environmental impacts of the technologies developed, changes in the system level requirements that might alter the technical targets, and progress of each technology development effort toward achieving the technical targets.	A-G

3.3.6 Milestones

Figure 3.3.4 shows the interrelationship of milestones, tasks, supporting inputs and outputs from other Program elements from FY 2004 through FY 2010. This information is also summarized in Table B.3 in Appendix B.

Figure 3.3.4. Hydrogen Storage R&D Milestone Chart



For chart details see next page.

Milestones

1 Complete feasibility study of hybrid tank concepts.
2 Go/No-Go: Decision on compressed and cryogenic tank technologies for on-board vehicular applications.
3 Complete construction of materials test facility.
4 Complete verification of test facility.
5 Reproducibly demonstrate 4wt% material capacity on carbon nanotubes.
6 Complete prototype complex hydride integrated system meeting 2005 targets.
7 Go/No-Go: Decision point on carbon nanotubes.
8 Down-select on-board reversible metal hydride materials.
9 Go/No-Go: Decision point on advanced carbon-based materials.
10 Complete prototype complex hydride integrated system meeting 2010 targets.
11 Go/No-Go: Decision on continuation of on-board reversible metal hydride R&D.
12 Complete preliminary estimates of efficiency for off-board regeneration.
13 Down-select from chemical hydrogen regeneration processes.
14 Demonstrate efficient chemical hydrogen regeneration laboratory process.
15 Complete chemical hydrogen storage life-cycle analyses.
16 Down-select from chemical hydrogen storage approaches for 2010 targets.
17 Complete prototype chemical hydrogen storage integrated system.
18 Demonstrate scaled-up chemical hydrogen regeneration process.
19 Identify advanced chemical hydrogen regeneration laboratory process with potential to meet 2015 targets.
20 Go/No-Go: Decision point on chemical storage R&D for 2015 targets.
21 Down-select from new material concepts to meet 2010 targets.
22 Down-select the most promising new material concepts for continued development.
23 Complete baseline analyses of on-board storage options for 2010 targets.
24 Update onboard storage targets.
25 Complete analyses of on-board storage options for 2010 and 2015 targets.

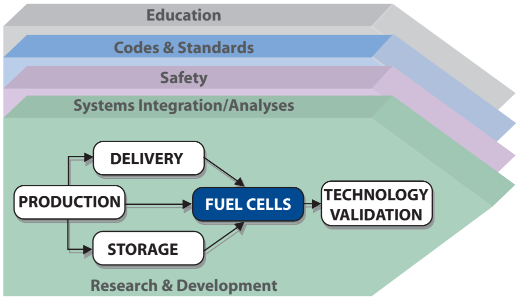
Outputs

St1 Output to Fuel Cells and Technology Validation: Compressed and cryogenic liquid storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.
St2 Output to Fuel Cells and Technology Validation: Advanced compressed/cryogenic tank technologies.
St3 Output to Fuel Cells and Technology Validation: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.
St4 Output to Delivery, Fuel Cells and Technology Validation: Full-cycle, integrated chemical hydrogen system meeting 2010 targets.
St5 Output to Delivery, Systems Analysis and Systems Integration: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.
St6 Output to Delivery, Systems Analysis and Systems Integration: Finalon-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary on-board storage system candidate.

Inputs

Sf3 Input from Safety: Safety requirements and protocols for refueling.
C4 Input from Codes and Standards: Standards for compressed gaseous on-board storage.
Sf4 Input from Safety: Safety requirements for on-board storage.
C5 Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification.
C6 Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.
P2 Input from Production: Assessment of fuel contaminant composition.
D1 Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.
D2 Input from Delivery: Hydrogen contaminant composition and issues.
C7 Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
C9 Input from Codes and Standards: Materials compatibility technical reference.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
D9 Input from Delivery: Off-board storage technology.
P6 Input from Production: Assessment of fuel contaminant composition.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.
Sf5 Input from Safety: Safety requirements and protocols for refueling.

3.4 Fuel Cells



Fuel cells have the potential to replace the internal combustion engine in vehicles and to provide power in stationary and portable power applications because they are energy efficient, clean and fuel flexible. Hydrogen or any hydrogen-rich fuel can be used by this emerging technology. For transportation applications, the Program is focusing on direct hydrogen fuel cells, in which hydrogen is stored on board and is supplied by a hydrogen generation, delivery, and fueling infrastructure. This infrastructure is being developed in parallel with the fuel cell development efforts.

Prior to August 2004, significant fuel cell activity resources supported on-board vehicle fuel processing, where hydrogen could be produced from fuels such as gasoline, methanol, ethanol, natural gas or other hydrocarbons, supplied by the existing infrastructure. Subsequently, DOE has decided to discontinue on-board fuel processing R&D. Further discussion relating to this decision can be found in Programmatic Status (section 3.4.3).

For distributed generation applications, fuel cell systems will likely be fueled with natural gas or liquefied petroleum gas (LPG, consisting predominantly of propane) in the near term and in the longer term by renewable fuels. Fuel cells for auxiliary power units in trucks will use either diesel or LPG and recreational vehicles will be powered by LPG alone. In small consumer electronics, hydrogen or methanol will be the fuel of choice for fuel cell systems.

3.4.1 Technical Goal and Objectives

Goal

Develop and demonstrate fuel cell power system technologies for transportation, stationary and portable applications.

Objectives

- By 2010, develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW; by 2015, a cost of $30/kW.
- By 2010, develop a distributed generation PEM fuel cell system operating on natural gas or LPG that achieves 40% electrical efficiency and 40,000 hours durability at $400-$750/kW.
- By 2010, develop a fuel cell system for consumer electronics with (<50 W) an energy density of 1,000 Wh/L.
- By 2010, develop a fuel cell system for auxiliary power units (3-30 kW) with a specific power of 100 W/kg and a power density of 100 W/L.

3.4.2 Technical Approach

Fuel cell research and development will emphasize high efficiency and durability and low material and manufacturing costs of the fuel cell stack, and balance-of-plant components like air compressors, and sensors and controls. However, each application – light vehicle transportation, auxiliary power units (APUs) for heavy duty vehicles, stationary, and portable power for consumer electronics—requires a different approach for technology development. Specifically, polymer electrolyte membrane (PEM) fuel cells, shown in Figure 3.4.1, are the current focus for light duty vehicles because they have fast start capability and operate at low temperatures. Solid oxide fuel cells (SOFCs) generate more power (have higher power density) and are more applicable as APUs on heavy duty vehicles where systems may run for extended periods without frequent start and stop cycles. Direct methanol fuel cells (DMFCs) are well suited for portable power applications in consumer electronic devices where the power requirements are low and the cost targets are not as stringent as for transportation applications. The emphasis of the Program is fuel replacement for light duty vehicles to reduce our nation's dependence on imported petroleum. In addition to this transportation fuel cell application focus, i.e. direct hydrogen fuel cell vehicles, the program also supports stationary, portable power and auxiliary power applications to a limited degree where earlier market entry would assist in the development of a fuel cell manufacturing base.

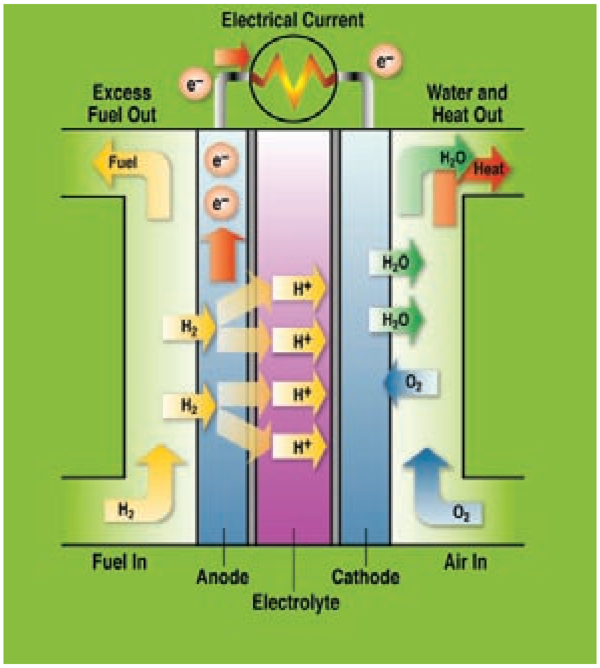


Figure 3.4.1. Polymer Electrolyte Membrane Fuel Cell

To meet the efficiency, durability and cost requirements for fuel cells, research and development will focus on identifying less expensive new materials and novel fabrication methods for membranes, catalysts and bipolar plates. Testing of these new materials and fabrication methods will be carried out by industry, national laboratories and universities. Progress has already been made in developing fuel cell membranes that are capable of operating at 120ºC or above for better thermal management. In addition, advances continue to be made in minimizing precious metal loading, assessing and improving component durability, and developing thin catalyst coatings for membranes, high-volume fabrication processes, and highly conductive, gas-impermeable bipolar plates.

In comparison to prior years, much less emphasis will be placed on fuel cell systems development. Instead, R&D efforts will focus on materials, components, and enabling technologies for low-cost fuel cell power systems operating on direct hydrogen for transportation, reformed natural gas or LPG for stationary applications, reformed diesel or LPG for auxilary power and methanol for consumer electronic applications. Validation of fuel cell technology targets related to performance, reliability, durability and environmental benefits will be conducted in the Hydrogen Infrastructure and Fuel Cell Vehicle Learning Demonstration. The Technology Validation Program element (see section 3.5) will provide data under real-world conditions and, in turn, supply valuable fuel cell results to help refine and direct future activities for fuel cell R&D.

Fuel cell R&D will taper and eventually end once the technical targets are achieved and the technologies are commercially adopted. When major cost milestones are met for stationary and transportation applications, the R&D in those areas will conclude. If specific cost performance and durability issues remain, R&D could be extended, assuming the cost of a continued effort is justified by the anticipated benefits.

3.4.3 Programmatic Status

As mentioned earlier, the Fuel Cell team conducted a review of on-board fuel processing for transportation applications during 2004. In August of 2004 DOE decided to discontinue on-board fuel processing R&D.

Specific criteria for the on-board fuel processing decision are shown in Table 3.4.1.

Table 3.4.1 DOE On-Board Fuel Processing Go/No-Go Criteria

Attribute	Units	2004 Demo Criteria	Current Status (2/2004)	Ultimate Target	Probability of Reaching Ultimate Target
Durability	hours	2000 and >50 stop/starts	1000	5,000 and 20,000 starts	medium
Power Density	W_e/L	700	700	2,000	medium
Efficiency	%	78	78	>80	high
Start–up Energy	MJ/50 kW_e	<2	7	<2	low
Start–up Time (+20°C)	sec	<60 to 90% traction power	600	<30 to 90% traction power <2 to 10%	low
Transient Response	sec	<5, 10% to 90% and 90% to 10%	10	<1, 10% to 90%, and 90% to 10%	low
Turndown	ratio	20:1	20:1	> 50:1	medium
Sulfur Content	ppb	<50 out from 30 ppm in	130	<10 out from 30 ppm in	medium
Cost	\$/kW_e	n/a	65	<10	low

A review of on-board fuel processing activities was conducted. It concluded that, based on the current state of the technology, it was unlikely that on-board fuel processing would improve sufficiently to support the transition to a hydrogen economy. This decision included consideration of the following key factors:

- The Hydrogen Fuel Initiative accelerated hydrogen technology development and lessened the contribution that on-board fuel processing could make as a transitional technology;
- Compared to today's gasoline hybrid electric vehicle technologies, on-board fuel processing for fuel cell vehicles offered only marginal improvements in efficiency and emissions; and
- Existing technical and cost targets cannot be met with current fuel processing technologies and no clear path forward has been articulated for meeting the difficult criteria associated with full implementation/integration of on-board fuel processing in fuel cell vehicles.

While on-board fuel processing activities will be terminated, the fuel processing activity will continue. Development projects supporting on-board fuel processing systems will be terminated or redirected. The Program continues to develop fuel processors for stationary applications and to develop fundamental catalysts suitable for a variety of fuel processing applications, such as auxiliary power applications (APU). Fuel processing research for APU will support the 21st Century Truck Initiative and the Office of Fossil Energy's Solid-State Energy Conversion Alliance (SECA).

Current Activities.

Table 3.4.2 summarizes the current activities of the Fuel Cells Program element.

Table 3.4.2 Current Fuel Cell Activities

Challenge	Approach	Activities
Transportation Systems		
Efficient, cost-effective compressor / expander technologies and thermal/water management systems	• New engineering approaches to compressor/expander technologies (e.g. lubricant-free) • Improve efficiencies and performance • Reduce weight and cost • Develop thermal and water management systems	• **Honeywell:** Integrated thermal/water management system that efficiently uses the fuel cell waste heat and water • **Mechanology:** Toroidal intersecting vane compressor/expander module • **Honeywell:** Turbo compressor for operation in PEMFC transportation systems • **Advanced Fluids (SBIR):** Improved coolant (water/glycol with nanoparticles) for use in PEM fuel cell systems • **Oak Ridge National Laboratory:** Carbon foam technology to recover water from fuel cell exhaust and humidify inlet air
Effective, reliable physical and chemical sensors	• Develop accurate, reliable, fast-responding sensors to measure physical properties and chemical species. • Reduce cost and footprint	• **Honeywell:** Physical sensor technology meeting customer requirements • **UTC Fuel Cells:** Physical and chemical sensors for fuel cell application • **Lawrence Livermore National Laboratory:** Hydrogen safety and performance sensors • **Oak Ridge National Laboratory:** Fiber optic temperature sensor
System and market analysis	• Assess potential for cost reductions to reach customer-acceptable levels • Evaluate the potential market demand and economics of fuel cell systems	• **National Renewable Energy Laboratory:** Fuel cell vehicle system analysis, trade-offs and optimization[a] • **New project:** Cost analysis of fuel cell systems[a] • **Argonne National Lab:** System analysis, trade-offs and optimization[a]
Stationary Systems		
High-temperature membranes for stationary applications	• Development of high-temperature membranes to facilitate combined heat and power applications meeting 40,000 hour durability requirement	• **Plug Power:** Poly-benzimidazole membranes
Stationary fuel cell system development and demonstrations	• Develop and demonstrate integrated systems for distributed generation and back-up power	• **UTC Fuel Cells:** Distributed generation • **Plug Power:** Back-up power • **IdaTech:** Combined heat and power • **National Renewable Energy Laboratory:** Computer aided engineering (CAE) for durability of fuel cell components[a]
System and market analysis	• Perform economic analysis of fuel cells and their associated markets	• **Battelle:** Economic analysis of stationary fuel cell markets[a]

---

[a] Also listed in Systems Analysis Table 5.4.1.

Fuel Processors		
Distributed natural gas or LPG fueled	• Develop technology for reforming natural gas or LPG • Develop advanced catalysts	• **Nuvera:** Advanced reforming module for stationary applications • **ChevronTexaco:** Sorption- enhanced reformer for low-CO hydrogen production • **Argonne National Laboratory:** Develop advanced fuel processing and catalyst technology • **Oak Ridge National Laboratory:** Catalytic oxidation for hydrogen sulfide removal
Efficient fuel-flexible fuel processors. Transportation applications will end in FY2005	• Reduce cost, weight, and size • Simplify systems and improve efficiency	• **Catalytica:** New catalyst, plate-based reactor for gasoline steam reforming • **University of Michigan:** Microchannel fuel processing
Stack Components		
Low-cost, durable plates, membranes, catalysts, membrane electrode assemblies (MEAs), and high temperature membranes	• Develop new, lower-cost, longer-life materials • Investigate new MEA configurations and low cost catalyses • Determine fuel/air contaminant thresholds • Develop MEAs that tolerate excursions to 120 °C and/or operate at RH 25-50%. • Develop membranes that tolerate -40°C and fuel cells that start up at -20°C. • Evaluate catalyst recycling and reuse technologies	• **3M:** Advanced MEAs for 120°C operation and low cost manufacturing methods • **DeNora/DuPont:** New cathode alloys, high temperature MEAs with increased kinetics • **UTC Fuel Cells:** High temperature membranes with improved kinetics and CO tolerance • **DuPont:** Perfluorosulfonic acid membranes with extended lifetimes • **3M:** Perfluorosulfonic acid membranes with extended lifetimes • **Arkema (formerly Atofina Chemicals, Inc.):** Polyvinylidenefluoride-based membranes • **Cabot Superior Micropowders:** New cathode catalysts and structures for low platinum loading • **3M:** Innovative low cost technology to synthesize new non-precious metal catalysts and their supports • **University of S. Carolina:** Metallic nanoclusters as PEM fuel cell catalysts • **Ballard:** Metal/chalcogen based cathode catalysts • **Ion Power:** Catalyst coated fuel cell membrane and catalyst coated fuel processing component recycling and/or re-manufacture/reuse • **Engelhard:** Recover and recycle precious metals • **Porvair:** Pre-pilot scale production of net shape molded low cost carbon/carbon composite bipolar plates • **Oak Ridge National Laboratory:** Metallic bipolar plate alloy using thermal nitriding technology • **Los Alamos National Laboratory:** Advanced membranes, non-precious metal catalysts, and electrode technologies • **Argonne National Laboratory:** Advanced membranes and non-precious metal catalysts • **Lawrence Berkeley National Laboratory:** New electrocatalysts using materials-by-design approach • **Oak Ridge National Laboratory:** Characterize structural changes in membrane • **National Institute of Standards and Technology:** Characterize water transport in membrane • **Naval Research Laboratory:** Develop metal oxides as catalyst supports to reduce platinum loading • **Brookhaven National Laboratory:** Low platinum loading catalysts • **Case Western Reserve University:** Novel concepts for high-temperature/low humidity membrane application • **Los Alamos National Laboratory:** Investigate impact of freeze on the performance and durability of specific fuel cell components • **T/J Technologies (SBIR):** Low-cost polyphenylsulfonic acid (PPSA) membrane • **Farassis Energy (SBIR):** Low-cost cathode catalysts using novel combinatorial screening • **Nuvant (SBIR):** Low-cost cathode catalysts using high throughput, rapid screening methods • **Pacific Fuel Cell Corp. (STTR):** Nanocomposite membranes for high temperature PEMFCs

Portable Power/APUs/Off-Road Applications		
Auxiliary Power Unit (APU) system for heavy truck application to reduce idling of the main heavy duty engine	• Analysis and design of SOFC APU system • Develop and test subsystem components • Perform system integration and packaging • Perform vehicle integration	• **Cummins Power Generation:** Design, develop and perform in-vehicle demonstration of a diesel-fueled SOFC power system • **Delphi:** Build and test a full APU system in a laboratory demonstration with simulated load cycles • **Pacific Northwest National Laboratory:** Dynamic systems model and analysis capability for SOFC for APU
Consumer Electronics System	• Design, develop, fabricate and validate fuel cell systems for small portable power applications, such as cell phones and computers	• **MTI Microfuel Cells:** DMFC prototype for consumer electronics • **Polyfuel Inc:** DMFC system for all-day, wireless computing • **Giner (SBIR):** 20W DMFC stack using combined mixed reactant configuration • **Microcell (SBIR):** 20W regenerative PEMFC system with metal hydride fuel storage • **Renew Power (I&I):** Powering cell phones with fuel cells using renewable fuels
System which will allow PEM fuel cells to operate in off-road applications	• Characterize the concentration and distribution of contaminants found in off-road environments • Determine the impact of contaminants on fuel cell performance • Design a filtration system to mitigate the impact of off-road contaminants	• **IdaTech:** Team with UC Davis, Donaldson, and Toro to design, build, and test a system for off-road application

All the current R&D activities focus on advanced concepts, enabling technologies and the technical challenges discussed in the following section.

3.4.4 Technical Challenges

Cost and durability are the major challenges to fuel cell commercialization. Size, weight, and thermal and water management are also barriers to the commercialization of fuel cells. For transportation applications, fuel cell technologies face more stringent cost and durability requirements. In stationary power applications, raising the operating temperature of PEMs to increase fuel cell performance will also improve heat and power cogeneration and overall system efficiency.

Transportation Systems

Fuel cell power systems must be reduced in cost before they can be competitive with gasoline internal combustion engines (ICEs). The cost for automotive ICE power plants is currently about $25-35/kW; a fuel cell system needs to cost less than $50/kW for the technology to be competitive.

The durability of fuel cell systems has not been established. Fuel cell power systems will be required to be as durable and reliable as current automotive engines, i.e., 5,000 hour lifespan (150,000 miles equivalent) and able to function over the full range of vehicle operating conditions (-40° to +40° C).

Lightweight, compact on-board hydrogen storage systems and economically-viable hydrogen production and delivery also present challenges (see sections 3.1, 3.2 and 3.3).

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues. Fuel cell operation at lower temperatures creates a small difference between the operating and ambient temperatures necessitating large heat exchangers and humidifiers. These components use part of the power that is produced, reducing overall system efficiency.

Finally, the size and weight of current fuel cell systems must be further reduced to meet the packaging requirements for automobiles. Size and weight reduction applies not only to the fuel cell stack (catalysts, membranes, gas diffusion media, bipolar plates), but also to the ancillary components (e.g., compressor/ expander, heat exchangers, humidifiers, and sensors) making up the balance of plant.

Stationary/Distributed Generation Systems

Even though the specific performance requirements for stationary applications differ from transportation applications, some of the technical challenges are the same. For example, the overall cost of stationary fuel cell power systems must also be competitive with conventional technologies. Stationary systems, however, have an acceptable price point considerably higher than transportation systems; stationary systems are projected to cost $400–$750/kW for widespread commercialization and as much as $1000/kW for initial applications.

Performance of fuel cells for stationary applications for more than a few thousand hours must still be demonstrated but market acceptance of stationary applications will likely necessitate more than 40,000 hours of reliable operation at a temperature between -35^o C and 40^{o}C.

The low operating temperature of PEM fuel cells limits the amount of heat that can be effectively used in combined heat and power (CHP) applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems. Improved system designs that will enable CHP efficiencies exceeding 80% are also needed. Technologies that allow cooling to be provided from the heat rejected from stationary fuel cell systems (such as through regenerating desiccants in a desiccant cooling cycle) also need to be evaluated. Hybrid systems or other viable methods to decrease start-up times need to be developed for stationary fuel cell back-up power applications, which operate on direct hydrogen.

Portable Power Systems

Technical issues unique to fuel cell power systems for consumer electronics include: system and component miniaturization; small-scale fuel processing; microcompressors; fuel storage, distribution, and recharging for low-power applications; and system integration and packaging. Passive operation at near-ambient conditions and insensitivity to orientation are necessary for the low-power applications. Fuel delivery and storage, as well as safety, codes, and standards are important for consumer electronics and APUs.

3.4.4.1 Technical Targets

Tables 3.4.3 and 3.4.4 list the DOE technical targets specifically for integrated fuel cell power systems and PEM fuel cell stacks operating on direct hydrogen for transportation applications. These targets have been developed through the FreedomCAR and Fuel Partnership. Tables 3.4.5 through 3.4.7 list the DOE technical targets for stationary applications. The targets have been developed with input from developers of stationary fuel cell power systems, and have been established for small (3–25 kW) and large (50–250 kW) power levels. The targets assume a sulfur level in the natural gas or LPG of less than 6 ppm (average value). These R&D targets do not go beyond 2010 because stationary applications are closer to market than transportation applications. The 2010 targets are those that would be neccessary for successful commercialization.

Tables 3.4.8 and 3.4.9 list the DOE technical targets for consumer electronics, APUs, and truck refrigeration. The consumer electronics table is based on direct methanol fuel cell technology and the APUs and truck refrigeration table is based on solid oxide fuel cell technology and is consistent with the DOE Fossil Energy's SECA targets.

Tables 3.4.10 and 3.4.11 list DOE technical targets for automotive and stationary fuel cell system sensors and automotive compressor/expander units. All input powers to the compressor are specified for +40°C ambient air conditions and overall 50% system efficiency regardless of whether or not an expander is used. This requires that a higher stack voltage be used for those cases for which no expander is present; therefore, the stack must be slightly larger to compensate for such cases.

Tables 3.4.12 through 3.4.15 list DOE technical targets for fuel cell components: membranes, electrodes/catalysts, membrane electrode assemblies (MEAs), and bipolar plates. This reflects a shift in program focus from development of stack systems to more component-level research. These tables will assist component developers in evaluating progress without testing full systems.

Table 3.4.16 lists a first draft specification of hydrogen quality required as input into the fuel cell system.

All targets must be achieved simultaneously; however, status is not necessarily reported from a single system.

Table 3.4.3. Technical Targets: 80-kW_e (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen[a]

Characteristic	Units	2004 Status	2005	2010	2015
Energy efficiency[b] @ 25% of rated power	%	59	60	60	60
Energy efficiency @ rated power	%	50	50	50	50
Power density	W/L	450[c]	500	650	650
Specific power	W/kg	420[c]	500	650	650
Cost[d]	$/$kW_e$	120[e]	125	45	30
Transient response (time from 10% to 90% of rated power)	sec	1.5	2	1	1
Cold start–up time to 90% of rated power @–20°C ambient temp @+20°C ambient temp	 sec sec	 120 60	 60 30	 30 15	 30 15
Durability with cycling	hours	~1000[f]	2000	5000[g]	5000[g]
Survivability[h]	°C	–20	–30	–40	–40

[a] Targets exclude hydrogen storage.

[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

[c] Based on corresponding data in Table 3.4.4 divided by 3 to account for ancillaries.

[d] Based on 2002$ and cost projected to high-volume (500,000 stacks per year).

[e] Based on 2004 TIAX Study and will be periodically updated.

[f] Durability is being evaluated through the Technology Validation activities. Steady-state durability is 9,000 hours.

[g] Includes typical drive cycle.

[h] Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

Table 3.4.4. Technical Targets: 80-kW_e (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]

Characteristic	Units	2004 Status	2005	2010	2015
Stack power density[b]	W/L	1330[c]	1500	2000	2000
Stack specific power	W/kg	1260[c]	1500	2000	2000
Stack efficiency[d] @ 25% of rated power	%	65	65	65	65
Stack efficiency[d] @ rated power	%	55	55	55	55
Precious metal loading[e]	g/kW	1.3	2.7	0.3	0.2
Cost[f]	$\$/kW_e$	75[g]	65	30	20
Durability with cycling	hours	~1000[h]	2000	5000[i]	5000[i]
Transient response (time for 10% to 90% of rated power)	sec	1	2	1	1
Cold startup time to 90% of rated power					
@ –20ºC ambient temperature	sec	120	60	30	30
@ +20ºC ambient temperature	sec	<60	30	15	15
Survivability[j]	ºC	–40	–30	–40	–40

[a] Excludes hydrogen storage and fuel cell ancillaries: thermal, water, air management systems.

[b] Power refers to net power (i.e., stack power minus auxiliary power). Volume is "box" volume, including dead space, and is defined as the water-displaced volume times 1.5 (packaging factor).

[c] Average from Fuel Cells 2000, http://www.fuelcells.org/info/charts.html#fcvs, April 2004

[d] Ratio of output DC energy to lower heating value of hydrogen fuel stream. Peak efficiency occurs at about 25% rated power. Assumes system efficiency is 92% of stack efficiency.

[e] Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power. Precious metal target based on cost target of <$\$3/kW_e$ precious metals in MEA [@$450/troy ounce ($15/g), <0.2 g/kW_e]

[f] Based on 2002$ and cost projected to high-volume (500,000 stacks per year).

[g] Based on 2004 TIAX Study and will be periodically updated.

[h] Durability is being evaluated through Technology Validation activities. Steady-state durability is 9,000 hours.

[i] Includes typical drive cycle.

[j] Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

Table 3.4.5. Technical Targets[a]: Integrated Stationary PEM Fuel Cell Power Systems Operating on Natural Gas or LPG Containing 6 ppm Sulfur, Average

Characteristic	Units	Small (3–25 kW)			Large (50–250 kW)		
		2004 Status	2005	2010	2004 Status	2005	2010
Electrical Energy Efficiency[b] @ rated power	%	30[c]	32	35	30[c]	32	40
CHP Energy Efficiency[d] @ rated power	%	75[c]	75	80	75[c]	75	80
Cost[e]	$\$/kW_e$	3000	1500	1000	2500	1500	750
Transient Response Time (from 10% to 90% power)	msec	< 3	< 3	< 3	< 3	< 3	< 3
Cold Start-up Time[f] (to rated power @ –20°C ambient) Continuous use application	min	<90	<60	<30	<90	<60	<30
Survivability (min and max ambient temperature)	°C	–25 +40	–30 +40	–35 +40	–25 +40	–30 +40	–35 +40
Durability @ <10% rated power degradation	hour	>8,000	16,000	40,000	15,000	20,000	40,000
Noise	dB(A)	<70 @ 1 m	<65 @ 1 m	<60 @ 1 m	<65 @ 10 m	<60 @ 10 m	<55 @ 10 m
Emissions (Combined NO_X, CO, SO_X, Hydrocarbon, Particulates)	g/ 1000 kW_e	<15	<10	<9	<8	<2	<1.5

[a] Includes fuel processor, stack, and all ancillaries.

[b] Ratio of DC output energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant.

[c] For LPG, efficiencies are 1.5 percentage points lower than natural gas because the reforming process is more complex.

[d] Ratio of DC output energy plus recovered thermal energy to the LHV of the input fuel (natural gas or LPG) average value at rated power over life of power plant

[e] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.

[f] Not applicable to backup power because this application does not use a fuel processor.

Table 3.4.6. Technical Targets: Stationary Fuel Cell Stack Systems Operating on Hydrogen-Containing Fuel from a Fuel Processor (Natural Gas or LPG)[a]

Characteristic	Units	2004 Status	2005	2010
Cost[b]				
Small (3–25 kW)	$/kW$_e$	2000	1000	750
Large (50–250 kW)	$/kW$_e$	1500	1000	530
Durability				
Small (3–25 kW)	hours	>8,000	16,000	40,000
Large (50–250 kW)	hours	15,000	20,000	40,000
Transient Response Time (for 10% to 90% of rated power)	sec	<3	<3	1
Cold Start–up Time (to rated power @ –20ºC)	min	<2	<1	<0.5
Survivability (min & max ambient temperature)	ºC	–25 +40	–30 +40	–35 +40
CO tolerance[c]				
steady state (with 2% max air bleed)	ppm	50	500	500
transient	ppm	100	500	1000

[a] Excludes fuel processing/delivery system. Includes fuel cell ancillaries: thermal, water, air management systems.

[b] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.

[c] CO tolerance requirements assume capability of fuel processor to reduce CO. Targets for the stack CO tolerance are subject to trade-offs between reducing CO in the fuel processor and enhancing CO tolerance in the stack. It is assumed that H_2S is removed in the fuel processor.

Table 3.4.7. Technical Targets: Stationary Fuel Processors to Generate Hydrogen-Containing Fuel Gas from Natural Gas or LPG[a]

Characteristic	Units	2004 status	2005	2010
Cost[b]				
Small (3–25 kW)	$/kW$_e$	1000	500	250
Large (50–250 kW)	$/kW$_e$	1000	500	220
Cold Start–up Time[c] to rated power @ –20°C ambient	min	<90	<60	<30
Transient Response Time (for 10% to 90% power)	min	<5	<4	1
Durability[d]				
Small (3–25 kW)	hours	>8,000	16,000	40,000
Large (50–250 kW)	hours	15,000	20,000	40,000
Survivability (min and max ambient temperature)	°C	–25 +40	–30 +40	–35 +40
CO content in product stream[e]				
Steady State	ppm	10	5	1
Transient	ppm	100	50	25
H_2S content in product stream	ppbv (dry)	<10	<5	<2
NH_3 content in product stream	ppm	<1[f]	<0.1	<0.01

[a] Excludes fuel storage; includes controls, shift reactors, CO cleanup, heat exchangers.

[b] Includes projected cost advantage of high-volume production (2,000 units/year). Current cost does not include integrated auxiliaries, battery and power regulator necessary for black start.

[c] Not applicable to backup power because this application does not use a fuel processor.

[d] Time between catalyst and major component replacement; performance targets must be achieved at the end of the durability period.

[e] Dependent on stack development (CO tolerance) progress.

[f] 1ppm is detection limit for NH_3.

Table 3.4.8. Technical Targets: Consumer Electronics (sub-Watt to 50-Watt)

Characteristic	Units	2004 Status	2006	2010
Specific Power	W/kg	10–20	30	100
Power Density	W/L	10–15	30	100
Energy Density	W–h/L	50–200	500	1,000
Cost	$/W	40[a]	5	3
Lifetime	hours	<1,000	1,000	5,000

[a] Fuel Cell Seminar Abstracts, 2004, p. 290.

Table 3.4.9. Technical Targets: Auxiliary Power Units (3–5 kW rated, 5–10 kW peak) and Truck Refrigeration Units (10–30kW rated)

Characteristic	Units	2004[a] Status	2006	2010	2015
Specific Power	W/kg	35[b]	70	100	100
Power Density	W/L	35[b]	70	100	100
Efficiency @ Rated Power[c]	%LHV	15	25	35	40
Cost[d]	$\$/\text{kW}_e$	>2,000	<800	400	400
Cycle Capability (from cold start) over operating lifetime	number of cycles	5	40	150	250
Durability	hours	100	2,000	20,000	35,000
Start-up Time	min	60–90	30–45	15–30	15–30

[a] Estimate of current capability based on cell and small stack laboratory developments.

[b] Without power conditioning.

[c] Electrical efficiency only—does not include any efficiency aspects of the heating or cooling likely being provided.

[d] Cost based on high-volume manufacturing quantities (100,000 units/year).

Table 3.4.10. Technical Targets: Sensors for Automotive and Stationary Fuel Cell Systems[a]

All sensors require industrial standard output, e.g., 4~20mA, 1~5V.DC, 0~5V.DC, 0~10V.DC

Sensor	2010 Requirement
Carbon Monoxide	(a) Stored H_2 at 99.999% at transportation fueling station • 0.1 – 0.5 ppm • Operational temperature: <150°C • Response time: 0.1–1 sec • Gas environment: dry hydrogen at 1–700 atm total pressure • Accuracy: ≤2% full scale
	(b) Reformate from stationary fuel processor to PEM stack • 100–1000 ppm CO sensors • Operational temperature: 250°C • Response time: 0.1–1 sec • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: ≤2% full scale
	(c) Between shift reactors and PSA • 0.1–2% CO sensor 250°–400°C • Operational temperature: 250°– 400°C • Response time: 0.1–1 sec • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: ≤2% full scale
Hydrogen in fuel processor output	• Measurement range: 25%–100% • Operating temperature: 70°–150°C • Response time: 0.1–1 sec for 90% response to step change • Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30%–75% total H_2, CO_2, N_2 • Accuracy: ≤2% full scale
Hydrogen in ambient air (safety sensor)	• Measurement range: 1– 5% • Temperature range: –30°C to 80°C • Response time: under 1 sec • Accuracy: <5% full scale • Gas environment: ambient air, 10%–98% RH range • Lifetime: 5 years • Interference resistant (e.g., hydrocarbons)
Sulfur compounds (H_2S, SO_2, organic sulfur)	(a) H_2 to storage, ambient temperature • Operating temperature: up to 300°C • Measurement range: 0.01–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor
	(b) From fuel processor • Operating temperature: up to 300°C • Measurement range: 0.01–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor

Flow rate of fuel processor output	• Flow rate range: 30–300 SLPM (3–25kW) and 800–15,000 SLPM (50–250 kW) • Temperature: 0–100°C • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Ammonia	• Operating temperature: 70–150°C • Measurement range: 0.5–5 ppm • Selectivity: <1 ppm from gas mixtures • Lifetime: 5–10 years • Response time: <1 min at 0.5 ppm • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Temperature	• Operating range: –40°C to 150°C • Response time: in the –40°–100°C range <0.5 sec with 1.5% full–scale accuracy; in the 100°–150°C range, a response time <1 sec with 2% full–scale accuracy • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure • Insensitive to flow velocity
Relative humidity for cathode and anode gas streams	• Operating temperature: 0°C to 120°C • Relative humidity: 20%–100% • Accuracy: 1% full scale • Gas environment: high–humidity reformer/partial oxidation gas: H_2 30%–75%, CO_2, N_2, H_2O, CO at 1–3 atm
Oxygen in cathode exit	• Measurement range: 0%–50% O_2 • Operating temperature: 30˚–120°C • Response time: <0.5 sec • Accuracy: 1% full scale • Gas environment: H_2, CO_2, N_2, H_2O at 1–3 atm total pressure
Differential pressure in fuel cell stack	• Range: 0–1 psi (or 0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30˚–120°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% of full scale • Other: measure in the presence of liquid and gas phases
Flow rate for direct hydrogen system	• Flow rate maximum: 2500 SLPM for wet H_2 • Flow rate maximum: 1000 SLPM for dry H_2 • Gas environment: H_2 dry (see table 3.4.16 for concentration), 25□100% RH

[a] Sensors for transportation must enable conformation to size, weight, and cost constraints.

Table 3.4.11. Technical Targets: Compressor/Expanders for Transportation Fuel Cell Systems 80-kW_e Unit-Hydrogen

Characteristic	Units	2004 Status	2005	2010	2015
Input Power [a] at Full Load, 40°C Ambient Air (with Expander / without Expander)	kW_e	6.3/13.7[b]	6.3/13.7	5.4/12.8	5.4/12.8
Overall Motor/Motor Controller Conversion Efficiency, DC Input	%	85	85	85	85
Input Power at Full Load, 20°C Ambient Air (with Expander / without Expander)	kW_e	5.2/12.4[b]	5.2/12.4	4.4/11.6	4.4/11.6
Compressor/Expander Efficiency at Full Flow (C/E Only)[c]	%	75/80[d]	75/80	80/80	80/80
Compressor/Expander Efficiency at 20–25% of Full Flow (C/E Only) /Compressor at 1.3 PR/Expander at 1.2 PR	%	45/30[d]	55/45	60/50	60/50
System Volume[e]	liters	22[b]	15	15	15
System Weight[e]	kg	22[b]	15	15	15
System Cost[f]	$	700	600	400	200
Turndown Ratio		10:1	10:1	10:1	10:1
Noise at Maximum Flow (excluding air flow noise at air inlet and exhaust)	dB(A) at 1 meter	65	65	65	65
Transient Time for 10–90% of Maximum Airflow	sec	1	1	1	1

[a] Input power to the shaft to power a compressor/expander, or compressor only system, including a motor/motor controller with an overall efficiency of 85%. 80-kW_e compressor/expander unit for hydrogen/air flow – 90 g/sec (dry) maximum flow for compressor, compressor outlet pressure is specified to be 2.5 atm. Expander (if used) inlet flow conditions are assumed to be 93 g/sec (at full flow), 80°C and 2.2 atm.

[b] Projected.

[c] The pressure ratio is allowed to float as a function of load. Inlet temperature and pressure used for efficiency calculations are 20-40ºC and 2.5 atm.

[d] Measure blade efficiency.

[e] Weight and volume include the motor and motor controller.

[f] Cost targets based on a manufacturing volume of 100,000 units per year, includes cost of motor and motor controller.

Table 3.4.12. Technical Targets: Membranes for Transportation Applications

Characteristic	Units	2004 Status	2005	2010	2015
Membrane Conductivity at					
Operating Temperature	S/cm	0.10	0.10	0.10	0.10
Room temperature	S/cm	0.07	0.07	0.07	0.07
–20°C	S/cm	0.01	0.01	0.01	0.01
Operating Temperature	°C	≤80	≤120	≤120	≤120
Inlet water vapor partial pressure	kPa (absolute)	50	25	1.5	1.5
Oxygen cross–over[a]	mA/cm^2	5	5	2	2
Hydrogen cross–over[a]	mA/cm^2	5	5	2	2
Cost	\$/m^2	65[b]	200	40	40
Durability with cycling					
At operating temp of ≤80°C	hours	~1000[c]	2000	5000[d]	5000[d]
At operating temp of >80°C	hours	not available[e]		2000	5000[d]
Survivability	°C	–20	–30	–40	–40
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes

[a] Tested in MEA at 1 atm O$_2$ or H$_2$ at nominal stack operating temperature.

[b] Based on 2004 TIAX Study and will be periodically updated.

[c] Durability is being evaluated. Steady-state durability is 9,000 hours.

[d] Includes typical driving cycles.

[e] High-temperature membranes are still in a development stage and durability data are not available.

Table 3.4.13. Technical Targets: Electrocatalysts for Transportation Applications

Characteristic	Units	2004 Status		Targets (Stack)		
		Cell	Stack	2005	2010	2015
PGM Total Content	g/kW rated	0.6	1.3	2.67	0.5	0.4
PGM Total Loading[a]	mg PGM/cm^2 electrode area	0.45	0.8	0.7	0.3	0.2
Cost	$/kW[b]	9	20[c]	40	8	6
Durability with cycling At operating temp of ≤80°C At operating temp of >80°C	 hours hours	 >2000 not available[f]	 ~1000[d] not available[f]	 2000	 5000[e] 2000	 5000[e] 5000
Mass Activity[g]	A/mg$_{\text{Pt}}$ @900mV$_{\text{iR–free}}$	0.28	0.11	0.30	0.44	0.44
Activity[g]	μA/cm^2 @ 900mV$_{\text{iR–free}}$	550	180	600	720	720
Non–Pt Catalyst Activity per volume of supported catalyst	A/cm^3 @ 800 mV$_{\text{iR–free}}$	8	not available	50	>130	300

[a] Derived from achieving performance at rated power targets specified in Table 3.4.14. Loadings may have to be lower.

[b] Based on platinum cost of $450/troy ounce = $15/g, and loading < 0.2 g/kWe

[c] Based on 2004 TIAX Study and will be periodically updated.

[d] Durability is being evaluated. Steady-state durability is 9,000 hours.

[e] Includes typical driving cycles.

[f] High-temperature membranes are still in a development stage and durability data is not available.

[g] Test at 80°C; H$_2$/O$_2$; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5.

Table 3.4.14. Technical Targets: MEAs

Characteristic	Units	2004 Status	2005	2010	2015
Operating Temperature	°C	≤80	≤120	≤120	≤120
Inlet water vapor partial pressure	kPa (absolute)	50	25	1.5	1.5
Cost[a]	$/kW	40[b]	50	15	10
Durability with cycling					
At operating temp of ≤80°C	hours	~1000[c]	2000	5000[d]	5000[d]
At operating temp of >80°C	hours	not available[e]		2000	5000[d]
Survivability Temperature	°C	–20	–30	–40	–40
Total Catalyst Loading (both electrodes)[f]	g/kW (rated)	1.1	2.7	0.33	0.20
Performance @ ¼ power (0.8V)	mA/cm^2	200	250	400	400
	mW/cm^2	160	200	320	320
Performance @ rated power	mW/cm^2	600	800	1280	1280
Extent of performance degradation over lifetime[g]	%	10	10	10	10
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes

[a] Based on 2002$ and cost projected to high-volume (500,000 stacks per year).

[b] Based on 2004 TIAX Study and will be periodically updated.

[c] Durability is being evaluated. Steady-state durability is 9,000 hours.

[d] Includes typical driving cycles.

[e] High-temperature membranes are still in a development stage and durability data are not available.

[f] Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power.
Precious metal target based on cost target of <$3/kW precious metals in MEA [@$450/troy ounce ($15/g) and loading of < 0.2 g/kW_e].

[g] Degradation target includes factor for tolerance of the MEA to impurities in the fuel and air supply.

Table 3.4.15. Technical Targets: Bipolar Plates

Characteristic	Units	2004 Status	2010	2015
Cost	\$/kW	10	6	4
Weight	kg/kW	0.36	<1	<1
H_2 Permeation Rate	$cm^3\ sec^{-1}\ cm^{-2}$ @ 80°C, 3 atm (equivalent to <0.1 mA/cm^2)	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$
Corrosion	$\mu A/cm^2$	<1[a]	<1[b]	<1[b]
Electrical Conductivity	S/cm	>600	>100	>100
Resistivity[c]	ohm/cm^2	<0.02	0.01	0.01
Flexural Strength	MPa	>34	>4 (crush)	>4 (crush)
Flexibility	% deflection at mid–span	1.5 to 3.5	3 to 5	3 to 5

[a] Based on coated metal plates.

[b] May be as low as 1 nA/cm^2 if all corrosion product ions remain in ionomer.

[c] Includes contact resistance.

Table 3.4.16. Hydrogen Quality

Component	Level
Hydrogen	>99.9
Sulfur	10 ppb
CO	0.1 ppm
CO_2	5 ppm
NH_3	1 ppm
NMHC on a C–1 basis	100 ppm
Particulates	Conform to ISO 14687

3.4.4.2 Barriers

Of the many issues discussed here, cost and durability present two of the most significant barriers to the achievement of clean, reliable, cost-effective systems.

A. **Durability.** Durability of fuel cell stacks, which must include tolerance to impurities and mechanical durability, has not been established. Tolerance to other impurities, such as sulfur and possibly ammonia, is also necessary. MEA stability for automotive drive cycles has not been demonstrated. Operation at low relative humidity (25-50% RH) and startup from sub-freezing temperatures have not been demonstrated.

To compete against other distributed power generation systems, stationary fuel cells must achieve greater than 40,000 hours durability. Sulfur-tolerant catalysts and membrane materials are required to achieve this durability target, and research must elucidate failure mechanisms. Benchmarking of the state-of-the-art R&D systems is also necessary.

Current fuel processing systems have not achieved required durability, due in large part to the impurities contained in the fuels entering the reformer. Limited data are available on the effects of fuel composition, additives, impurities (e.g., sulfur) and contaminants on fuel processor catalyst and subsystem component durability. The effect of carbon formation on catalyst activity for various fuels and the effect of operating conditions on durability are not adequately quantified. Sulfur removal technology and impurity-tolerant catalysts and/or removal processes are required.

B. **Cost**. Materials and manufacturing costs are too high for bipolar plates, catalysts, membranes and gas diffusion layers (GDLs). Lower cost, lighter, corrosion-resistant bipolar plates and low-cost, high-performance membranes, and catalysts enabling ultra-low precious metal loading are required to make fuel cells competitive. The use of non-precious metal catalysts will also reduce the cost of MEAs. Low-cost, high-volume manufacturing processes are also necessary.

The cost of fuel processors is high because the operating temperature requires costly high-temperature materials, the low activity of shift catalysts requires large reactors, precious metal catalysts must be used, and the complexity of the fuel processor requires multiple reactors and thermal integration. Substitution of lower-cost materials (particularly reduced Pt or non-Pt catalysts) and components, and integration of subsystems and functions are required to achieve cost goals.

C. **Electrode Performance.** Voltage losses at the cathode are too high to meet efficiency targets simultaneously with the other targets. Anode and cathode performance depend on precious metal loading, which is currently too high (at the cathode) to meet cost targets. In addition, power densities at the higher voltages required for high-efficiency operation are currently too low to meet cost and packaging targets. Current activities are focused on cathode performance because the kinetics at the cathode are ~100 times slower than at the anode.

D. **Thermal, Air and Water Management.** Thermal management processes include heat use, cooling, and steam generation. Higher temperature membranes and/or improved heat utilization, cooling, and humidification techniques are needed. The low operating temperature of PEM fuel cells results in a relatively small difference between the fuel cell stack operating temperature and ambient air temperature that is not conducive to conventional heat rejection approaches and limits the use of heat generated by the fuel cell (approximately 50% of the energy supplied by the fuel). More efficient heat recovery systems, improved system designs, advanced heat exchangers and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) systems, particularly for distributed generation power. Water management techniques to address humidification requirements and maintain water balance are required.

E. **Compressors/Expanders.** Automotive-type compressors/expanders that minimize parasitic power consumption and meet packaging and cost requirements are not available. To validate functionality in laboratory testing, current systems often use off-the-shelf compressors that are not specifically designed for fuel cell applications, resulting in systems that are heavy, costly, and inefficient. Automotive-type compressors/expanders that meet the FreedomCAR and Fuel Cell Partnership technical guidelines need to be engineered and integrated with the fuel cell stack so that the overall system meets packaging, cost, and performance requirements.

F. **Fuel Cell Power System Integration**. The interdependency of fuel cell subsystems is an important consideration in the development of individual components for propulsion and APUs. The interdependency of the system components will affect the packaging, response, and efficiency of the power system. Development of a validated system model and periodic benchmarking of integrated fuel cell power systems, subsystems, and components are required to assess technology status. Ultimately, operation of components and subsystems will be validated in the integrated systems developed outside the Program. Careful system integration is required to achieve overall system efficiency and cost targets. Full-sized, integrated systems with improved catalysts and reactors that demonstrate the required operating characteristics and efficiency for stationary applications must be developed. Maximum fuel processor efficiency is necessary to achieve target efficiencies for economic viability. Data and models for fuel impacts on fuel processor performance and emissions are limited.

G. **Power Electronics.** Distributed generation fuel cell power systems will require energy management strategies and power electronics that enable the fuel cell power system to manage power transients and load-following requirements efficiently and cost effectively. Grid interconnection may also be a major commercialization issue for many distributed fuel cell power applications as with all emerging distributed power generation technologies (grid interconnection issues are being addressed by the Office of Distributed Energy Resources). Priority power management issues include developing a universal dc buss, high-frequency power conditioner, integrated transfer switch and inverter, and grid-independent electronics.

H. **Sensors.** Sensors are required that meet performance and cost targets for measuring physical conditions and chemical species in fuel cell systems. Current sensors do not perform within the required ambient and process conditions, do not possess the required accuracy, range and response time, and/or are too costly. Performance in humid environments is also a concern.

I. **Hydrogen Purification/Carbon Monoxide Cleanup.** A fuel processor must produce high-quality hydrogen to prevent degradation of the fuel cell stack. Liquid fuels contain impurities such as sulfur compounds. These compounds and their derivatives, as well as carbon monoxide, must be removed to prevent loss of performance in the fuel cell. To prevent fuel cell catalyst poisoning, the fuel processor needs to deliver a hydrogen stream with CO levels of less than 10 ppm under most operating conditions and a maximum of 100 ppm during transients and startup. Current CO cleanup systems produce a fuel stream with an acceptable CO level under steady-state operation, but require an extensive control system for transient and startup operation. Improved membranes for hydrogen separation are needed to meet fuel purity requirements under transient and startup operation.

J. Startup Time/Transient Operation. Fuel cell systems take longer to cold start (30 second minimum) compared to other distributed power generation systems, especially backup power systems. Stationary fuel processors start up slowly and do not respond rapidly to variations in power demand. R&D to address startup time through the use of hybrid systems or other viable methods is needed. Fuel cell power plants will be required to meet rapid startup needs and to follow load variations. Some other means of bridging the gap between the current status and 2010 targets must be used, such as hydrogen storage tanks.

3.4.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.4.16. Concerns regarding safety will be addressed within each task in coordination with the appropriate program element. The barriers associated with each task (see Section 3.4.4.2) are also reported.

Table 3.4.16. Technical Task Descriptions

Task	Description	Barriers
Transportation Systems		
1	**Chemical and Physical System Sensors** **Chemical Sensors: Prototype Development** • Measure the CO concentration at the entrance to the fuel cell stack. • Monitor ambient concentrations of hydrogen for safety in the presence of other species found in the ambient air. • Measure the concentration of sulfur compounds such as H_2S, SO_2, and organic sulfur compounds. • Measure the concentration of ammonia in high-humidity stream in the presence of other constituents. • Measure oxygen concentration at the cathode exit. **Physical Sensors: Prototype Development** • Measure the flow rate of hydrogen into the fuel cell at 1–3 atm total pressure. • Fast-response temperature sensors that operate in high humidity gas streams and are insensitive to flow velocity. • Measure the relative humidity of anode and cathode gas streams.	H

2	**Sensors Meeting 2010 Targets** **Chemical Sensors: Verification** • Measure the CO concentration at the entrance to the fuel cell stack. • Determine hydrogen concentration at the fuel cell inlet in the presence of other constituents. • Monitor ambient concentrations of hydrogen for safety in the presence of other species found in the ambient air. • Measure the concentration of sulfur compounds such as H_2S, SO_2, and organic sulfur compounds in the presence of other constituents. • Measure the concentration of ammonia in high-humidity streams and in the presence of other constituents. • Measure oxygen concentration at the cathode exit. **Physical Sensors: Verification** • Devices for measuring the flow rate of hydrogen into the fuel cell at 1–3 atm total pressure. • Fast-response temperature sensors that operate in high humidity streams and are insensitive to flow velocity. • Measure the relative humidity for the anode and cathode gas streams.	H
3	**Benchmarking, Hardware Evaluation, and Analyses** • Test and evaluate fuel cell power systems under simulated automotive drive and rigorous durability cycles. • Quantify fuel cell power system emissions. • Conduct analyses for overall and specific component costs for transportation fuel cell systems	B, F
4	**Air, Water, and Thermal Management** • Develop and test low-cost, high-efficiency, lubrication-free compressors, expanders, motors, motor controllers and blowers (turbo, torroidal intersecting vane) • Investigate and develop advanced heat rejection technologies and materials (compact humidifiers, heat exchangers, and radiators)	D, E
5	**Compressors Meeting 2010 Guidelines** • Verify advanced compressors/motor/expanders and blowers that meet the 2010 targets for weight, volume, performance and cost.	E
6	**Direct Methanol Fuel Cells** • Design and test advanced cathode catalysts with low Pt loading. • Develop membranes and MEAs with reduced methanol crossover. • Build and evaluate improved-performance direct-methanol single cell. • Design and build DMFC stack system with improved power density, efficiency, and water management. • Test and evaluate DMFC stack. • Develop and test DMFCs for consumer electronic devices.	B, C, D, F
7	**Auxiliary/Portable Power** • Advanced methanol oxidation catalyst, and MEAs with low Pt-loading for DMFCs. • Miniature fluid handling technologies for DMFC systems. • Low-cost, high-volume manufacturing processes for auxiliary/portable power fuel cells. • Miniature fuel processors for PEMFC and solid oxide fuel cell (SOFC) systems. • Determine system requirements for fuel cell APUs for HDVs. • Verify fuel cell technologies for APUs (to 30 kW), consumer electronic devices (< 50 W), and off-road systems. • Test and evaluate fuel cell APUs for HDVs under simulated duty and rigorous durability cycles.	A, B, C, F, I

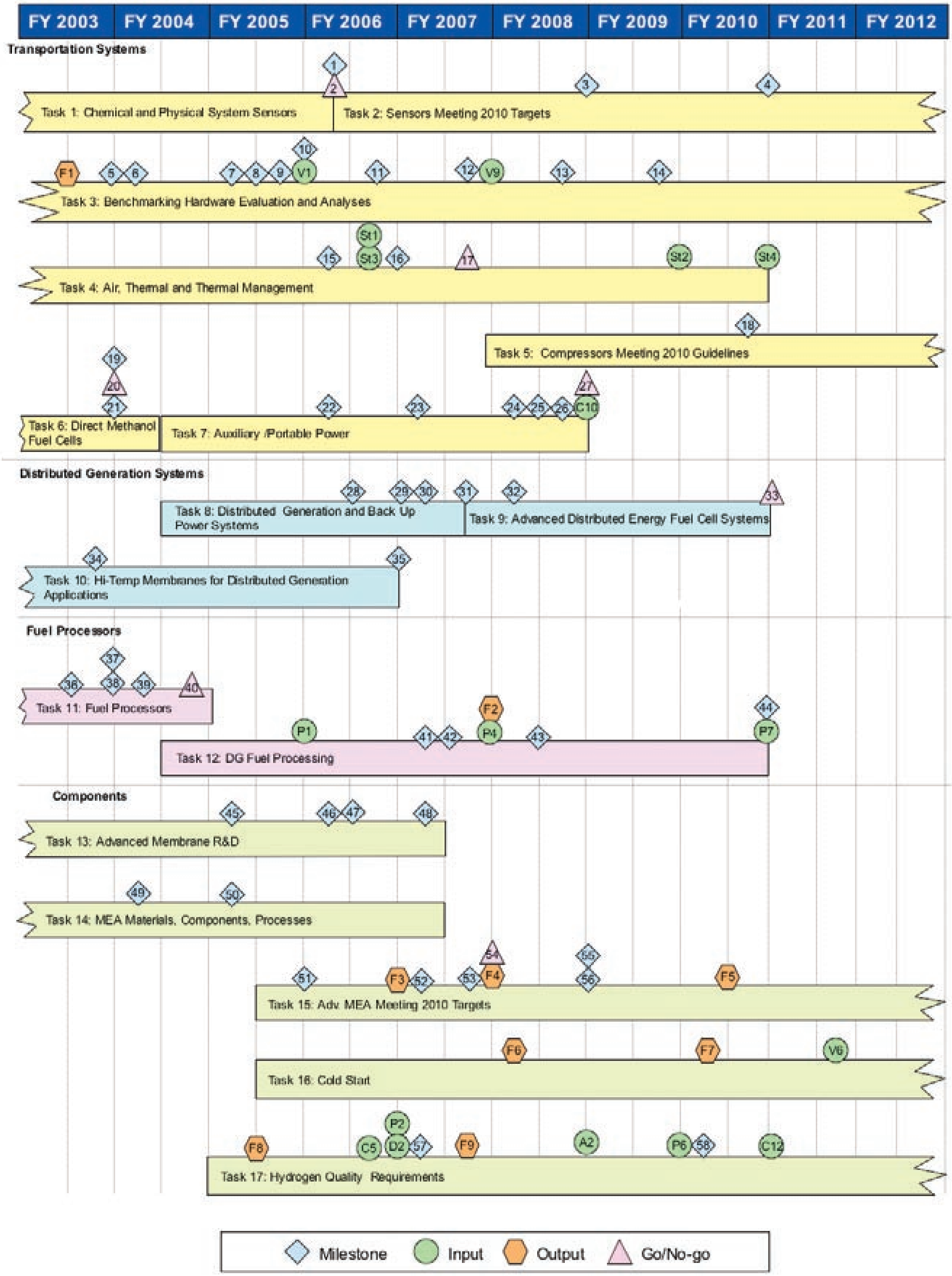
Distributed Generation Systems		
8	**Distributed Generation and Back-up Power Systems** • Stationary fuel cell system that meets the 2005 technical targets for distributed generation systems. • Mitigate technical, commercial, and cost barriers to stationary fuel cells. • CHP fuel cell systems to cost-effectively recover thermal energy to meet some or all of the building's heating/cooling requirements. • Power systems for back-up or peak shaving applications for commercial/industrial operations. • Identify and understand failure mechanisms to enable improvements in reliability and durability. • Work with DER and utility partners to address interconnectivity to grid issues.	A, G, H, J
9	**Advanced Distributed Energy Fuel Cell Systems** • Stationary fuel cell system that can operate on natural gas or LPG at 40% or higher electrical efficiency. • Advanced stationary fuel cell system that can achieve a cold start up time of less than 1 minute. • Demonstrate through accelerated testing a stationary fuel cell system showing potential to achieve >40,000-hour durability. • Test improved heat recovery system that improves net system efficiency. • Advanced heat exchangers, condensers, and humidifiers. • Improve system humidification to reduce overall energy required to humidify gases while reducing size and cost. • Investigate heat generated cooling (such as desiccant cycles).	A, G, H, J
10	**High-Temperature Membranes for Distributed Generation Applications** • Highly conducting, high temperature membranes capable of achieving 100-150°C with improved electrical and mechanical properties. • Demonstrate improved CO tolerance. • Lower cost high-temperature membranes. *Note - This task was initiated under the Fuel Cells for Buildings Program (Office of Power Technologies) and feeds into Task 13	A, D, I
Fuel Processors		
11	**Fuel Processors** • Fuel processing catalysts (reforming, shift, desulfurization, etc.) having higher activities, greater stability, lower cost and that enable lower reactor operating temperatures. • Evaluate alternative fuel processing techniques, such as absorber enhancement. • Complete testing and evaluation of system performance and emissions on conventional and alternative fuels over steady-state and transient operation. • Verify and improve fuel processor model and system analyses.	A, B, F, I, J
12	**Distributed Generation Fuel Processing** • Fuel processing systems that can reform natural gas or LPG to hydrogen for stationary applications. • Fuel processing systems that meet technical and cost targets for 2005. • Advanced water-gas-shift catalysts and reactor designs that meet requirements for operational space velocity.	A, B, F, D, G, I, J,

Stack Components		
13	**Advanced Membrane RD&D (See Task 10)** • Investigate new approaches/electrode structures to achieve good adhesion between new membranes and catalyst layer. • Proton-conducting fuel cell membranes for operation at ≤120°C for transportation. • Improve understanding of nature of local structure in catalyst layer. • Increase knowledge of proton conduction in high-temperature membrane systems. • Membranes with nonaqueous proton-conducting phases for stationary fuel cell membranes for operation at >120°C. • Investigate membranes that can function at low hydration levels, <25%. • Fabricate and test MEAs meeting technical targets in single cells. • Investigate membrane/MEA long-term stability and durability. • Verify advanced membranes in subscale stack.	A, C, D, I
14	**MEA Materials, Components, Processes** • Low-cost polymer membranes having higher ionic conductivity, improved humidification properties, and lower gas permeability than state-of-the-art membranes. • Improved gas diffusion layer on full-size cells. • Investigate the effects of sulfur impurities on catalyst performance. • Design, synthesize, and evaluate alternative catalyst formulations and structures (to reduce or eliminate precious metal loading) for impurity tolerance and oxygen reduction. • Alternative bipolar plate materials/coatings that are low-cost, lightweight, corrosion-resistant, and impermeable. • Fabricate and test MEAs in full-size single cells. • Methods for producing low-cost, high-rate fabrication of fuel cell components (e.g., bipolar plates, membranes, MEAs, and gas diffusion layers). • Verify reproducibility of full-size components produced in high-rate manufacturing processes. • Integrate components in subscale stack system to verify performance, i.e., increased efficiency, power density, and reliability compared with previous development efforts.	A, B, C
15	**Advanced MEA Meeting 2010 Targets** • Incorporate advanced cathode and membrane in MEA with Pt loading at 2010 targets. • Verify advanced MEA in single cell. • Verify advanced MEA in stack. • Demonstrate low-cost, high-volume manufacturing processes for advanced MEAs. • Establish durability of advanced MEAs for 2010 targets for transportation and stationary applications.	A, B, C, D
16	**Cold Start** • Investigate new approaches for water management to mitigate the effects of exposure to subfreezing environment. • Determine kinetics of water phase change at freezing temperatures in fuel cell membranes. • Characterize morphological changes and localized stresses in fuel cell components associated with water phase transition during freezing conditions. • Membrane and gas diffusion layer materials to enhance freeze tolerance and improve subfreezing operation and robustness.	A, B, C, D, H, J
17	**Hydrogen Quality Requirements** • Determine the effects of very low level of sulfur compounds (<100 ppb of SO_2 and <20 ppb of H_2S) on fuel cell performance. • Determine the effects of organic materials such as formaldehyde and formic acid and of combustion diesel fumes on fuel cell performance as a function of impurity concentration and operating temperature. • Characterize the effects of salts (NaCl, $CaCl_2$) on properties of fuel cell catalyst layer, membrane, gas diffusion layer, and graphite flow fields or other bipolar plate materials; quantify effects of low levels of salts on long-term fuel cell performance.	A, B, C, H, I

3.4.6 Milestones

Figure 3.4.2 shows the interrelationship of milestone, tasks, supporting inputs, and technology program outputs for the Fuel Cell Program element from FY 2004 through FY 2010. This information is also summarized in Table B.4 in Appendix B.

Figure 3.4.2. Hydrogen Fuel Cell R&D Milestone Chart



For chart details see next page.

Milestones

1 Complete development and testing of low-cost, high-sensitivity sensors.
2 Go/No-Go: The status of sensors and controls technologies will be assessed and compared with the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.
3 Develop laboratory-scale physical and chemical sensors with improved response time and lower cost.
4 Develop physical and chemical sensors meeting 2010 targets.
5 Deliver model of FCV system.
6 Complete modeling of the availability and economics of platinum group metals.
7 Complete initial evaluation of 25-50-kW advanced integration, atmospheric gasoline reformed system.
8 Quantify fuel cell power system emissions.
9 Evaluate progress towards meeting FY2005 fuel cell cost target.
10 Complete analysis of overall and specific component costs for transportation fuel cell systems.
11 Evaluate progress towards meeting FY2010 fuel cell cost target.
12 Evaluate progress towards meeting FY2010 fuel cell cost target.
13 Evaluate progress towards meeting FY2010 fuel cell cost target.
14 Evaluate progress towards meeting FY2010 fuel cell cost target.
15 Complete development of heat rejection technologies (compact humidifiers, heat exchangers, and radiators).
16 Complete development and testing of low-cost, high-efficiency, lubrication-free compressors, expanders, blowers, motors, and motor controllers.
17 Go/No-Go: The status of air management and thermal management technologies will be assessed and compared to the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.
18 Complete development of compressor, expander, motor blower and motor controller meeting 2010 targets.
19 Identify main routes of DMFC performance degradation.
20 Go/No-Go: Decision to discontinue DMFC R&D for transportation applications.
21 Down-select design scenarios for vehicular fuel cell APUs for further study.
22 Complete evaluation of fuel cell system designs for APUs.
23 Complete design of filtration unit for off-road applications.
24 Evaluate 3-10 kW APU system towards meeting 80 W/kg and 80 W/L targets.
25 Evaluate 20-50 W portable power fuel cell system towards meeting 2006 targets.
26 Portable power fuel cell technology available for industry evaluation.
27 Go/No-Go: Decision on whether to continue auxiliary power, portable power and off-road R&D based on the progress towards meeting 2010 targets.
28 Complete testing on 50 kW stationary beta module system.
29 Complete economic analysis report.
30 Demonstrate prototype back up power system.
31 Complete 15,000 hour, stationary fuel cell system test.
32 Demonstrate the effective utilization of fuel cell thermal energy for heating to meet combined heat and power (CHP) efficiency targets.
33 Go/No-Go: Decision on whether to continue stationary fuel cell system based on progress towards meeting durability, cost and electrical efficiency simultaneously.
34 Demonstrate performance (600 mV at 400 mA/cm^2) of an ultra-thin membrane ($< 75\ \mu m$) in an MEA under atmospheric conditions at 120°C in a 30-cm^2 cell.
35 Complete full-scale MEA evaluation in short stack.
36 Demonstrate fuel-flexible fuel processor meeting year 2005 targets for efficiency, power density and specific power. Measure startup capability.
37 Verify quick-start concept in brass-board prototype system demonstrating capability to meet 2010 startup technical target.
38 Verify small scale, microchannel reformer.
39 Fabricate prototype ion transport membrane module.
40 Go/No-Go: Decision to discontinue fuel processing R&D.
41 Verify fuel processing subsystem performance for distributed generation towards meeting system targets for 2010.
42 Absorption-enhanced natural gas reformer start-up/shut down cycle, transient and durability testing.
43 Develop base metal shift catalysts that enhance conversion to hydrogen and reduce conversion to methane (<1% methane).
44 Develop tolerance of reforming catalysts to fuel containing 1 ppm sulfur.
45 Evaluate 120°C membrane in MEA/single cell.
46 Evaluate 120°C MEA in <10 kW stack.
47 Demonstrate MEA in single cell meeting 2005 platinum loading and performance targets.
48 Evaluate first generation 150°C membrane in MEA/single cell.
49 Evaluate reproducibility (physical and performance) of full-size bipolar plates in high-rate manufacturing processes.
50 Evaluate reproducibility (physical and performance) of MEAs in high-rate manufacturing processes.
51 Initiate 2,000-hour test with advanced membrane & standard GDL.
52 Develop 120°C membrane for operation at < 25% RH.
53 Complete 2,000 hour durability test of advanced MEA for stationary fuel cell application.
54 Go/No-Go: Evaluate precious metal reclamation processes to determine whether to scale-up or terminate.
55 Develop technology for platinum group metal recycling.
56 Evaluate a MEA running on re-manufactured catalyst coated membranes.
57 Develop a method for cleaning sulfur-poisoned platinum catalyst layers in stacks, with minimum interruption of fuel cell operation.
58 Develop a method for cleaning sulfur- and nitrogen-oxide poisoned platinum catalyst layers in stacks, with minimum interruption of fuel cell operation.

Outputs

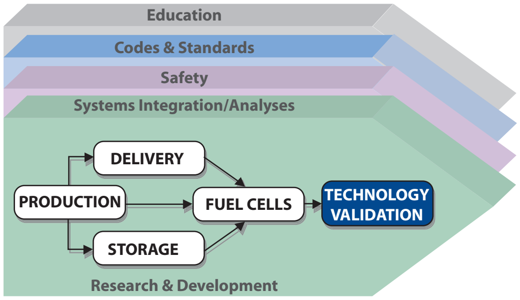
F1 Output to Systems Analysis and Systems Integration: Develop a critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions, and cost.
F2 Output to Production: Research results of advanced reformer development.
F3 Output to Technology Validation: Laboratory PEM technology with 2,000 hours durability.

F4	Output to Technology Validation: Complete 4,000 hour testing of advanced MEA for stationary and transportation applications.
F5	Output to Technology Validation: Laboratory PEM technology with 5,000 hours durability.
F6	Output to Technology Validation: Verify cold-start in 60 s of short stack.
F7	Output to Technology Validation: Technology short stack survivability at -40°C.
F8	Output to Systems Analysis and Systems Integration: Develop preliminary hydrogen purity/impurity requirements.
F9	Output to Systems Analysis and Systems Integration: Updated hydrogen purity/impurity requirements.

Inputs

V1	Input from Technology Validation: Validate maximum fuel cell system efficiency.
V9	Input from Technology Validation: Final report on safety and O&M of three refueling stations.
St1	Input from Storage: Compressed and cryogenic liquid storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.
St3	Input from Storage: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.
St2	Input from Storage: Advanced compressed/cryogenic tank technologies.
St4	Input from Storage: Full-cycle, integrated chemical hydride system meeting 2010 targets.
C10	Input from Codes and Standards: Final draft standard (balloting) for portable fuel cells (UL).
P1	Input from Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P4	Input from Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P7	Input from Production: Hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
V6	Input from Technology Validation: Validate cold start-up capability (in a vehicle with an 8-hour soak) meeting 2005 requirements (specific cold-start energy).
C5	Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
P2	Input from Production: Assessment of fuel contaminant composition.
D2	Input from Delivery: Hydrogen contaminant composition and issues.
A2	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
P6	Input from Production: Assessment of fuel contaminant composition.
C12	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.

3.5 Technology Validation



The Technology Validation Program element is focusing on conducting learning demonstrations that emphasize co-development and integration of hydrogen infrastructure in parallel with hydrogen fuel cell-powered vehicles to enable an industry commercialization decision by 2015. Technology validation will test, demonstrate and validate total system solutions and use the results to refocus hydrogen R&D as appropriate.

3.5.1 Technical Goal and Objectives

Goal

Validate total system solutions for integrated hydrogen and fuel cell technologies for transportation, infrastructure and electric generation under real-world operating conditions for both the transition and mature market periods.

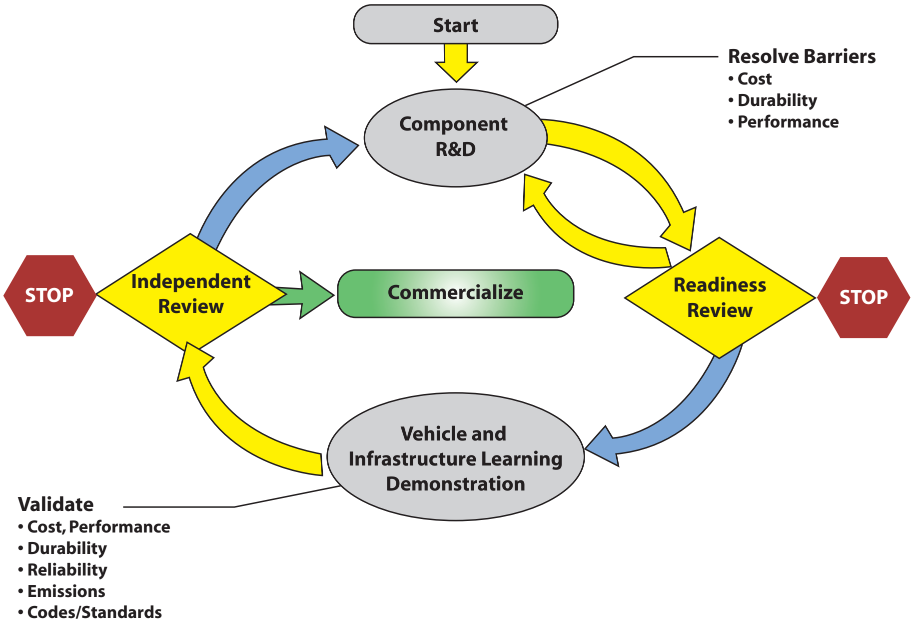
Objectives

- By 2008, validate an electrolyzer that is powered by a wind turbine at a capital cost of the electrolyzer of $600/kWe and 68% efficiency including compression to 5,000 psi when built in quantities of 1,000.
- By 2009, validate hydrogen vehicles that have greater than 250-mile range, 2,000-hour fuel cell durability and hydrogen infrastructure that results in a hydrogen production cost of less than $3.00/gge (untaxed), and safe and convenient refueling by trained drivers.
- By 2011, validate an integrated biomass/wind or geothermal electrolyzer-to-hydrogen system to produce hydrogen for $2.85/gge at the plant gate (untaxed).
- By 2015, validate hydrogen vehicles that have 300+ mile range and 5,000 hours fuel cell durability, and hydrogen infrastructure that results in a hydrogen production cost of $1.50/gge (untaxed), and safe and convenient refueling by trained drivers.

3.5.2 Technical Approach

The Technology Validation Program element will implement integrated, complex total systems (i.e., hydrogen production facilities and 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 validation learning demonstrations bring together teams of automotive and energy companies working together to address fuel cell vehicle and hydrogen infrastructure interface issues and to identify future research needs. The results of the validations will be used to provide feedback on progress and to efficiently manage the other Program element activities and to refocus research and development as needed.

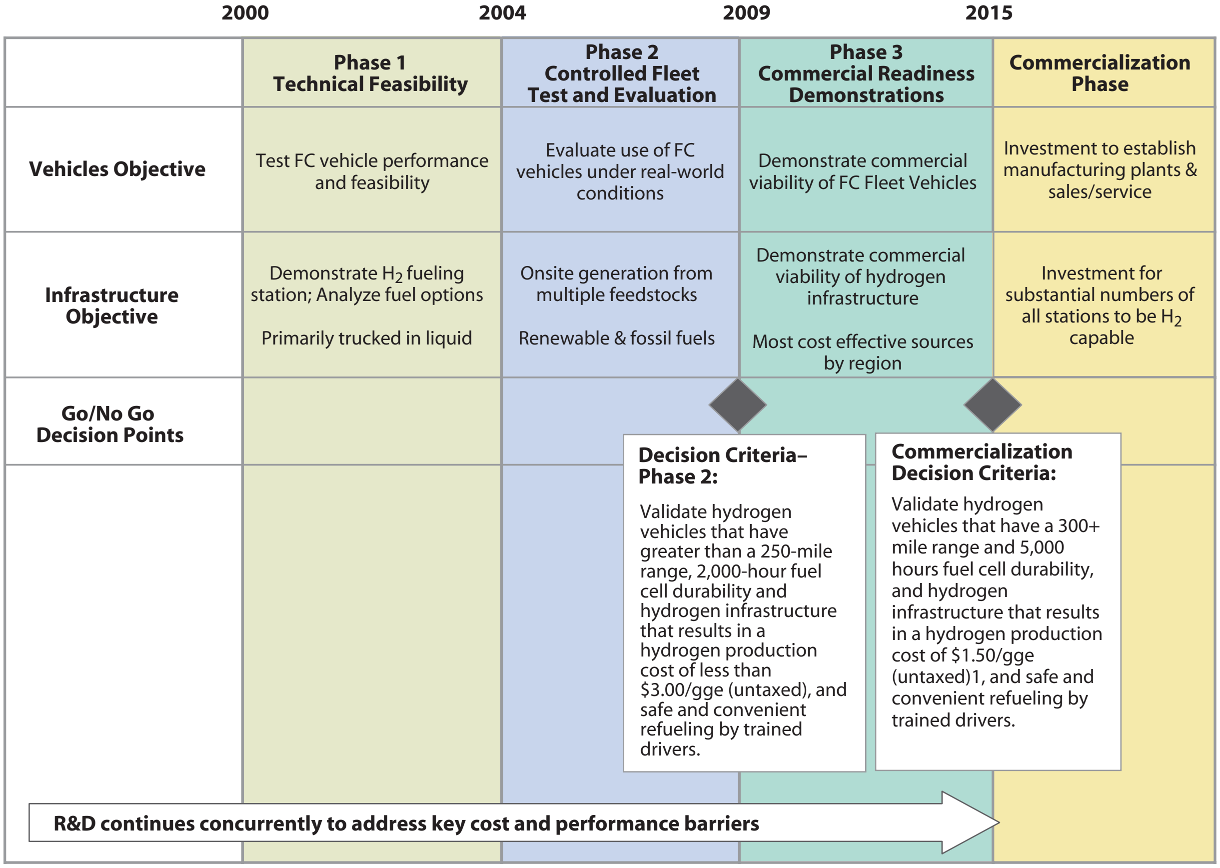
Figure 3.5.1. The Role of Technology Validation



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 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 to validate the technical approach being taken and redirect it as necessary.

To accomplish all of the objectives, a three-phase effort is envisioned with performance milestones that have to be met at the end of phases 2 and 3. (Figure 3.5.2). The current Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project is phase 2 to be followed by phase 3, which is the pre-commercialization project to be completed by 2015.

Figure 3.5.2. Transportation and Infrastructure Timeline



2000 2004 2009 2015

	Phase 1 Technical Feasibility	Phase 2 Controlled Fleet Test and Evaluation	Phase 3 Commercial Readiness Demonstrations	Commercialization Phase
Vehicles Objective	Test FC vehicle performance and feasibility	Evaluate use of FC vehicles under real-world conditions	Demonstrate commercial viability of FC Fleet Vehicles	Investment to establish manufacturing plants & sales/service
Infrastructure Objective	Demonstrate H_2 fueling station; Analyze fuel options Primarily trucked in liquid	Onsite generation from multiple feedstocks Renewable & fossil fuels	Demonstrate commercial viability of hydrogen infrastructure Most cost effective sources by region	Investment for substantial numbers of all stations to be H_2 capable
Go/No Go Decision Points				

Decision Criteria–Phase 2:

Validate hydrogen vehicles that have greater than a 250-mile range, 2,000-hour fuel cell durability and hydrogen infrastructure that results in a hydrogen production cost of less than $3.00/gge (untaxed), and safe and convenient refueling by trained drivers.

Commercialization Decision Criteria:

Validate hydrogen vehicles that have a 300+ mile range and 5,000 hours fuel cell durability, and hydrogen infrastructure that results in a hydrogen production cost of $1.50/gge (untaxed)1, and safe and convenient refueling by trained drivers.

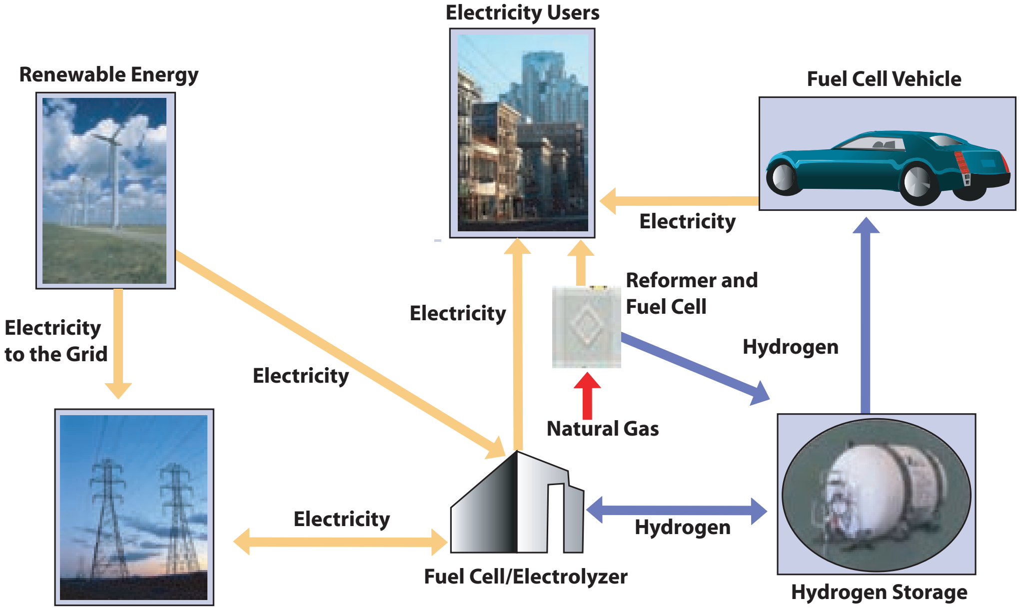
R&D continues concurrently to address key cost and performance barriers

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. However, electrolyzers 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.

The energy station concept includes steady production of hydrogen from natural gas for vehicles and use of a fuel cell or alternative power systems to produce electricity. When excess hydrogen is available, it is stored for use when electricity demand is high and to refuel vehicles. The advantages of producing both hydrogen and electricity in energy stations include the following: it provides access to lower cost natural gas because of the higher volume required; it facilitates staged implementation of refueling components to better match the demand from vehicles; and it allows use of a larger reformer or the fuel cell itself (internal reformation) that will lower the per-unit capital costs of hydrogen production.

Power parks can combine these near-term hydrogen production technologies into a single system that produces hydrogen and electricity. 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 (see Figure 3.5.3). Analysis of the power park concept is ongoing and a future validation test is planned that will include the option of a vehicle fuel cell being a back-up electric generator.

Figure 3.5.3. Example of a Power Park Concept



Technical analyses will be initiated and used to assess current and guide future activities, including analyses of the following:

- Vehicle component and vehicle system performance maps
- Early infrastructure options
- Energy stations
- Power parks that include integrated renewable hydrogen production systems that combine electrolysis powered by wind, solar, hydropower, or geothermal with natural gas or biomass gasification systems

Analysis of a vehicle fuel cell power generator as a back-up power option for distributed power systems will be considered along with other power park options.

3.5.3 Programmatic Status

Table 3.5.1 summarizes current technology validation activities, which focus on hydrogen vehicles and infrastructure, energy stations, power parks, and renewable/hydrogen system demonstrations.

Current Activities

Table 3.5.1 Current Technology Validation Activities

Organization	Activities
Hydrogen Vehicles and Infrastructure	
DaimlerChrysler/ BP, Ford/BP, GM/Shell, Texaco Energy Systems/ Hyundai	The Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project will be a learning demonstration that will help DOE refocus its research and development efforts, provide insight into vehicle and infrastructure interface issues, assess the status of the industry and help address codes, standards and safety issues
California Fuel Cell Partnership (CaFCP)	The CaFCP is helping to encourage early introduction of fuel cell (FC) passenger cars and buses in California. 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.
General Motors and Selected Universities	Develop and test student-designed hybrid fuel cell and internal combustion engine vehicles.
Natural Gas to Hydrogen Refueling Stations	
SunLine Services Group, Inc. and Hydradix	Operating a hydrogen fuel cell vehicle (FCV) refueling station in Coachella Valley, California that uses hydrogen made from natural gas autothermal reformation and electrolysis of water using electricity generated from PV arrays.
Air Products and Chemicals Inc.	Build and operate a steam methane reformation refueling station at the Pennsylvania State University in State College, Pennsylvania, that can produce hydrogen for less than $3.00/gge (untaxed) when built in quantity. Novel compression and fueling apparatus to be incorporated and tested at Pennsylvania State University refueling station.
GTI	Demonstrate a natural gas-to-hydrogen refueling station that can produce hydrogen for less than $3.00/gge (untaxed) when built in quantity.
Stationary Hydrogen Fuel Cells for Co-Production of Hydrogen and Electricity (Energy Stations)	
Air Products and Chemicals Inc.	Build and operate energy station in Las Vegas, Nevada to validate $3.60/gge hydrogen cost and 8¢/kWh electricity cost (untaxed).
Air Products and Chemicals Inc.	Validating a high-temperature fuel cell as an energy station.

Renewable Hydrogen Production Systems and Power Parks	
Sandia National 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.
Clark Atlanta University	Developed technology to generate hydrogen from biomass and agricultural residue. Will test 1 kg/hour shift reactor using vapors from peanut shell pyrolysis. This technology is applicable to all forms of biomass.
Praxair	LAX Hydrogen Fueling Station – Design and demonstration of a small footprint hydrogen production facility suitable for placement at existing refueling stations.

3.5.4 Technical Challenges

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 total system solutions, such as FCVs and refueling infrastructure. To have confidence in these technologies, they must be evaluated in multiple systems to acquire sufficient data to validate statistical significance and be able to meet local, national, and international codes and standards. All integrated systems will have to meet safety regulations. A by-product of this approach to technology validation is that technical and system problems are revealed and component requirements can be better assessed.

The Learning Demonstration Project is an important first step towards bringing energy companies and automakers together to solve all elements of infrastructure and vehicle development that will support the President's Hydrogen Initiative in developing a path to a hydrogen economy. By 2009, when the project's targets of 2000 hours fuel cell durability operated in varied climates, 250 mile vehicle range and less than $3.00/gallon gasoline equivalent hydrogen fuel cost are validated, it will be an important measure that the industry commercialization decision by 2015 will be on schedule.

In addition, the demonstration of high temperature coproduction systems (energy stations) could potentially validate a complete system solution to meet a 2010 target for hydrogen fuel production cost of $1.50/gallon gasoline equivalent. The demonstration of power park concepts that utilize renewable and fossil fuel systems and automobile fuel cells as back-up or peaking power generation will allow utilities to increase overall efficiency in the electric generation system and allow automobile companies to increase the value of vehicle fuel cells.

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 individual component technical targets developed within the other subprograms 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 validated under real-world conditions as part of learning demonstration and validation efforts.

3.5.4.2 Barriers

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 both controlled and real-world conditions is very limited (i.e., data such as FCV system fuel efficiency and economy, thermal/water management integration, durability (stack degradation), and system durability). Most or all the information is proprietary. Vehicle drivability, operation, and survivability in extreme climates (particularly low temperature start-up and operation in hot/arid climates), 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 targets for component development.

B. **Storage.** Innovative packaging concepts, 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, efficiency and volume options for stationary applications. An understanding of composite tank operating cycle life and failure mechanisms and the introduction of potential impurities is lacking. Cycle life, storage density, fill-up times, regeneration cycle costs, energy efficiency, and availability 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 needs to be conceptualized and implemented. The overall hydrogen production efficiency and the quantity of greenhouse gas emissions in well-to-tank scenarios are not well understood in real world conditions. 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. Other concepts for energy stations, power parks, and mid-sized plants (i.e., 25,000 kg/day), including pipelines or mobile refuelers, need to be verified with respect to system performance, efficiency, and availability.

D. **Maintenance and Training Facilities.** Lack of facilities for maintaining hydrogen vehicles, personnel not trained in handling and maintenance of hydrogen and fuel cell 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 and operations and maintenance (O&M), including time and material costs, of FCVs are additional barriers.

E. **Codes and Standards.** Lack of adopted or validated codes and standards that will permit the deployment of refueling stations in a cost-effective and timely manner must be addressed. A database also needs to be assembled that is relevant to the development of codes and standards to ensure that future energy systems based on these technologies can be efficiently installed and operated. Data on the impact of constituent hydrogen impurities on fuel cell and storage systems needs to be validated under real-world operating conditions.

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 separations at high temperature and high pressure and their integrated impact on the hydrogen delivery system need to be demonstrated and validated.

G. **Hydrogen from Nuclear Power.** Validate data on reaction rates, nonequilibrium reactions and material properties 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 reactors are designed and developed for 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, cost, durability, and efficiency information for large integrated renewable electrolyzer systems that produce hydrogen. 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 or alternative-power production systems 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, or 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 barriers associated with each task (see section 3.5.4.2) are also included.

Table 3.5.2 Technical Task Descriptions

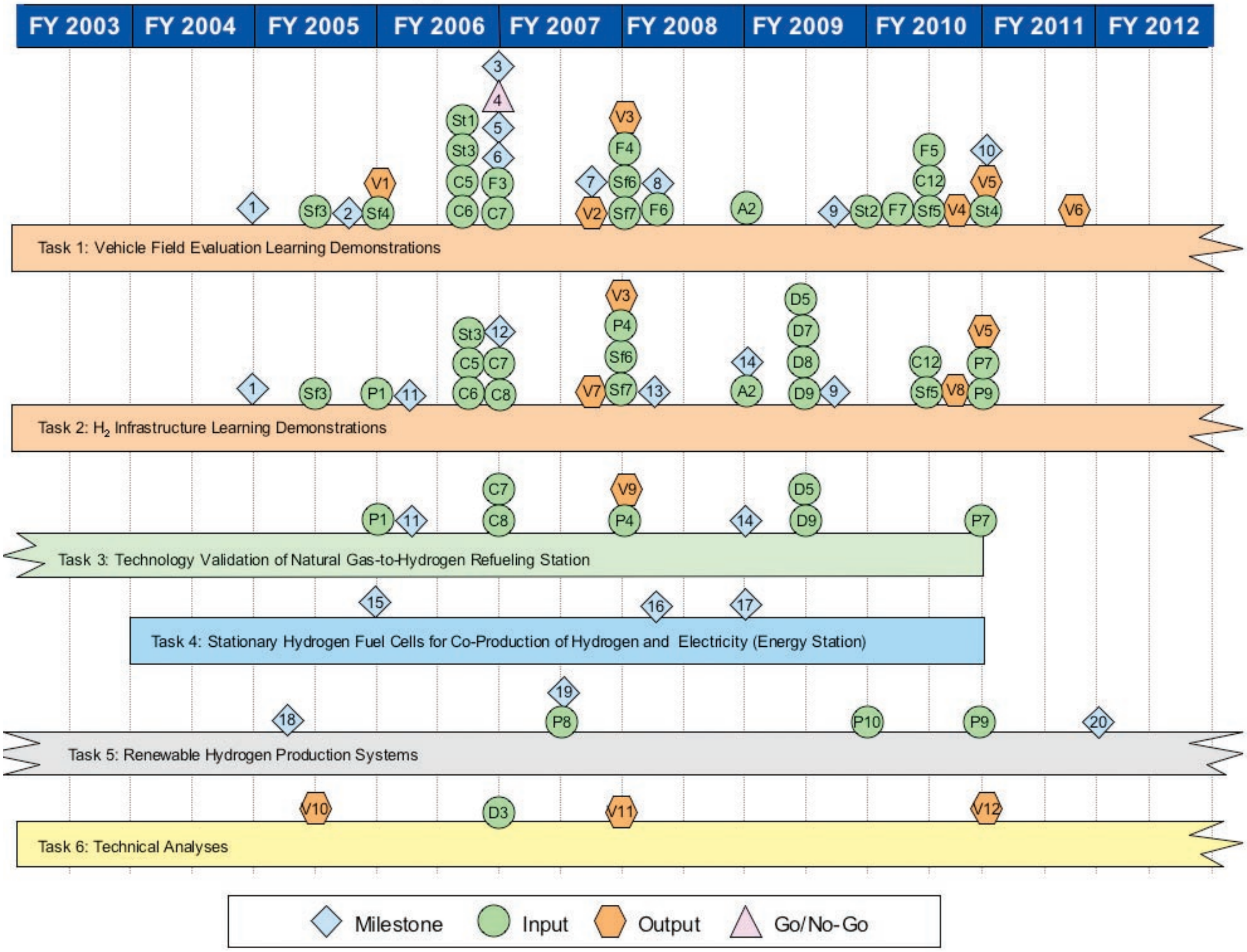
Task	Description	Barriers
1	**Vehicle Field Evaluation Learning Demonstrations** • Support acquisition of vehicles for controlled fleet demonstrations in strategic locations to collect data on FCV performance under real-world conditions. • Collect vehicle operating experience, including fuel economy, range, cost, drivability, cold-start, emissions, and durability. Data will be used for modeling, and composite results will be disseminated. • Identify maintenance, safety, and refueling requirements, including sensors and refueling connections. • Coordinate with and provide feedback to the FreedomCAR and Vehicle Technologies Program. • 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 ChallengeX Student Demonstration Program for hydrogen hybrid vehicle that uses a small 10-kW fuel cell to augment an internal combustion engine.	A, B, C, D, E
2	**Hydrogen Infrastructure Learning Demonstrations** • Design, construct, and operate 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 specific impurities), and safety. • Collect and disseminate composite operating data to verify component performance using uniform protocols that include safety procedures, risk mitigation, and communication plans. • Collect and disseminate composite data from refueling sites in different geographic areas to verify performance and reliability under real-world operating conditions, including fast-fill and driver acceptance.	B, C, D, E, H, I
3	**Technology Validation of Natural Gas-to-Hydrogen Refueling Stations** • Build and operate 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 composite operating data to verify component performance using uniform protocols that include safety procedures. • Collect and disseminate composite data from refueling sites in different geographic areas to verify performance and reliability under real-world operating conditions including fast-fill and driver acceptance.	B, C, D, E

4	**Stationary Hydrogen Fuel Cells for Coproduction of Hydrogen and Electricity (Energy Station)** • Demonstrate 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. • Collect and disseminate composite operating data to verify component performance using uniform protocols that include safety procedures. • Collect and disseminate composite data from refueling sites in different geographic areas to verify performance and reliability under real-world operating conditions including fast-fill and driver acceptance.	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, durability, and reliability under real-world operating conditions. • Collect operating data to verify component performance using uniform protocols that include safety procedures. • Assess the economic viability of renewable hydrogen production, including system size and siting requirements based on resource location and transport economics.	E, H
6	**Technical Analyses** • Validate and improve models to refocus the R&D Program. • Analyze early infrastructure. • Analyze integrated renewable hydrogen production systems that combine electrolysis powered by wind, solar, hydropower, or geothermal with biomass gasification systems. • Analyze advanced energy stations and power parks for production of both hydrogen and electricity from renewable and natural gas sources. • Analyze a vehicle fuel cell power generator as a back-up power option for distributed power systems.	A, B, C, D, F, G, H, I

3.5.6 Milestones

Figure 3.5.4 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 3.5.4. Technology Validation R&D Milestone Chart



For chart details see below and next page.

Milestones

1 Make awards to start fuel cell vehicle/infrastructure demonstration activity and for hydrogen co-production infrastructure facilities.
2 Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles.
3 Demonstrate (on a vehicle) compressed and cryogenic storage tanks achieving the 2005 energy and mass density targets.
4 Go/No-Go: Decision for purchase of additional vehicles based on projected vehicle performance and durability, and hydrogen cost criteria
5 Validate fuel cell demonstration vehicle range of ~ 200 miles and durability of ~ 1,000 hours.
6 Validate vehicle refueling time of 5 minutes or less.
7 Test results from student-designed hybrid fuel cell and internal combustion engine vehicles.
8 Validate (on a vehicle) 2.0 kWh/kg and 1.2 kWh/L compressed gas tank.
9 Validate FCVs with 250-mile range, 2,000-hour fuel cell durability, and a hydrogen cost of $3.00/gge (based on volume production).
10 Validate refueling time and durability for reversible complex hydride storage.
11 Validate cost of producing hydrogen in quantity of $3.00/gge untaxed.
12 Five stations and two maintenance facilities constructed with advanced sensor systems and operating procedures.
13 Total of eight stations and four maintenance facilities constructed with advanced sensor systems and operating procedures.
14 Validate $2.50/gge hydrogen cost.
15 Validate co-production system using 50 kW PEM fuel cell; hydrogen produced at $3.60/gge and electricity at 8 cents/kWhr.
16 Demonstrate prototype energy station for 6 months; projected durability >40,000 hours; electrical energy efficiency >40%; availability >0.80.
17 Validate prototype energy station for 12 months; projected durability >40,000 hours; electrical energy efficiency >40%; availability >0.85.
18 Demonstrate pyrolysis system for waste biomass.
19 Complete Power Park demonstrations and make recommendations for business case economics.
20 Validate $2.85/gge hydrogen cost from biomass/wind (untaxed and unpressurized) at the plant gate.

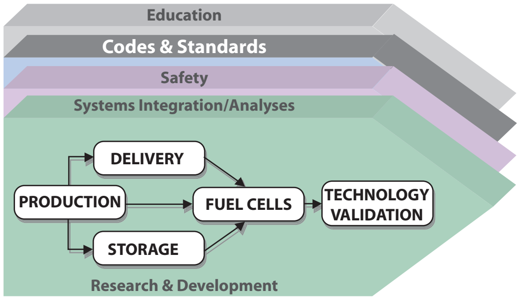
Outputs

V1 Output to Fuel Cells: Validate maximum fuel cell system efficiency.
V2 Output to Systems Analysis and Systems Integration: Final report for first generation vehicles, interim progress report for second generation vehicles, on performance, safety, and O&M.
V3 Output to Systems Analysis and Systems Integration: Technology Status Report and re-focused R&D recommendations.
V4 Output to Systems Analysis and Systems Integration: Final report for second generation vehicles on performance, safety, and O&M.
V5 Output to Systems Analysis and Systems Integration: Technology Status Report and re-focused R&D recommendations.
V6 Output to Fuel Cells: Validate Cold Start-Up capability (in a vehicle with an 8-hour soak) meeting 2005 requirements (specify cold-start energy)
V7 Output to Systems Analysis and Systems Integration: Final report on infrastructure and hydrogen quality for first generation vehicles.
V8 Output to Systems Analysis and Systems Integration: Final report on infrastructure, including impact of hydrogen quality for second generation vehicles.
V9 Output to Program: Submit final report on safety and O&M of three refueling stations.
V10 Output to Systems Analysis and Systems Integration: Hydrogen refueling station analysis - proposed interstate refueling station locations.
V11 Output to Systems Analysis and Systems Integration: Composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.
V12 Output to Systems Analysis and Systems Integration: Final composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.

Inputs

Sf3 Input from Safety: Safety requirements and protocols for refueling.
Sf4 Input from Safety: Safety requirements for on-board storage.
St1 Input from Storage: Compressed and cryogenic storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.
St3 Input from Storage: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.
C5 Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
C6 Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.
F3 Input from Fuel Cells: Laboratory PEM technology with 2,000 hours durability.
C7 Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (NFPA).
F4 Input from Fuel Cells: Complete 4,000 hour testing of advanced MEA for stationary and transportation applications.
Sf6 Input from Safety: Sensor meeting technical targets.
Sf7 Input from Safety: Final peer reviewed Best Practices Handbook.
F6 Input from Fuel Cells: Verify cold start in 60 s of short stack.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
St2 Input from Storage: Advanced compressed/cryogenic tank technologies.
F7 Input from Fuel Cells: Technology with short-stack survivability at -40°C.
F5 Input from Fuel Cells: Laboratory PEM technology with 5,000 hours durability.
C12 Input from Codes and Standards: Final Hydrogen fuel quality standard as ISO Standard.
Sf5 Input from Safety: Safety requirements and protocols for refueling.
St4 Input from Storage: Full-cycle, integrated chemical hydride system meeting 2010 targets
P1 Input from Production: Verify hydrogen production technologies for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
C8 Input from Codes and Standards: Draft standards (balloting) for refueling stations (NFPA).
P4 Input from Production: Verify hydrogen production technologies for distributed systems using natural gas or liquid fuels with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration, assuming 100s of units of production per year.
D5 Input from Delivery: Compression technology recommended for validation.
D7 Input from Delivery: Recommendations liquefaction technology for potential validation.
D8 Input from Delivery: Recommended pipeline technology for validation.
D9 Input from Delivery: Off-board storage technology .
P7 Input from Production: Verify hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.
P9 Input from Production: Electrolysis system making hydrogen for $2.85/gge delivered.
P8 Input from Production: Down-select of high-temperature electrolysis technology based on research results.
P10 Input from Production: Hydrogen production system making hydrogen for $1.90/gge from biomass at the plant gate.
D3 Input from Delivery: Hydrogen delivery infrastructure analysis results.

3.6 Hydrogen Codes and Standards



The U.S. and most countries in the world have established laws and regulations that require commercial products to meet all applicable codes and standards to demonstrate that they are safe, perform as designed, and are compatible in systems in which they are used. Hydrogen has an established history of industrial use as a chemical feedstock, but its use as an energy carrier on a large-scale commercial basis remains largely untested and undeveloped. The development and promulgation of codes and standards are essential to establish a market-receptive environment for commercial, hydrogen-based products and systems.

Codes- Model building codes are guidelines for the design of the built environment (e.g. buildings and facilities). Codes are generally adopted by local jurisdictions, thereby achieving a force of law. Codes often refer to or invoke standards for the equipment used within the built environment.

Standards - Standards are rules, guidelines, conditions or characteristics for products or related processes, and generally apply to equipment or components. Standards achieve a regulatory-like status when they are referred to in codes or through government regulations.

DOE's focus is the research and development needed to strengthen the scientific basis for technical requirements incorporated in national and international standards, codes and regulations. DOE is also sponsoring a national effort by industry, standards and model code development organizations, and government to prepare, review and promulgate hydrogen codes and standards needed to expedite hydrogen infrastructure development and to help enable the emergence of hydrogen as a significant energy carrier. In addition, DOE is also supporting the harmonization of essential requirements for the safe use of hydrogen by consumers in the U.S. and through the International Partnership for a Hydrogen Economy (IPHE).

The aim of this Program element is to identify those codes and standards that will be necessary or helpful in the implementation of the hydrogen economy, to facilitate their development, and to support publicly-available research that will be necessary to develop a scientific and technical basis for such codes and standards.

3.6.1 Goal and Objectives

Goal

Perform underlying research to enable codes and standards to be developed for the safe use of hydrogen in all applications. Facilitate the development and harmonization of international codes and standards.

Objectives

- By 2006, facilitate the adoption of the most recently available model codes (e.g., ICC) in key regions; complete research and development on hydrogen release scenarios; and provide a sound basis for model code development and adoption.

- By 2007, support and facilitate the drafting of model building codes for hydrogen applications (i.e., NFPA 5000) by the National Fire Protection Association (NFPA).

- By 2007, support and facilitate the completion of the ISO standards for hydrogen refueling and on-board storage.

- By 2008, support and facilitate the completion of standards for bulk hydrogen storage (e.g., NFPA 55) with experimental data and input from Technology Validation Program element activities.

- By 2010, support and facilitate development of Global Technical Regulations (GTR) for hydrogen vehicle systems under the United Nations Economic Commission for Europe, World Forum for Harmonization of Vehicle Regulations, and Working Party on Pollution and Energy Program (ECE-WP29/GRPE).

- By 2015, complete necessary codes and standards that support the commercialization of hydrogen technologies.

3.6.2 Technical Approach

The Hydrogen, Fuel Cells & Infrastructure Technologies Program recognizes that domestic and international codes and standards must be established along with affordable hydrogen and fuel cell technologies to enable the timely commercialization and safe use of hydrogen technologies. The lack of codes and standards applicable to hydrogen as an energy carrier is a major institutional barrier to deploying hydrogen technologies and developing a hydrogen economy. It is in the national interest to eliminate this potential barrier. As such, this Program element works with domestic and international Standard Development Organizations (SDOs) to facilitate the development of performance-based standards. These standards are then referenced by building codes to expedite regulatory approval of hydrogen technologies. This approach ensures that U.S. consumers can purchase products that are safe and reliable, regardless of their country of origin, and that U.S. companies can compete internationally.

The key U.S. and international SDOs developing and publishing the majority of hydrogen codes and standards are shown in Table 3.6.1. These organizations typically work with the public and private sectors to develop codes and standards.

Table 3.6.1. Organizations Involved in Codes and Standards Development and Publication

Organization	Responsibility
Domestic Codes and Standards	
American Society for Testing and Materials (ASTM)	Materials testing standards and protocols
American National Standards Institute (ANSI)	Certifies consensus methodology of and serves as clearinghouse for codes and standards development
American Petroleum Institute (API)	Equipment standards
American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE)	Equipment design and performance standards
American Society of Mechanical Engineers (ASME)	Equipment design and performance standards
Compressed Gas Association (CGA)	Equipment design and performance standards
CSA America (CSA)	Equipment standards

International Association of Plumbing and Mechanical Officials (IAPMO)	Mechanical building code
Institute of Electrical and Electronic Engineers (IEEE)	Electrical standards
International Code Council, Inc. (ICC)	Family of model building codes
National Fire Protection Association (NFPA)	Model building codes, standards
Natural Gas Institute (NGI)	Natural gas vehicle standards
Society of Automotive Engineers (SAE)	Vehicle standards
Underwriters Laboratories (UL)	Equipment and performance testing standards
International Codes and Standards	
International Electrotechnical Commission (IEC)	International performance standards
International Organization for Standardization (ISO)	International performance standards

Recently, a national agenda for hydrogen codes and standards has emerged through a collaborative effort among DOE, industry, standards development organizations (SDOs) and model code development organizations (CDOs). This collaboration has enabled significant progress in the development of codes and standards for hydrogen applications. For example, provisions for hydrogen use are included in the International Code Council's (ICC) International Building, Residential, Fire, Mechanical and Fuel Gas model codes. Additional provisions, such as underground storage of liquid hydrogen and canopy storage of gaseous hydrogen, will be incorporated in a future edition of the ICC model codes.

The Codes and Standards Tech Team under the FreedomCAR and Fuel Partnership has developed and maintains an RD&D roadmap to establish a firm scientific and technical basis for codes and standards. The roadmap identifies key experimental and analytical needs to support codes and standards development. Data and information obtained through implementation of the roadmap are provided to the appropriate standards and model code development organization. The Tech Team also reviews the DOE RD&D projects annually so that the results generated effectively support codes and standards development.

Research to Facilitate Domestic Codes and Standards Development

A primary role of this Program element is to perform R&D that supports the development of hydrogen codes and standards. This R&D focuses on basic hydrogen properties and behavior, as well as the testing of materials and components that support standards development.

In the development of hydrogen codes and standards, the Hydrogen, Fuel Cells & Infrastructure Technologies Program acts as a facilitator in the standards development process and provides funding to support this process. One result of DOE's effort is the creation of "national templates," which identify players and establish relationships to facilitate codes and standards development. Through these relationships, DOE and the major SDOs and CDOs coordinate the preparation of critical standards and codes for hydrogen technologies in vehicular and stationary applications. The structure provided by the templates is implemented through the DOE Hydrogen Codes and Standards Coordinating Committee (HCSCC). The HCSCC provides a forum for the codes and standard community to keep participants aware of progress in implementing the templates and discuss issues and concerns that may arise. It is also important to note that state and local governments must incorporate standards and model codes in regulations for the standards and codes to be enforceable.

The Program is also assuming a communication and education role, so that timely, accurate, and relevant information is prepared and disseminated to stakeholders. An important part of implementing the national templates is to maintain an awareness of the status of and changes in hydrogen code and standards. To this end, DOE maintains a matrix (posted at www.hydrogensafety.info) that lists codes and standards by application area and for each code and standard listed, provides a brief description, technical contacts and current status.

Information about current codes and standards issues is also provided though the Hydrogen Safety Newsletter published monthly by the National Hydrogen Association (NHA) and available at the same Web site as the matrix. DOE has also created an interactive Web site (www.fuelcellstandards.com) that allows searching for information on codes and standards under several search criteria, including application and geographic region. The Web site also tracks activities in codes and standards and provides a convenient site for information on codes and standards. To improve access to current hydrogen codes and standards, the DOE is working with ANSI to create a hydrogen portal on ANSI's national standards network. The portal will provide electronic access to key hydrogen standards and model codes.

The ICC and the NFPA are the two major organizations in the U.S. that develop model codes. Typical model codes available for adoption by state and local governments are listed in Table 3.6.2. Many of these model codes have been or are being amended to incorporate requirements for hydrogen applications.

Table 3.6.2. Typical Model Codes

Model Code	Content
Fire Code	Regulations affecting or relating to structures, processes, premises, and safeguards regarding fire and explosions.
Building Code	Ensures public health, safety, and welfare as they are affected by repair, alteration, change of occupancy, addition, and location of existing buildings.
Electrical Code	Ensures public safety, health, and general welfare through proper electrical installation, including alterations, repairs, replacement, equipment, appliances, fixtures, and appurtenances.
Property Maintenance Code	Ensures adequate safety and health as they are affected by existing building structures and premises.
Zoning Code	Enforces land use restrictions and implements land use plan.
Energy Conservation Code	Ensures adequate practices for appliances, HVAC, insulation, and windows for low cost operation.
Residential Code	Applies to the construction, alteration, movement, enlargement, replacement, repair, use, and occupancy of one- and two-family dwellings.
Plumbing Code	Regulates the erection, installation, alternation, repairs, relocation, and replacement, in addition to use or maintenance, of plumbing systems.
Mechanical Code	Regulates the design, installation, maintenance, alteration, and inspection of mechanical systems that are permanently installed and used to control environmental conditions and related processes.
Fuel Gas Code	Regulates the design, installation, maintenance, alteration, and inspection of fuel gas piping systems, fuel gas utilization equipment, and related accessories.
Performance Code	Establishes requirements to provide acceptable levels of safety for fire fighters.

Table 3.6.3 summarizes the various roles that the private sector and federal government have in the development process. The federal government's traditional role has been to serve as a facilitator/developer for standards that cover technologies or applications that are of national interest. Examples include the involvement of the U.S. Coast Guard in standards for marine use; the Department of Transportation (DOT) for interstate pipelines, tunnels, railroads and interstate highways; and DOE for appliances (e.g. voluntary Energy Star Program). In each case, the private sector plays a significant role in the process.

The federal government also plays an important role in the adoption process, which involves converting a voluntary standard or model code into a law or regulation. Congress may pass laws governing both residential and commercial building design and construction to ensure public safety. Certain agencies of the federal government may also be granted authority by Congress to adopt and implement regulatory programs.

Table 3.6.3. Private and Federal Sector Role in Codes and Standards Development

Private Sector		Government Sector		
Standard/Model Code Development Organizations	Other Private Sector Firms	Federal	State	Local
Develop consensus-based codes and standards with open participation of industry and other stakeholders.	Develop hydrogen technologies and work with SDOs to develop standards.	Perform underlying research to facilitate development of codes and standards, support necessary research and other safety investigations, and communicate relevant information to stakeholders (including state and local government agencies).	Evaluate codes and standards that have been developed and decide whether to adopt in whole, part, or with changes.	Evaluate codes and standards that have been developed and decide whether to adopt in whole, part, or with changes.

International Codes and Standards Development

The Hydrogen, Fuel Cells & Infrastructure Technologies Program supports the development of international codes and standards to facilitate trade between the U.S. and other countries. The Program element coordinates and supports the participation of U.S. experts at key international codes and standards development organization meetings sponsored by ISO, IEC and ECE-WP29/GRPE. Through its coordination of the domestic codes and standards agenda, the Program element facilitates national consensus positions on international standards. The Program element also supports and coordinates the U.S. Technical Advisory Groups (TAGs) for ISO TC197 (Hydrogen Technologies) and IEC TC105 (Fuel Cell Technology). The TAGs provide a national forum for industry and government experts to develop consensus positions on proposed ISO and IEC documents and actions. The Program element also works with the EPA and DOT/NHTSA to provide technical expertise on issues before the WP29/GRPE.

3.6.3 Programmatic Status

Current Activities

The current Hydrogen Codes and Standards Program element activities are summarized in Table 3.6.4.

Table 3.6.4. Ongoing Activities for Hydrogen Codes and Standards

Activity	Objective	Organizations
U.S. Domestic Codes and Standards Development Activities		
Stakeholder Meetings and Technical Forums	Supports technical and coordination meetings to ensure communications among key stakeholders.	NREL, PNNL, LANL, SNL, NHA
Technical Expertise	Supports hydrogen safety research and provides expert technical representation at key industry forums and codes and standards development meetings, such as the ICC and NFPA model code revision process	SNL, NREL, LANL
Consensus Codes and Standards Development	Supports coordinated development of codes and standards through a national consensus process	NREL, SNL, SAE, CSA, NHA, NFPA, ICC, ANSI
Information Dissemination	Supports information forums for local chapters of building and fire code officials, and the development of case studies on the permitting of hydrogen refueling stations.	PNNL, NHA
Research, Testing, and Certification	Supports focused research and testing needed to verify the technical basis for hydrogen codes and standards and for certification of components and equipment.	SNL, NREL
Training Modules and Informational Videos	Supports the development of mixed media training modules and informational videos for local code officials, fire marshals, and other fire and safety professionals.	PNNL
National Template for Standards, Codes, and Regulations	Identifies key areas of standards, codes, and regulations for hydrogen vehicles and hydrogen fueling/service/parking facilities and designates lead and supporting organizations.	NREL
Codes and Standards Matrix Database	Provides inventory and tracking of relevant domestic codes and standards: identifies gaps, minimizes overlap, and ensures that a complete set of necessary standards is written.	NREL, ANSI
U.S. International Codes and Standards Development Activities		
International Stakeholder, Consensus Development, and Harmonization Meetings	Supports the international codes and standards development activities of ISO TC197, IEC TC105, and the International Partnership for a Hydrogen Economy (IPHE)	LANL, NREL
Technical Expertise and Underlying Research Activities	Provides representation and technical expertise in support of U.S. concerns at key international codes and standards development organization meetings and forums, including ISO, IEC, and United Nations Economic Commission for Europe (WP29/GRPE).	LANL, NREL, SNL

Status of Equipment Standards

Domestic Standards

The status of domestic standards in each application area is described below. Up to date information on the development of fuel cell equipment standards is maintained at www.fuelcellstandards.com.

Stationary Fuel Cell Standards

Stationary fuel cell standards are the most comprehensively available standards within hydrogen technologies, as the phosphoric acid fuel cell has been commercially available for more than 20 years. Standards are being revised or developed to more adequately represent emerging fuel cell technologies. Figure 3.6.1 illustrates the significant efforts underway for standards development related to stationary fuel cells.

Figure 3.6.1. Domestic Codes and Standards for Stationary Fuel Cells

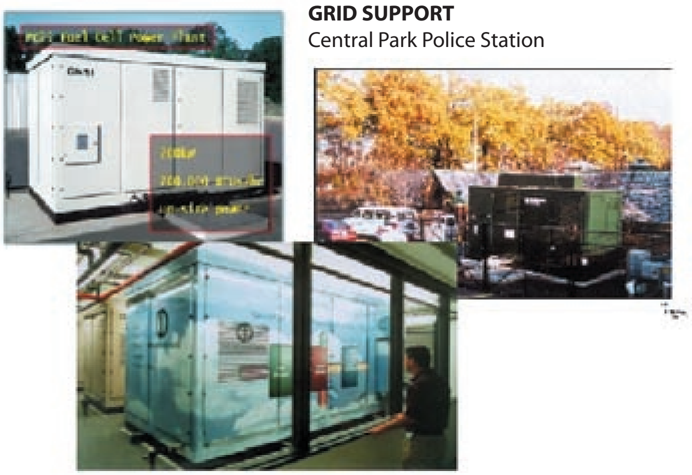
ICC Family Codes
Fire, Fuel, Mechanical
Electrical (Approved)

CSA CAS No. 33
Component
Acceptance Service
(Published)

NFPA 853
Installation at Stationary
Fuel Cell Power Plants
(Published)

NFPA 70 Article 692
National Electric Code
Fuel Cell Systems
(Published)

UL 1741
Inverters & Converters
(Published)



GRID SUPPORT
Central Park Police Station

UL 2266
Telecommunications
(Proposed)

UL 2265
Replacement FC Units
(Under development)

ANSI/CSA FC1-2004
Fuel Cell Power Systems
(Published)

IEEE P1547.1-4
Interconnection
(in Progress)

CGA G5.3 Hydrogen
Commercial Specification
(Published)

NFPA 110
Standby Power Systems
(Published)

CSA US Requirements
1.01 FC Supplemental
(Published)

CGA US G-5.4
H2 Piping at
Consumer Sites
(Published)

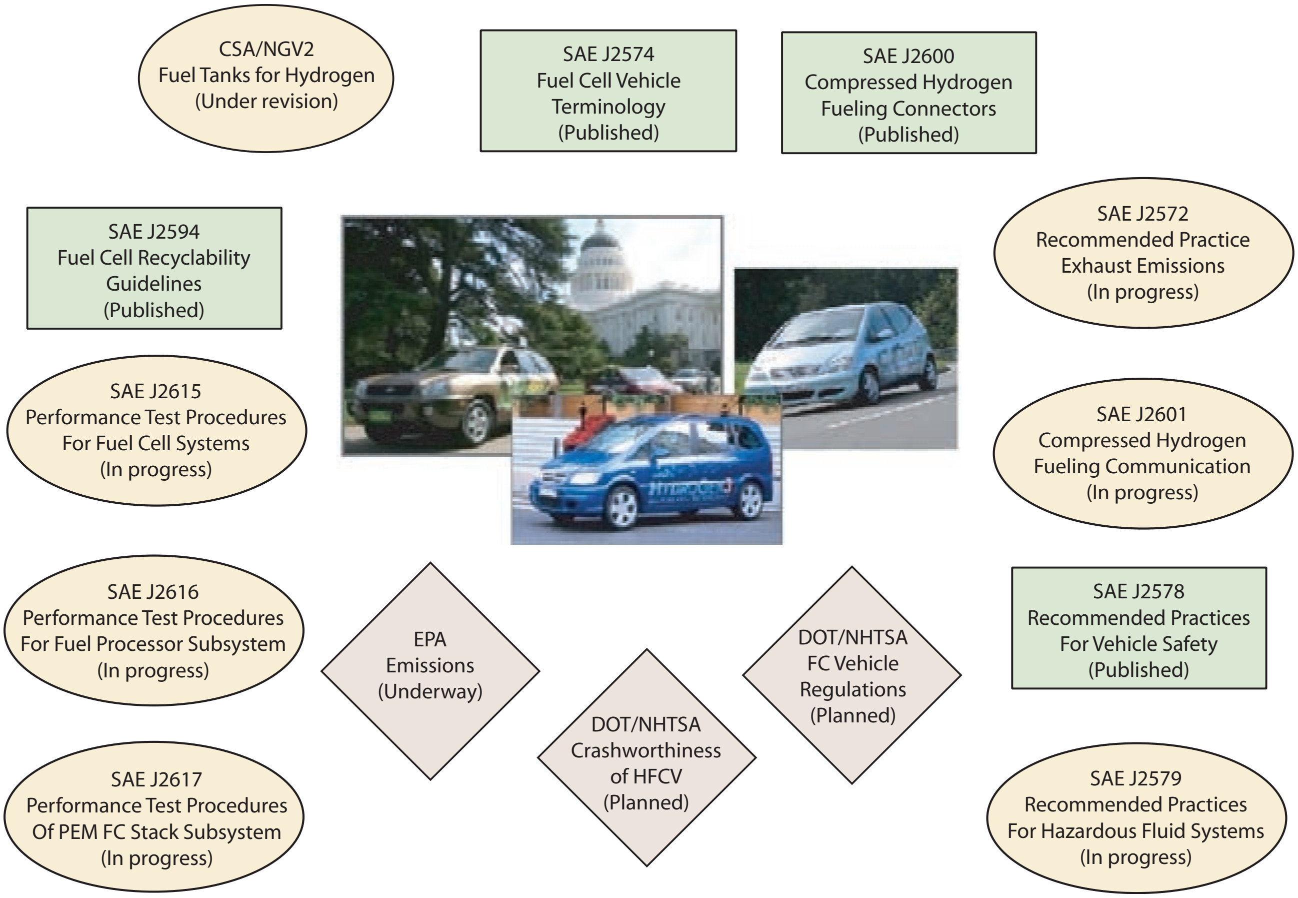
UL 2075
Flammable Gas Sensors
(Published)

NFPA Codes
Fuel, Electrical, Storage
(Under review for H2)

Fuel Cell Vehicle Standards

A comprehensive effort is underway for the development of standards for automotive technologies. SAE, working with technical experts from automotive, industrial gas and fuel cell companies, has developed a list of the standards that are needed for the commercialization of fuel cell vehicles. Figure 3.6.2 shows the standards under development for fuel cell vehicle applications.

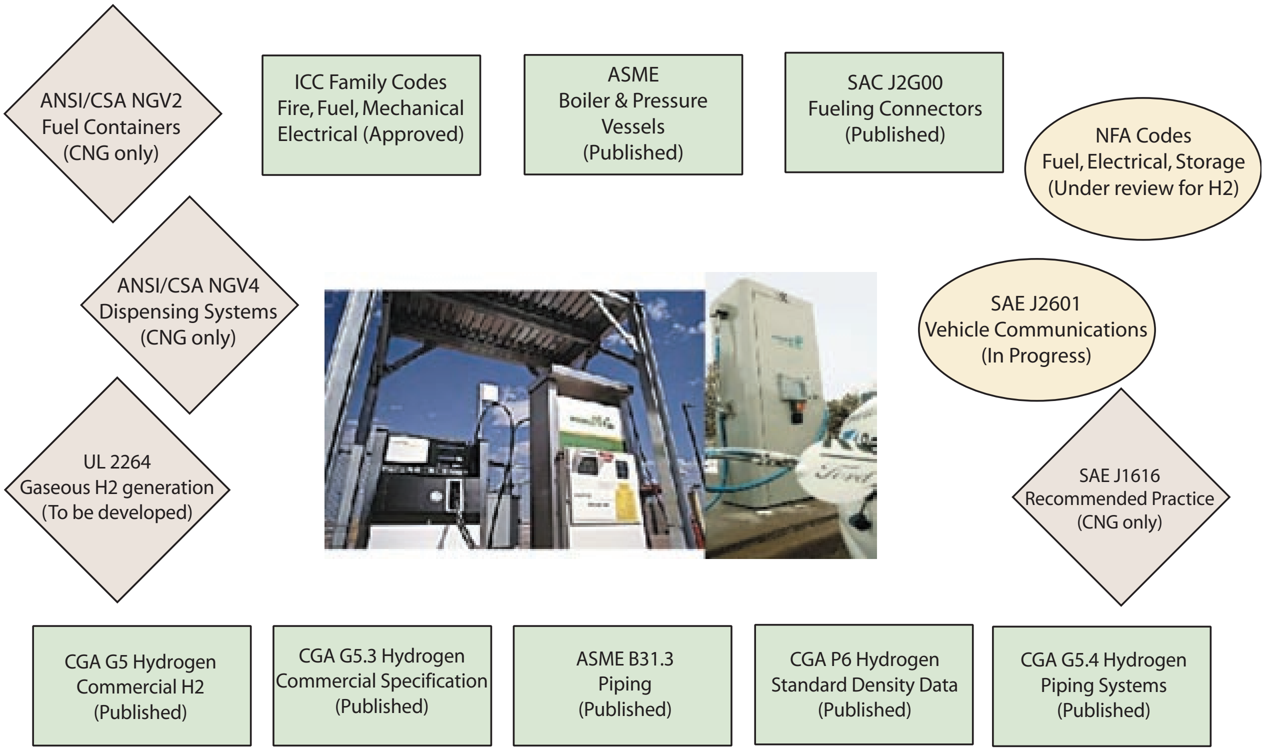
Figure 3.6.2. Domestic Codes and Standards for Hydrogen-fueled Vehicles



Refueling Station Standards

The development of standards for hydrogen fueling stations is underway. Although standards have been developed for commercial production, delivery and use of hydrogen, these industry-based design requirements and standard operating procedures are not suitable for dealing with hydrogen in a consumer environment. Efforts are focused on developing new standards, or clarifying the language or constraints in established standards to account for the significant differences in hazards and risks. Figure 3.6.3 shows the standards development efforts for fueling stations. In all cases, safety is ensured through comprehensive engineering reviews, hazard evaluations and risk mitigation plans.

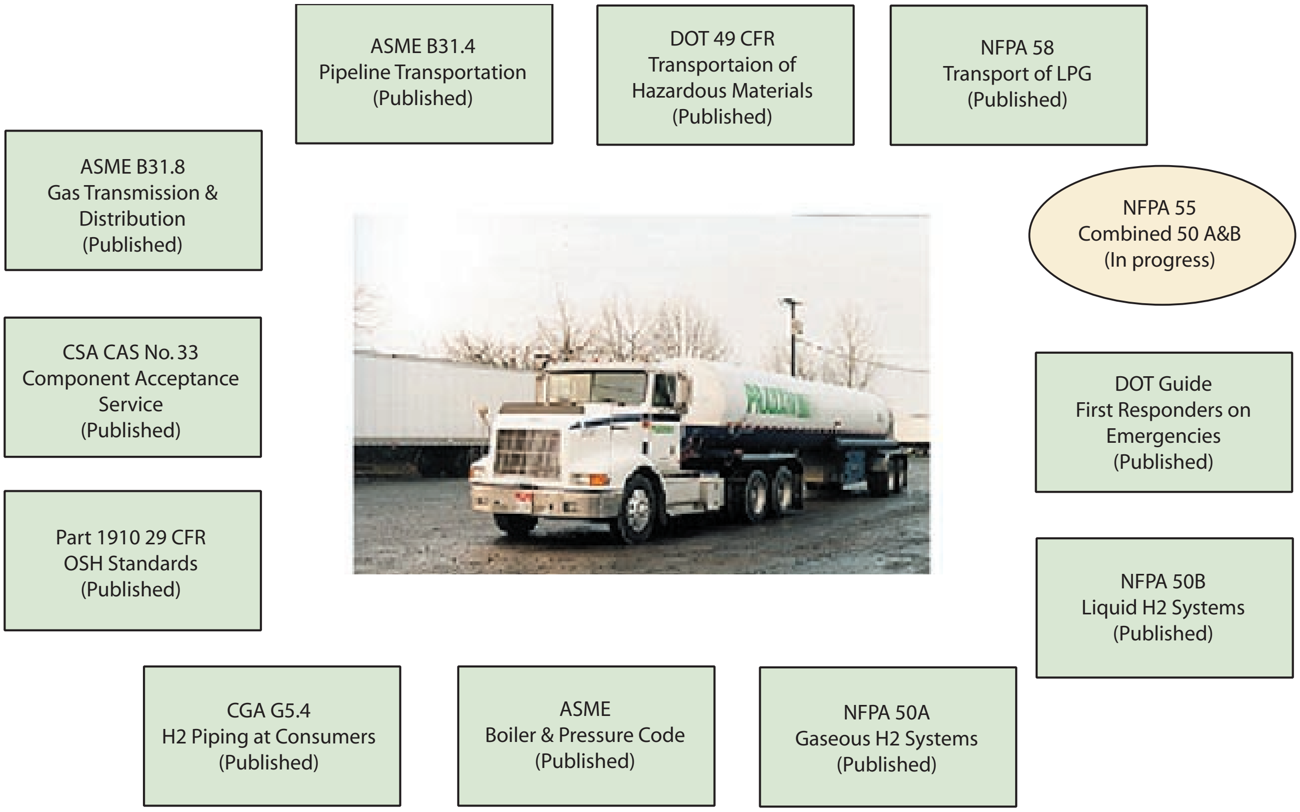
Figure 3.6.3. Status of Domestic Codes and Standards for Hydrogen Fueling Stations



Hydrogen Transportation Standards

Since the 1950s, hydrogen has been transported across the U.S. using DOT federal regulations for the safe transport of hydrogen in bulk and small portable containers. An effort is underway to update these standards to address the range of technologies now available. Figure 3.6.4 illustrates the status of standards for the transport of hydrogen.

Figure 3.6.4. Domestic Codes and Standards for Hydrogen Transport



International Standards

Three separate but related international efforts are underway to develop new technology standards through the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC) and the World Forum for Harmonization of Vehicle Regulations.

International Organization for Standardization

ISO is a worldwide federation of national standards bodies from more than 140 countries. Established in 1947, its mission is to promote standardization to facilitate the exchange of goods and services, and to facilitate cooperation in intellectual, scientific, technological and economic activities. ISO standards are developed through a consensus process.

The following ISO Technical Committees are working on standards related to hydrogen and fuel cells:

- **TC 22 - Road Vehicles:** compatibility, interchangeability, and safety, with particular attention to terminology and test procedures for mopeds, motorcycles, motor vehicles, trailers, semi-trailers, light trailers, combination vehicles, and articulated vehicles. The Electric Road Vehicle Subcommittee (SC21) is addressing operation of vehicles, safety, and energy storage.

- **TC 197 - Hydrogen Technologies:** systems and devices for the production, storage, transport, measurement, and use of hydrogen. Working groups address standards for gaseous and liquid fuel tanks for vehicles, multimodal transport of liquid hydrogen, airport refueling facility, hydrogen safety, hydrogen and hydrogen blends, hydrogen fuel quality, water electrolysis, fuel processing, and transportable gas storage devices.

- **TC 58 - Gas Cylinders:** fittings and characteristics related to the use and manufacture of high-pressure gas storage. The working group on gas compatibility and materials coordinates with TC 197.

International Electrotechnical Commission

IEC is a leading global organization for preparing and publishing international standards for electrical, electronic and related technologies. The IEC is developing standards for the electrical interface to fuel cells. IEC Technical Committee 105 is primarily addressing stationary fuel cell power plants, but has also addressed portable and propulsion fuel cells. The working groups in TC 105 include: Terminology, Fuel Cell Modules, Stationary Safety, Performance, Installation, Propulsion, and Safety and Performance of Portable Fuel Cells.

World Forum for Harmonization of Vehicle Regulations

Within the U.N. framework on GRPE, the European Union recognized a need to harmonize vehicle regulations. The original agreement was signed in 1958, with contracting parties including most European countries, Australia, Japan and South Africa, but not the United States. Contracting parties have two years to adopt standards developed under the 1958 agreement. Requirements ("regulations" or "directives") under this agreement are based on the "type" approval process, wherein an authority works with a technical service to assess compliance of components and systems (such as a vehicle). European countries use the "type" approval process, while the U.S. uses a self-certification process.

Since the initial agreement, the ECE WP29 developed a new "accelerated" agreement to allow the development of global legal requirements. The 1998 agreement has most European countries, Canada, China, Japan, Korea, South Africa and the U.S. as contracting parties. This new concept is termed Global Technical Regulations (GTR). These regulations are essentially technical requirements; therefore, they allow the use of different approval processes and global harmonization of legal requirements for all vehicles. The GRPE established an Ad Hoc Group to draft regulations for gaseous and liquid hydrogen systems. The ISO process and that instituted by the GRPE will harmonize the differences between both standards. In June 2002, the GRPE voted to move all actions for the introduction of fuel cell vehicles under the 1998 agreement to accelerate the development and adoption of a GTR. This Program element will monitor and participate in this process in support of the EPA and DOT/NHTSA lead responsibilities.

3.6.4 Challenges

A major challenge to the commercialization of hydrogen technologies is the lack of available data necessary to develop and validate standards. The Program sponsors a comprehensive, long-term RD&D effort to develop the scientific and technical basis for requirements incorporated in standards and model codes.

Another challenge to the commercialization of hydrogen technologies is the availability of appropriate codes and standards to ensure consistency and, if possible, uniformity of requirements and facilitate deployment. Certification to applicable standards facilitates approval by local code officials and safety inspectors. Uniform standards are needed because manufacturers cannot cost-effectively manufacture multiple products that would be required to meet different and inconsistent standards.

Domestically, competition between the individual SDOs could impact the adoption of new codes for hydrogen and fuel cell technologies. Because of the typical three- to five-year development cycle, some demonstration projects could be delayed or incur additional development costs. The DOE has worked with SDOs, CDOs and industry to minimize duplication in domestic codes and standards development. International standards developed by ISO and IEC will have an increasing impact on U.S. hydrogen and fuel cell interests. The U.S., Japan and Europe, among others, have accelerated efforts in this area, and the Program supports cooperative and coordinated development of international standards.

3.6.4.1 Targets

Since the development of the model codes or domestic and international standards is a voluntary, industry-led process, the federal government can influence but cannot direct this process. The Codes and Standards Program element activities will focus on assisting the commercial acceptance of hydrogen and fuel cell technologies.

Working with state and local code officials, the Hydrogen, Fuel Cells & Infrastructure Technologies Program will develop training programs to explain the new technologies, provide case studies of installations and operation, and communicate the changes in the codes as they pertain to the new technology. The Codes and Standards Program element will also work with state and local government officials to assist in the adoption of approved model codes through education and outreach in cooperation with the Education Program element (deferred).

This Program element will provide expertise and technical data on hydrogen properties, and hydrogen and fuel cell technologies to facilitate the development of standards and codes. Additionally, the Program element will provide support for industry and laboratory experts to participate in critical international standards development meetings and workshops.

The Program element will continue to work directly with the SDOs, by providing technical support to facilitate identification and development of new standards for hydrogen technologies, fuel cell systems and system monitoring and safety. Table 3.6.5 lists the high priority items for the Codes and Standards Program element.

Finally, this Program element supports focused research for testing and certifying hydrogen components and equipment.

Table 3.6.5. High Priorities for Development

Items	Content
Piping (Non-transport)	Hydrogen-specific piping design, installation, and certification standards.
Storage	Hydrogen storage tank standards for portable, stationary and vehicular use.
Materials Guide	Materials reference guide for design and installation.
Hydrogen Quality	Hydrogen specifications and testing methods.
Mass Measurement	Methods to quantify hydrogen mass measurement to determine appliance efficiency and consumer sales at refueling stations.
Transport	Standards for pipelines, delivery and ancillary equipment.

3.6.4.2 Barriers

The barriers are summarized below.

A. Limited Government Influence on Model Codes. The code development process is voluntary, so the government can affect its progression, but buy-in is ultimately required from code publishing groups.

B. Competition between SDOs and CDOs. The competition between various organizations hinders the creation of consistent hydrogen codes and standards.

C. Limited State Funds for New Codes. Budgetary shortfalls in many states and local jurisdictions impact the adoption of codes and standards, since they do not always have the funds for purchasing new codes or for training building and fire officials.

D. Large Number of Local Government Jurisdictions (approximately 44,000). The large number of jurisdictions hinders the universal adoption of codes and standards.

E. Lack of Consistency in Training of Officials. The training of code officials is not mandated and varies significantly. There are a large number of jurisdictions and variation in training facilities and requirements.

F. Limited DOE Role in the Development of International Standards. Governments can participate and influence the development of codes and standards, but they cannot direct the development of international standards.

G. Inadequate Representation at International Forums. Participation in international forums and meetings is voluntary and, to date, has been ad hoc rather than planned and coordinated in advance.

H. International Competitiveness. Economic competition complicates development of international standards.

I. Conflicts between Domestic and International Standards. National positions can complicate the harmonization of domestic and international standards.

J. Lack of National Consensus on Codes and Standards. Competitive issues hinder consensus.

K. Lack of Sustained Domestic Industry Support at International Technical Committees. Cost, time and availability of domestic hydrogen experts has limited consistent support of the activities conducted within the international technical committees.

L. Competitiveness in Sales of Published Standards. The development and licensing of codes and standards is a business, and the competitiveness associated with the adoption of one set of codes and standards inhibits harmonization.

M. Jurisdictional Legacy Issues. NFPA codes are historically adopted by some states and local jurisdictions; others accept the ICC codes. Jurisdictions that adhere to a specific code family may not reference the most recent codes and standards available.

N. Insufficient Technical Data to Revise Standards. Research activities are underway to develop and verify the technical data needed to support codes and standards development, retrofitting existing infrastructure and universal parking certification, but are not yet completed.

O. Affordable Insurance is Not Available. New technologies not yet recognized in codes and standards will have difficulty in obtaining reasonable insurance.

P. Large Footprint Requirements for Hydrogen Fueling Stations. The existing set-back and other safety requirements result in large footprints.

Q. Parking and Other Access Restrictions. Complete access to parking, tunnels and other travel areas has not yet been secured.

3.6.5 Task Descriptions

Task descriptions for the Hydrogen Codes and Standards Program element are presented in Table 3.6.7. To complete these tasks, this Program element will collect and analyze data from the Production, Delivery, Storage, Fuel Cells, Education (deferred) and Technology Validation subprograms on an on-going basis.

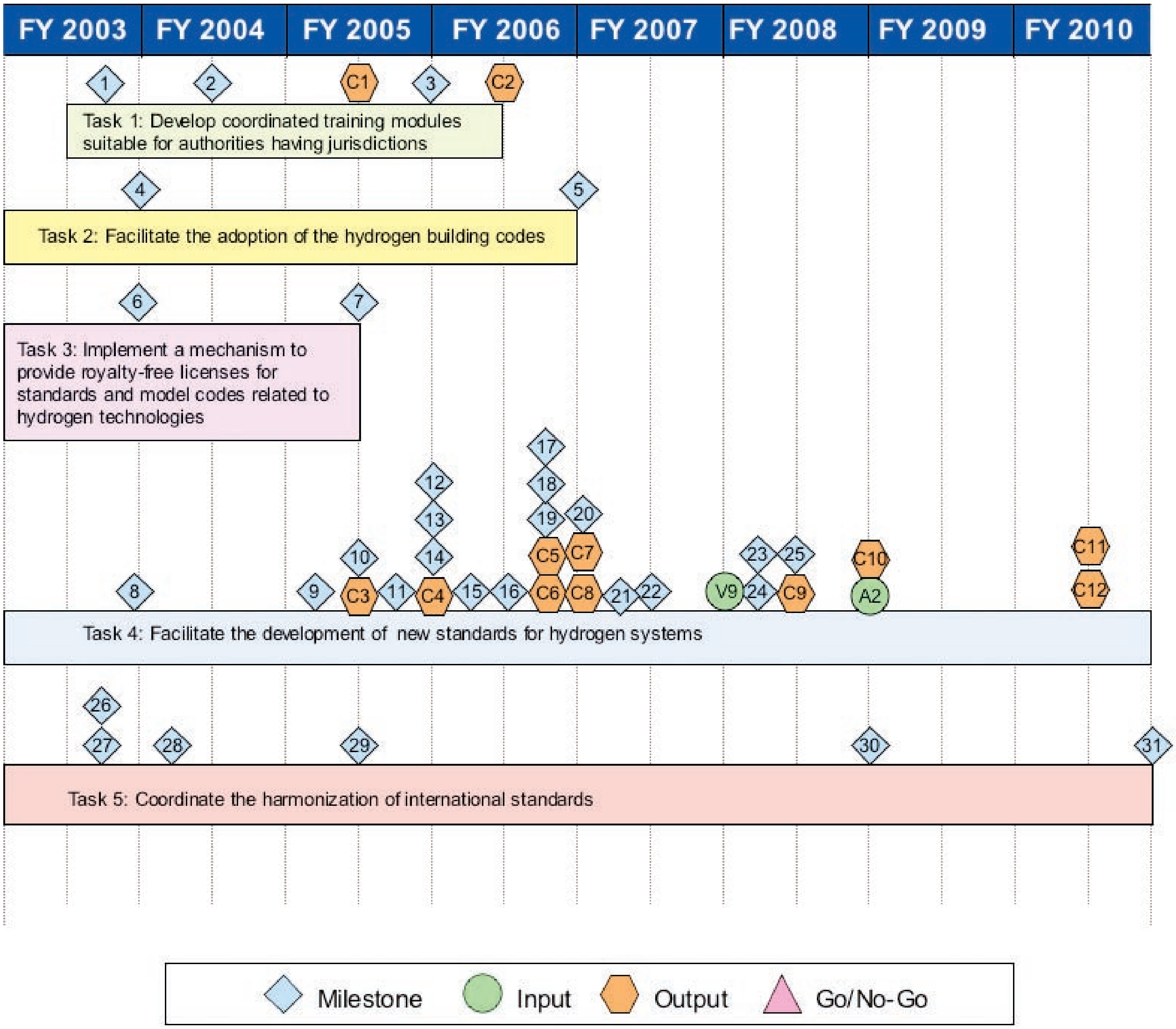
Table 3.6.7. Task Descriptions

	Description	Barriers
1	**Develop coordinated training modules suitable for authorities having jurisdiction**	C, D, E
2	**Perform R&D of hydrogen properties and behavior and coordinate participating organizations to facilitate the adoption of the hydrogen building codes**	C, D
3	**Implement a mechanism to provide royalty-free licenses for standards and model codes related to hydrogen technologies**	A, B
4	**Perform component R&D and integrated systems analysis to support the development of new standards for hydrogen systems**	F, G, H, I, J, K, M, N, O, P, Q
5	**Coordinate the harmonization of international standards** • Facilitate the development of U.S. consensus for international standards • Facilitate unified approach to standards development among key countries in Europe and the Pacific Rim • Develop mechanism to license ISO standards	F, G, H, I, J, L

3.6.6 Milestones

Figure 3.6.5 shows the interrelationship of milestones, tasks, supporting inputs and outputs from other Program elements from FY 2004 through FY 2010. This information is also summarized in Table B.6 in Appendix B.

Figure 3.6.5. Hydrogen Codes and Standards R&D Milestone Chart



For chart details see next page.

Milestones

1 Produce a curriculum for training modules.
2 Collaborate with ICC and NFPA to develop first- order continuing education for code officials.
3 Coordination plan with Education Program element for state and local official training established.
4 Coordination Committee for hydrogen technical experts to support the code development process established.
5 Complete analytical experiments and data collection for hydrogen release scenarios as needed to support code development (Phase 1).
6 Generic licensing agreement drafted and estimated licensing costs established.
7 Final generic licensing agreement, schedule of critical licensing agreements, and budget requirements developed for FY05 and beyond.
8 Workshop to identify and develop critical research objectives that impact model codes held.
9 Initiate experimental validation of large hydrogen releases and jet flame tests completed.
10 Final code changes that incorporate underground storage of liquid hydrogen and canopy-top storage of gaseous hydrogen for fueling stations (NFPC, ICC) completed.
11 Perform tests of walled hydrogen storage systems.
12 Complete detailed scenario analysis risk assessments.
13 Draft standards for dispensing systems (dispenser, hoses, hose assemblies, temperature compensating devices, breakaway devices, etc.) available (CSA America).
14 Draft standards for compressed gaseous on-board storage available (CSA HGV-2).
15 Draft standards for sensors and leak detection equipment developed (UL).
16 Draft standards for portable fuel cells completed (UL).
17 Develop small leak characterization for building releases and pressure release devices (PRD).
18 Technical assessment of metallic and composite bulk storage containers completed (ASME).
19 Draft standards for refueling stations completed (NFPA).
20 Implement research program to support new technical committees for the key standards including fueling interface, and fuel storage.
21 Templates of commercially viable footprints for fueling stations that incorporate advanced technologies developed.
22 Complete Model unintended release in complex metal hydrides.
23 Final draft standard (balloting) for sensors and leak detection equipment developed (UL).
24 Final draft standards completed for transportable composite containers for balloting (ASME).
25 Materials compatibility technical reference updated.
26 Negotiate agreement with DOT/NHTSA at Working Party on Pollution and Energy meeting.
27 Mechanism to support appropriate U.S. Technical Advisory Groups (TAG) through CSA America and CGA in place.
28 Initiate the development of the next generation Sourcebook to include Japan, Europe, Canada & U.S. (PATH).
29 Roadmap for global technical regulations (GTR) published.
30 General licensing agreement for ISO standards in place.
31 Draft regulation for comprehensive hydrogen fuel cell vehicle requirements as a GTR approved (UN Global Technical Regulation).

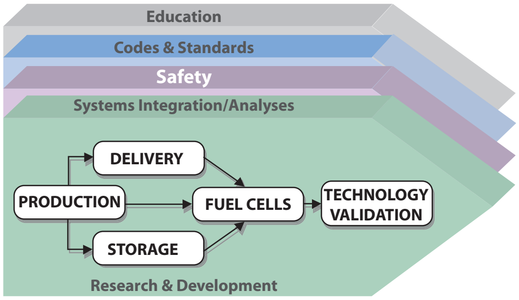
Outputs

C1 Output to Education: Training modules for current practices.
C2 Output to Education: Training modules for amended practices for new technologies.
C3 Output to Production and Delivery: Preliminary Assessment of Safety, Codes and Standards requirements for the hydrogen delivery infrastructure.
C4 Output to Storage: Standards for compressed gaseous on-board storage.
C5 Output to Program: Completed hydrogen fuel quality standard as ISO Technical Specification.
C6 Output to Delivery, Storage and Technology Validation: Technical assessment of Standards requirements for metallic and composite bulk storage tanks.
C7 Output to Delivery, Storage and Technology Validation: Final standards (balloting) for fuel dispensing systems (CSA America).
C8 Output to Technical Validation and Delivery: Draft standards (balloting) for refueling stations (NFPA).
C9 Output to Delivery and Storage: Materials compatibility technical reference.
C10 Output to Fuel Cells: Final draft standard (balloting) for portable fuel cells (UL).
C11 Output to Delivery: Codes and Standards for delivery infrastructure complete.
C12 Output to Program: Final hydrogen fuel quality standard as ISO Standard.

Inputs

V9 Input from Technology Validation: Submit final report on safety and O&M of three refueling stations.
A2 Input from Analysis: Initial recommended hydrogen quality at each point in the system.

3.7. Hydrogen Safety



Safe practices in the production, storage, distribution and use of hydrogen are essential components in a hydrogen economy. The Safety Program element delineates the steps that the Hydrogen, Fuel Cells & Infrastructure Technologies Program is taking to ensure that its projects are performed in a safe manner and that lessons learned within the Program are used to promote safety throughout the hydrogen economy.

Like other fuels in use today, hydrogen can be used safely with appropriate handling and systems design. Its risk level as a fuel at atmospheric pressure is similar to that of fuels such as natural gas and liquid petroleum gas. Because of the smaller size of the molecule and the greater buoyancy of the gas, hydrogen requires storage, handling and use techniques that are different than those traditionally employed. The aim of this Program element is to ensure the safe use of hydrogen, and to understand, communicate and provide training on the safety hazards related to the use of hydrogen as a fuel. The Program element will also maintain a comprehensive database on hydrogen and hydrogen safety.

3.7.1 Goal and Objectives

Goal

Develop and implement the practices and procedures that will ensure safety in the operation, handling and use of hydrogen and hydrogen systems for all DOE projects and to utilize these practices and lessons learned to promote the safe use of hydrogen throughout the emerging hydrogen economy.

Objectives

- Starting in 2004, integrate safety procedures into new DOE projects to ensure that they all incorporate hydrogen safety requirements.

- By 2005, develop a comprehensive safety plan in collaboration with industry that establishes Program safety policy and guidelines. The Safety Review Panel, formed in FY 2004, will continue to provide expertise and guidance to the DOE, and will assist with identifying areas of additional research.

- By 2007, publish a handbook of “Best Management Practices for Safety.” The Handbook will be a “living” document that will provide guidance for ensuring safety for DOE hydrogen projects, while serving as a model for all hydrogen projects and for commercialization.

- Develop supporting research and development program to provide critical hydrogen behavior data and hydrogen sensor and leak detection technologies. This data will support the establishment of setback distances in building codes.

- Promote widespread sharing of safety-related information, procedures and lessons learned to first responders, jurisdictional authorities and other stakeholders.

3.7.2 Approach

The Safety Program element focuses on the following activities:

- Conduct safety reviews of current and future projects, including practices and procedures.
- Develop and provide a database on safety, including component reliability, materials, sensors and hydrogen releases.
- Develop a safety training program for emergency responders and authorities having jurisdiction.
- Develop safety-related components such as sensors and coating materials.
- Investigate system approaches for integrated safety in design.
- Determine whether the current safety classification accurately reflects the behavior of hydrogen.

Safety is always an important focus of DOE efforts, but it must receive special emphasis during these critical early stages of the envisioned hydrogen transition. The successful development of hydrogen as an energy carrier will require an exceptional safety record. The risks and consequences of any accident must be minimized or completely mitigated. Safety practices and procedures established now will carry into the future, and thus offer long-term benefits as well.

Comprehensive safety management is a necessary step in the safe operation, handling and use of hydrogen and related hydrogen systems. Safety management will ensure continued safe operations throughout the emerging hydrogen transition, provide experimental data for hydrogen safety scenarios, and work to improve the public's perception of hydrogen.

Safety Management

Safety management is implemented through the document, "Guidance for Safety Aspects of Proposed Hydrogen Projects" available on the DOE Web site (http://www.eere.energy.gov/hydrogenandfuelcells/). This document details safety plans that must be submitted for each DOE-funded project. Such systematic application of safety assessment methodologies reduces the likelihood that a potential risk may be overlooked, and allows a consistent measure of safety across all DOE-supported hydrogen projects. The safety plans of the learning demonstrations and the lessons learned under the Technology Validation Program element (see section 3.5) will play an important role in the development of safe practices that are essential for future commercialization.

Hydrogen Safety Review Panel

DOE formed an independent Hydrogen Safety Review Panel in FY 2004 to provide expert guidance on safety and hazard mitigation in DOE activities, programs and projects. Its objectives are to help DOE identify safety concerns; determine current status of regulations, policies, codes, standards and guidelines; and provide a national platform to discuss critical hydrogen safety issues. The Panel consists of a diverse set of experts representing a breadth of industries and organizations including insurance, fuel providers, aerospace, fire safety, engineering and others, providing well over one hundred years of collective safety experience. The Panel provides an independent assessment of safety plans, makes recommendations, and proposes alternatives and/or needs for additional analysis or review, as appropriate. Experience gained through the safety panel and learning demonstrations will form the basis for a "Handbook of Best Management Practices" to be published in 2007.

Safety Data

Data and its proper classification present a number of challenges confronting hydrogen use. For example, the way hydrogen is classified throughout the world is inconsistent. Some countries, including the U.S., currently classify hydrogen as a hazardous material, and not as a fuel. This classification directly impacts issues like storage and transportation through the regulations that consequently apply. One activity of the Program element will be to determine whether the current hazardous material classification accurately reflects the actual risk of hydrogen systems. The desired outcome of these activities is that hydrogen will be classified as a fuel for transport and handling, comparable to today's traditional fuels.

Other kinds of data needs also exist because hydrogen has been used primarily as a feedstock chemical (aside from aerospace applications, which are generally non-commercial). In addition, safety-related information, often corresponding to company-specific chemical processes and handling procedures, has been treated as proprietary. The widespread availability and communication of safety-related information will be crucial to ensure safe operation of future hydrogen fuel systems and thus are emphasized.

Although safety-by-design and passive mitigation systems are preferred, it will still be necessary to develop technologies to detect hydrogen releases or other system failures. This Program element will develop hydrogen sensors with the appropriate response time, sensitivity and accuracy for use in safety applications to reduce risk and help establish public confidence. For example, coatings that change color upon exposure to hydrogen can provide immediate visual evidence of a leak, while other coatings can be used to rapidly catalyze any small amounts of hydrogen that do escape.

Finally, the Safety Program element coordinates with the Education (deferred) and Codes and Standards Program elements to develop training materials and practices to foster the safety of projects and technologies. A thorough approach to safety will enable risks to be measured and mitigated, and assist in establishing affordable insurability.

3.7.3 Status

Before publishing this RD&D plan, DOE addressed hydrogen safety as a contractual requirement between funded parties, relying on existing protocols and practices by the national laboratories, universities and industry to review and enforce safety in R&D projects. Larger demonstration projects were required to provide third party safety reviews after an award, but before hardware testing. Some aspects of these safety evaluations included the appropriate use of applicable model building codes and equipment standards, the use of hydrogen sensors to help detect hydrogen leaks and modeling and testing of potential leak/accident scenarios.

Project safety is now pursued in large part through the efforts of the Hydrogen Safety Review panel. A principal activity of the Panel is to assess DOE hydrogen projects from a safety perspective, and make recommendations for improvement, where appropriate. An individual project assessment involves review of the project's safety plan, at a minimum, and may include a site visit by one or more Panel members.

The first site visit of the panel took place in March 2004 at the Las Vegas Hydrogen Energy Station in Nevada, shown in Figure 3.7.1. Through the end of FY04, the Panel will have completed five more site visit reviews and scheduled additional reviews for FY05. The Hydrogen, Fuel Cells & Infrastructure Technologies Program will continue to select a portfolio of projects for safety review. Review teams, consisting of Panel members, work with principal investigators and their teams through scheduled site visits.

Figure 3.7.1 Air Products Hydrogen Fueling Station in Las Vegas, Nevada

Project teams have also used access to panel expertise to tap the body of knowledge that already exists for dealing with hydrogen and hydrogen-related systems.

Another major issue on which the Safety Program element focuses is the information, materials and facilities for training and educating various audiences that are critical to the hydrogen transition. Industry and aerospace have a long history of safe hydrogen use, but the introduction of hydrogen as a commercial fuel in the hands of the general public introduces a host of new safety issues that must be addressed prior to the hydrogen economy's implementation. Accidents or other system failures within the established fuel infrastructure of commonly used fuels can and do occur. For any fuel, a suitably trained emergency response force is an essential element to minimize safety-related incidents. Training of first responders is of particular importance to the successful implementation of the hydrogen economy, especially in its nascent stages, as a loss in public confidence related to its safety could derail the entire transition strategy.


Figure 3.7.2 Emergency Responder Training at the HAMMER site in Richland, Washington.

The Volpentest **HA**zardous **M**aterials **M**anagement and **E**mergency **R**esponse (HAMMER) Training and Education Center is the result of a $29.9 million federal investment completed in 1997 at the Hanford Nuclear Reservation in Washington state. HAMMER was established to provide critical training in fire operations, nuclear materials handling and transport, occupational safety and health, and other areas relevant to the Hanford mission (see Figure 3.7.2). DOE plans to establish a national hydrogen safety training facility by expanding current training capabilities at HAMMER, beginning in FY 2005.

3.7.4 Challenges

Developing a comprehensive safety plan is challenging, partly because the database of safety information on many hydrogen components and systems is largely limited to industrial practice. Scientific and technical knowledge may also be limited because each company that produces and uses large quantities of hydrogen has established training practices that must be followed for liability reasons, and these practices may not be necessarily public information. Companies that use these practices comply with federal regulations, which are accepted by insurance providers. Any new information may not be published, perhaps due to company policy or because is may be considered proprietary.

The tendency for hydrogen to leak presents a challenge to its storage and delivery. As a flammable gas, leakage creates a safety hazard. The Safety Program element works with other Program elements to eliminate leakage and to develop design principles and systems that detect and mitigate the effects of hydrogen leakage.

There is a general lack of understanding of hydrogen and hydrogen safety needs among local government officials, fire marshals and the general public. It is common for new endeavors to encounter resistance simply because they are different from the known and accepted. Public opposition to siting of hydrogen refueling stations has occurred in several instances, even preventing operation of the station in some cases. Such public discomfort typically stems from misperceptions and confusion of hydrogen technologies with a "hydrogen bomb" or with the Hindenburg disaster. In other cases, the local regulatory authority may view one or more properties in isolation without considering other properties that could mitigate danger (e.g., hydrogen's tendency to rapidly disperse once released). Failing to consider the "big picture" may lead to over-restrictive policies that preclude implementation.

The general public who uses the published information in many handbooks or training programs may be getting limited or inaccurate information. For example, although hydrogen is listed as a Class B hazard, it is unclear that this classification is based on accurate or reproducible data. There also is no comprehensive handbook containing best management practices for hydrogen safety, to date. Once mandatory reporting is established for safety and reliability, training will be required to adequately educate appropriate government officials. Finally, all the data to be used in assessing the safety of hydrogen systems must meet the needs of insurance providers and other stakeholders. This Program element is working to fill these gaps through R&D, training, and tracking of safety-related incidents and lessons learned.

The technical challenges discussed elsewhere in this RD&D program plan must be overcome and the solutions demonstrated to be reliable, safe and cost-effective. That these solutions are safe must be convincingly communicated to not only crucial enablers of the technology like regulatory authorities, but also the public at large. In the end, a failure in public confidence with regard to the relative safety of hydrogen will render other implementation issues moot. Such challenges can and must be overcome, and documented through consistent, clear and timely communication.

3.7.4.1 Targets

Table 3.7.1 summarizes the technical targets associated with the Safety Program element that addresses sensor R&D.

Table 3.7.1. Targets for Hydrogen Safety Sensor R&D

- **Measurement Range: 0.1%-10%**
- **Operating Temperature: -30 to 80°C**
- **Response Time: under one second**
- **Accuracy: full scale**
- **Gas environment: ambient air, 10%-98% RH range**
- **Lifetime: 5 years**
- **Interference resistant (e.g., hydrocarbons)**

3.7.4.2 Barriers

This section details the barriers that must be overcome to achieve the goal and objectives of the Safety Program element.

A. Limited Historical Database. Only a small number of hydrogen technologies, systems and components are in operation. Only limited data is available on the operational and safety aspects of these technologies.

B. Proprietary Data. Hydrogen technologies, systems, and components are still in the pre-commercial development phase. Only limited non-proprietary data is available on the operational and safety aspects of these technologies. Sharing safety data is important for hydrogen projects funded under the Program.

C. Validation of Historical Data. The historical data used in assessing safety parameters for the production, storage, transport and utilization of hydrogen are several decades old. Validation of this data and an assessment of use may prove useful in the development of a hydrogen infrastructure.

D. Liability Issues. Potential liability issues and lack of insurability are serious concerns that could affect the commercialization of hydrogen technologies.

E. Variation in Standard Practice of Safety Assessments for Components and Energy Systems. Variations in safety practices and lack of standardization across hydrogen technical projects increase the risk of safety related incidents.

F. Safety is Not Always Treated as a Continuing Process. Safety practices will need to be maintained throughout the duration of the project.

G. Expense of Data Collection and Maintenance. Principal Investigators need to pursue the detailed collection and maintenance of all safety data and information regardless of the added expense.

H. Lack of Hydrogen Knowledge by Authorities Having Jurisdiction. Officials given the responsibility of approving the safety of installations of various technologies often have insufficient knowledge of hydrogen and its properties and characteristics to complete the approval.

I. Lack of Hydrogen Training Facilities for Emergency Responders. A suitably-trained emergency response force is an essential element of preventing an accidental hydrogen release from progressing from an incident with little or no damage to one of much greater consequences. The current level of responder experience with hydrogen technologies is lacking, in part because there are no current facilities in the U.S. offering emergency response training specific to hydrogen.

3.7.5 Task Descriptions

Task descriptions are presented in Table 3.7.2.

Table 3.7.2. Technical Task Descriptions

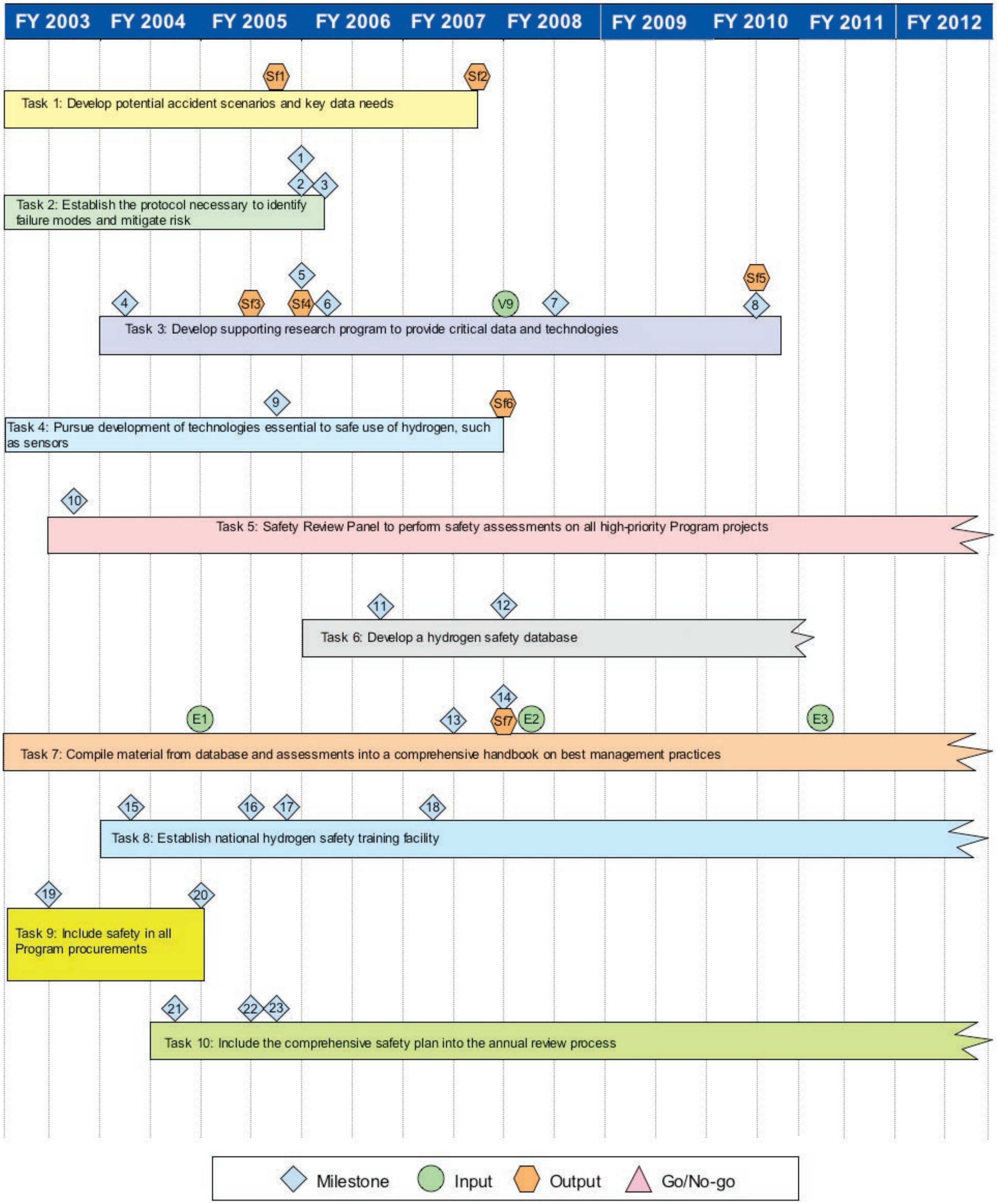
Task	Description	Barriers
1	**Develop potential accident scenarios and key data needs** • Identify what can go wrong. • Develop a system for classifying accident types. • Develop a methodology for estimating accident likelihood. • Develop and release a report of the most common accident scenarios.	A, B, C, G
2	**Establish the protocol necessary to identify failure modes and mitigate risk** • Draft protocol for identifying potential failure modes and risk mitigation. • Work with industry experts to review and revise the protocol. Release consensus protocol to become part of program solicitations.	A, B, C, G
3	**Develop supporting research program to provide critical data and technologies** • A supporting research program will be developed to provide missing data. The literature search performed to identify failure modes will be evaluated to identify the areas where additional research is necessary. • Explore systems approaches and "holistic" design strategies for development of systems that are inherently safer.	A, B, C, E, G
4	**Develop technologies essential to safe use of hydrogen, such as sensors**	D, E

5	**Safety Review Panel to perform safety assessments on Program projects** • Conduct site visits of selected projects. • Review safety plans of Program projects. • Provide input for Best Management Practices Handbook (see Task 7).	A, B, C, D, E, F, G
6	**Develop a hydrogen safety database** • Develop a repository for hydrogen safety data and information. • Compile data and populate database. • Publish database.	A, B, C
7	**Compile material from database and assessments into a comprehensive handbook on best management practices** • Safety Review Panel will prepare draft. • Publish final Best Management Practices Handbook and support the adoption of these practices throughout the hydrogen economy.	A, B, C, D, E, F, G, H, I
8	**Establish national hydrogen safety training facility** • Establish DOE HAMMER site as a central location for safety-related information and training. • Develop a five-year plan.	H, I
9	**Include safety in all Program procurements** • Develop guidelines for all DOE funded projects to include safety planning in all aspects of the project, including safety incident tracking. • Publish guidelines.	E, F, G
10	**Include the comprehensive safety plan into the annual review process** • Establish criteria for Annual Review process. • The Safety Review Panel will incorporate the safety-related comments of the Peer Review Team into its business practices.	F, G

3.7.6 Milestones

Figure 3.7.3 shows the interrelationship of milestones, tasks, supporting inputs from other Program elements and outputs for the Hydrogen Safety Program element for FY 2004 through FY2010. This information is also summarized in Table B.7 in Appendix B.

Figure 3.7.3. Hydrogen Safety R&D Milestone Chart



For chart details see next page.

Milestones

1 Prepare draft failure modes and risk mitigation protocol.
2 Conduct workshop to review draft protocol.
3 Release consensus protocol.
4 Initiate collaboration with NASA, DOT, and other agencies to establish and publish an interagency plan on the cooperation of hydrogen safety R&D.
5 Review existing data and hydrogen classification.
6 Develop design protocol that employs passive system or holistic design techniques.
7 Convene hydrogen safety workshops to communicate research findings and disseminate information to safety stakeholders.
8 Conduct research as needed to fill data gaps on hydrogen properties and behaviors.
9 Conduct workshop to identify key performance parameters for hydrogen sensors and leak detection devices.
10 Assemble panel of experts in hydrogen safety to provide expert technical guidance to funded projects.
11 Identify user needs for Safety database.
12 Publish Safety database.
13 Safety Review Panel to prepare draft of Best Management Practices Handbook.
14 Complete final peer-reviewed Handbook.
15 Kickoff meeting between HAMMER, DOE and national laboratory staff.
16 Consensus 5-Year Plan for HAMMER released.
17 First hydrogen safety class (non-prop) offered at HAMMER.
18 First hands-on training prop completed.
19 Develop guidelines for hydrogen safety planning and inclusion in procurements.
20 Publish guidelines for safety plans.
21 First DOE annual review incorporating new emphasis on safety.
22 Establish annual review criteria for safety.
23 Publish final annual review criteria for safety on DOE Web site.

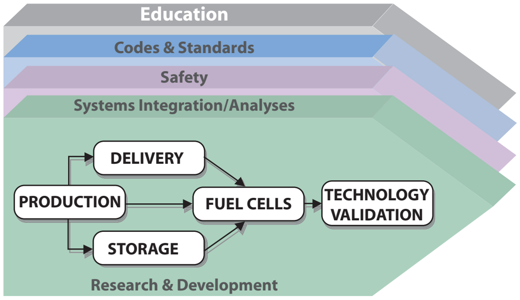
Outputs

Sf1 Output to Education: Report of common accident scenarios.
Sf2 Output to Education: Updated report of common accident scenarios.
Sf3 Output to Production, Delivery, Storage and Technology Validation: Safety requirements and protocols for refueling.
Sf4 Output to Storage and Technology Validation: Safety requirements for on-board storage.
Sf5 Output to Production, Delivery, Storage and Technology Validation: Safety requirements and protocols for refueling.
Sf6 Output to Technology Validation and Systems Integration: Sensor meeting technical targets.
Sf7 Output to Technology Validation, Education and Systems Integration: Final peer reviewed Best Practices Handbook.

Inputs

V9 Input from Technology Validation: Submit final report on safety and O&M of three refueling stations.
E1 Input from Education: Published initial perceptions report.
E2 Input from Education: Interim perceptions report.
E3 Input from Education: Final perceptions report.

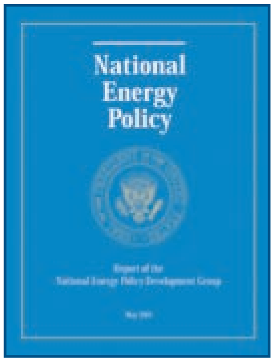
3.8 Education– Deferred



The Education Program element is deferred to FY 2006 subject to congressional appropriation.

The National Energy Policy and National Hydrogen Energy Roadmap, two guiding documents for DOE hydrogen activities, pay special attention to education.

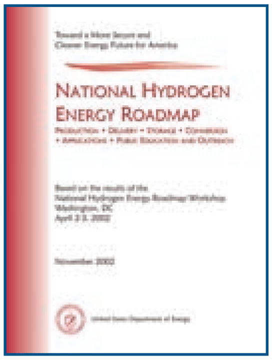
The National Energy Policy recommends that the Secretary of Energy develop an education campaign about hydrogen.


National Energy Policy

"The NEPD Group recommends that the President direct the Secretary of Energy to develop next-generation technology–including hydrogen.... Develop an education campaign that communicates the benefits of alternative forms of energy, including hydrogen..."

-National Energy Policy, May 2001[1]

The National Hydrogen Energy Roadmap, which lays the foundation for a national move toward the use of hydrogen energy, also establishes a priority for education activities and suggests that education is an appropriate activity for the federal government.


NATIONAL HYDROGEN ENERGY ROADMAP

"Educating consumers, industry leaders, and public policy makers about the benefits of hydrogen is critical to achieving the vision."

-National Hydrogen Energy Roadmap, November 2002[2]

Following the National Energy Policy and Roadmap recommendations, the Hydrogen, Fuel Cells & Infrastructure Technologies Program established the Education Program element to accomplish the overall objective of educating target audiences about the long-term benefits and near-term realities of hydrogen, fuel cell systems, and related infrastructure. The Education Program element will help audiences to do the following:

- Understand the general concept and value of a hydrogen economy
- Recognize the near-term realities and opportunities of hydrogen and fuel cell technologies
- Develop an accurate understanding of hydrogen safety issues
- Understand, where appropriate, their part in facilitating the transition to a hydrogen economy

---

[1] National Energy Policy: Report of the National Energy Policy Development Group (May 2001) U.S. Government Printing Office ISBN 0-16-050814-2 http://www.whitehouse.gov/energy/National-Energy-Policy.pdf

[2] National Hydrogen Energy Roadmap (November 2002) U.S. Department of Energy http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/national_h2_roadmap.pdf

Education crosscuts all of the Hydrogen, Fuel Cells & Infrastructure Technologies Program elements. The Production, Delivery, Storage, Fuel Cells, Codes and Standards, Safety and Technology Validation Program elements will provide formal and informal input to Education activities, particularly for materials development and technical information communicated through training. With regard to projects and tasks focused on the needs of specific target audiences, coordination with the Codes and Standards, Safety and Technology Validation Program elements is particularly important.

3.8.1 Goal and Objectives

Goal

Educate key audiences about the concept of a hydrogen economy and fuel cell and hydrogen systems to facilitate near-term demonstration and long-term commercialization and market acceptance of these technologies.

Objectives

By 2010 –

- Achieve a fourfold increase in the number of state and local government representatives who understand the concept of a hydrogen economy, and how it may affect them.*

- Achieve a fourfold increase in the number of students and teachers who understand the concept of a hydrogen economy, and how it may affect them.*

- Achieve a twofold increase in the number of large-scale end-users who understand the concept of a hydrogen economy, and how it may affect them.*

- Launch a comprehensive and coordinated public education campaign about the hydrogen economy and fuel cell technology.

3.8.2 Approach

Education Framework

Although this plan establishes a framework for the Education Program element and identifies activities for 2003–2011, it is not intended to limit or exclude the pursuit of any new or different opportunities that may arise over time. Projects outside the scope of this plan will be considered, as appropriate.

Coordination with Other Entities

Educational activities will be coordinated with other Program element activities – Technology Validation, Safety, and Codes and Standards, in particular – as well as other relevant activities conducted by DOE offices and programs, national laboratories, trade associations, industry and others. Careful consideration will also be given to coordination with the Energy Efficiency and Renewable Energy's (EERE's) Office of Communications and Outreach to ensure all Program materials are developed according to EERE design and format guidelines.

Also, to the extent possible, the development and implementation of education strategies will be coordinated with emerging local, state, and regional hydrogen, fuel cell and clean energy efforts. The Education Program element will work with DOE Regional Offices to facilitate networking among national, state and local educational entities.

---

*According to a 2004 baseline

Approach

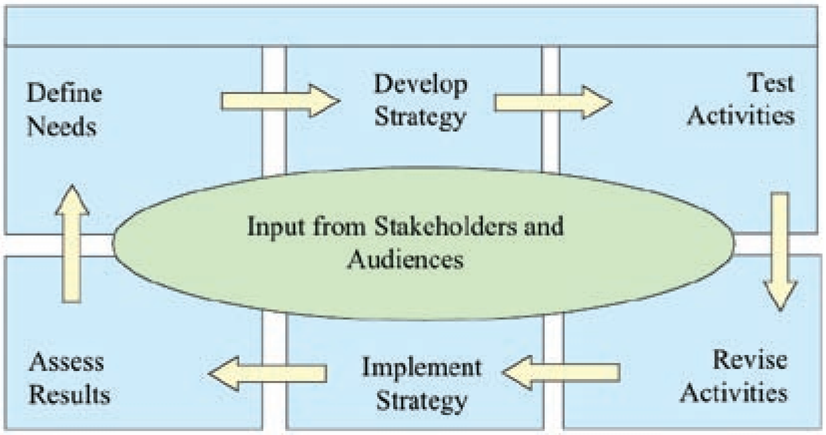
A comprehensive education campaign needs a foundation on which to build. This foundation consists of readily available "groundwork" materials that provide Program background and general information about hydrogen and fuel cells—as well as a means by which to distribute the information. Although a growing number of people now refer to the Web for their informational needs, printed documents, videos, and CDs remain in high demand. Education activities will rely on Web-based materials to the greatest extent possible, including creating a library of educational materials and building an effective distribution system to serve multiple target audiences. (Previously published materials will be reviewed and used as appropriate.) The information dissemination infrastructure will provide users and Program partners nationwide with quick and easy access to educational materials, and it will provide education activity managers with a mechanism for tracking use and collecting feedback that can improve the Program.

Once a Program foundation is established, attention can turn to activities that serve the specific needs of several key target audiences. Initial education efforts will focus on state and local governments, community groups and public citizens living in areas where near-term demonstration projects are planned, teachers and students, and (to a lesser extent) potential large-scale end-users—target audiences identified as critical to the successful implementation of near-term technology demonstrations and whose buy-in requires sustained education efforts. In addition, safety and code officials comprise another critical-need audience; appropriate education activities will be conducted in conjunction with the Safety and Codes and Standards Program elements. It is important to note that the timeline for implementing strategies to reach priority audiences will vary slightly, according to their education needs relative to the market-readiness of the technology.

Audience needs will be researched before new educational materials or programs are developed. Much of this research will be addressed by a national, scientific and statistically-valid baseline knowledge survey conducted in FY2004. The survey will be repeated in 2007 and 2010, and as funds allow, additional non-survey assessments of target audience needs will be conducted in interim years.

When possible and as often as practical, activities and materials will be tested and revised before being implemented or published to ensure their effectiveness. Once launched, they will be monitored and audiences will have an opportunity to provide feedback for consideration in future editions or revisions. This process will help to ensure that audience needs are served, education activities achieve success, and Program goals are met (see Figure 3.8.1).

Figure 3.8.1 Education Program Element Approach



Careful consideration will be given to the messaging. Clearly communicating the benefits of using hydrogen and fuel cell technologies is important, as is communicating the facts about hydrogen safety. The National Academies emphasized the importance of public education about hydrogen safety in its report, "The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs."[3] Specifically, the report recommends, "The DOE's public education Program should continue to focus on hydrogen safety, particularly the safe use of hydrogen in distributed production and in consumer environments."

The message must also communicate the technical challenges ahead; the critical research, development and demonstration activities needed to ensure successful commercialization; and the timeframe for the potential mass-market introduction of hydrogen and fuel cell technologies.

Program End-Point

Achieving the national vision for hydrogen and fuel cells will require a long-term RD&D strategy—and an even longer-term education strategy. DOE's RD&D effort for hydrogen fuel cell vehicles, for example, is intended to allow an industry commercialization decision to be made in 2015 and a subsequent vehicle introduction to dealer showrooms by 2020. Education is critical to prepare for that market introduction and to enable demonstration projects that can inform research and development activities prior to the 2015 decision. Local community resistance to near-term hydrogen demonstration projects, often rooted in a misunderstanding of hydrogen safety, can jeopardize implementation. In some cases, it has been strong enough to halt demonstrations altogether. Similarly, safety and code officials can facilitate or inhibit near-term demonstration projects. Education and training programs will help to ensure that the necessary hydrogen-specific codes are adopted and that emergency responders are well prepared.

Education is also required after the planned 2020 commercial introduction to facilitate market success and penetration beyond the niche of early adopters. A full-scale, national education campaign to reach the general public, if timed properly, could help overcome knowledge barriers, including safety concerns and facilitate market success, while also reflecting the market readiness of the technology. As the technology moves toward mainstream market penetration, a government role in education becomes less critical and a phase-out or ramping-down of government-funded education activities may be appropriate.

3.8.3 Programmatic Status

Stakeholder Input

To begin a dialogue with specialists on the content of and issues related to an educational program about hydrogen and fuel cells, DOE convened a workshop in Washington, D.C. in December 2002. More than 50 individuals participated, representing industry, government, non-governmental organizations, national laboratories and universities. Specific objectives were to solicit input regarding the following:

- Goals and objectives for the Hydrogen, Fuel Cells & Infrastructure Technologies Program's Education Program element
- Factors driving the need for educational activities
- Target audiences and relative priorities
- Activities to reach target audiences
- Educational projects and activities that DOE might support

---

[3] The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs (February 2004) National Research Council and National Academy of Engineering of the National Academies. National Academy Press, Washington, C2004, http://www.nap.edu/books/0309091632/html/

The Education Workshop was conducted in an open and participatory manner. Attendees met in plenary and parallel breakout sessions to discuss the eight target audience groups identified in Table 3.8.1, and gathered in plenary sessions to discuss common themes and crosscutting activities, as well as overall Program priorities.

Table 3.8.1 Key Objectives by Target Audience

Target Audience	Key Objectives
State and Local Government Representatives (e.g., city, county, state, and regional governments, agencies, and associations)	• Provide objective, accurate information that government representatives can rely on as part of their research to make informed decisions.
Large-Scale End Users (e.g., transit agencies, fleets, building associations and subdivisions, hospitals)	• Provide objective, accurate information that potential end users can use as part of their research to make informed decisions. • Support training for potential end users.
Educators and Students (e.g., primary and secondary schools, colleges, universities, and other post-secondary institutions)	• Improve the level and breadth of hydrogen and fuel cell education, using established resources wherever possible and appropriate. • Increase the number of schools teaching hydrogen and fuel cell courses. • Support and promote internships, academic research, and hands-on product demonstrations in these areas.
Code Writing Organizations	• Provide objective scientific and technical information to facilitate and expedite the implementation of codes and standards.
National Regulatory Agencies	• Provide objective scientific and technical information to support the timely development of hydrogen and fuel cell policies and regulations.
Professional, Labor, and Trade Organizations	• Support training for potential end-users and the labor force for a hydrogen infrastructure.
Financial Institutions (lenders, investors, and insurers)	• Provide objective, accurate information that these groups can use as part of their research to make informed decisions.
General Public	• Provide timely, objective, consumer-oriented information to support the transition to a hydrogen economy.

Of the eight target audience groups, participants placed a high priority on those whose immediate buy-in is important to overcome barriers to early hydrogen and fuel cell efforts. Participants singled out state and local government representatives, safety and code officials, and large-scale end users, in particular. Also, considering the need to develop the next generation workforce and provide accurate and objective information, students, teachers and the public were added to the list of priority audiences. (Federal government representatives and legislators were also discussed as a priority audience; within DOE's current organizational structure, however, activities to serve their needs largely fall under the purview of EERE and the EERE Office of Communications and Outreach).

Three cross-cutting areas also emerged as initial focal points of the Education Program element—information management, including dissemination of accurate, objective information; educational activities; and coalition and partnership building. Activities in these three cross-cutting areas, coupled with the target audience priorities, provide focus for Education Program element activities.

Planned Activities

In 2003 and 2004, the Program initiated several projects to build its new hydrogen education effort, as noted in Table 3.8.2 and illustrated in Figures 3.8.2 and 3.8.3.

Table 3.8.2 Current Hydrogen Technology Education Activities

Education Groundwork	
Baseline knowledge assessment	Oak Ridge National Laboratory, Opinion Research Corporation
Educational materials for multiple target audiences	National Hydrogen Association; Energy and Environmental Analysis and partners; Anderson Creative Group and partners; Argonne National Laboratory; Computer Systems Management, Inc., Hydrogen 2000, and others
K-12 Teachers and Students	
Comprehensive high school hydrogen technology curricula and teacher professional development	Lawrence Hall of Science at the University of California at Berkeley and partners
Comprehensive middle school hydrogen technology curricula and teacher professional development	National Energy Education Development (NEED) Project and partners
Colleges and Universities	
Hydrogen Technology Learning Centers	National Association of State Energy Officials; Florida Solar Energy Center, Rochester Institute of Technology, University of California at Davis, San Diego Miramar College; Virginia Tech, University of Maryland at College Park, Breakthrough Technologies Institute, Hampton Roads Clean Cities Coalition; North Carolina A&T, University of South Carolina, University of Georgia, University of Florida
"H2U" University Design Competition	National Hydrogen Association, other industry partners
State and Local Governments	
Hydrogen Learning Workshop Series	DOE Regional Offices, other state and local partners

Figure 3.8.2. Hands-on activities, such as this model fuel cell car race, allow students to delve into hydrogen and fuel cell technologies.
(Photo courtesy of Blanche Sheinkopf)

Figure 3.8.3. “Hydrogen 101” workshops provide an opportunity for state and local government officials to learn more about the hydrogen economy and fuel cell technology.
(Photo courtesy of the Maryland Energy Administration)

3.8.4 Challenges

Energy Secretary Spencer Abraham, in his foreword to the National Hydrogen Energy Roadmap, writes: “To talk about the ‘hydrogen economy’ is to talk about a world that is fundamentally different than the one we know now.” He also refers to the change in how we produce, store and use energy as “revolutionary.”

That the hydrogen economy is a revolutionary change from the world we know today is the fundamental challenge to the education activity. Although great momentum and enthusiasm exist among the hydrogen and fuel cell industries (due in part to the announcement of the President’s Hydrogen Fuel Initiative in January 2003), the public remains largely unaware of hydrogen as an energy carrier. People are, by nature, hesitant—or resistant—to change, particularly when that change requires embracing a technology based on unfamiliar principles (such as the electrochemical oxidation of hydrogen). Anecdotes about the Hindenburg tragedy also perpetuate false perceptions about the safety of hydrogen use and compound that resistance to change—despite the potential benefits of a hydrogen economy. In a December 2000 transportation energy survey conducted by Opinion Research Corporation International on behalf of the DOE, 1,000 people were asked the following question: “Consider a day when gasoline is no longer available. Which of the following do you think would be the worst fuel for use in personal vehicles: ethanol, hydrogen, or electricity?” Of the respondents who chose hydrogen as the worst fuel, more than 50% cited safety concerns, attributed largely to what they had heard or their own intuition. Another almost 20% reported that they didn’t know why hydrogen would be the worst—but that they simply thought it would be.

Therefore, an emphasis on safe practices for handling and using hydrogen is critical to advancing the development of the technology. Community resistance to the installation of local hydrogen fueling stations, for example, can slow and even prohibit project implementation. Moreover, when captured by the media, such misunderstandings can spread to other communities unfamiliar with hydrogen, thereby perpetuating fears about the safe use of hydrogen and jeopardizing other demonstration projects. It is the duty of the Program to educate the public on the safe use of hydrogen.

Dangers exist for the handling of any fuel. For many decades motorists were not allowed to pump their own gasoline because of safety concerns. Yet after 100 years of relying on internal combustion engines, a high degree of comfort has been instilled for using gasoline. Such familiarity and the convenience of our current energy infrastructure contribute to complacency with the status quo, which adds to the challenge of educating for change.

3.8.4.1 Barriers

Resistance to change and concerns about hydrogen safety comprise the overarching challenge for the Education Program element. The following section outlines barriers to implementing the education activities intended to address the challenge and meet Program goals and objectives.

A. **Lack of Awareness.** Interest in hydrogen and fuel cell technology is increasing, but there remains a general lack of awareness of hydrogen as an energy alternative. Moreover, although world events have drawn new attention to national energy security issues, there is little consensus about the severity of today's environmental problems or linkages to fuel choice. With little awareness, understanding, or recognition of these issues, there is little impetus for change, and target audiences are less inclined to embrace new technology.

B. **Lack of Demonstrations or Examples of Real World Use.** Hands-on, personal experience greatly enhances understanding and comfort with using any new technology. With the current limited number of real-world examples, however, local communities, as well as safety and other local government officials, may be reluctant to embrace hydrogen technology. They may also resist near-term demonstration projects based on a lack of information, particularly if they have questions related to hydrogen safety.

C. **Institutional Barriers and Access to Audiences.** Once audience information needs have been defined and educational materials or training workshops have been developed, they must reach their intended audiences to be effective. Institutional barriers can complicate or inhibit access to target audiences. Moreover, identifying the right organizations, as well as a champion within each organization to embrace hydrogen and fuel cell technologies, can be challenging.

D. **Regional Differences.** Educational needs will vary by audience, but they may also vary regionally. What applies to one state, county, city or district, may not apply to another. Serving the education needs of a single target audience may therefore require multiple approaches tailored to serve the needs of various regions. This strains resources and can complicate activities developed at the national level.

3.8.5 Task Descriptions

Task descriptions are presented in Table 3.8.3.

Table 3.8.3. Task Descriptions

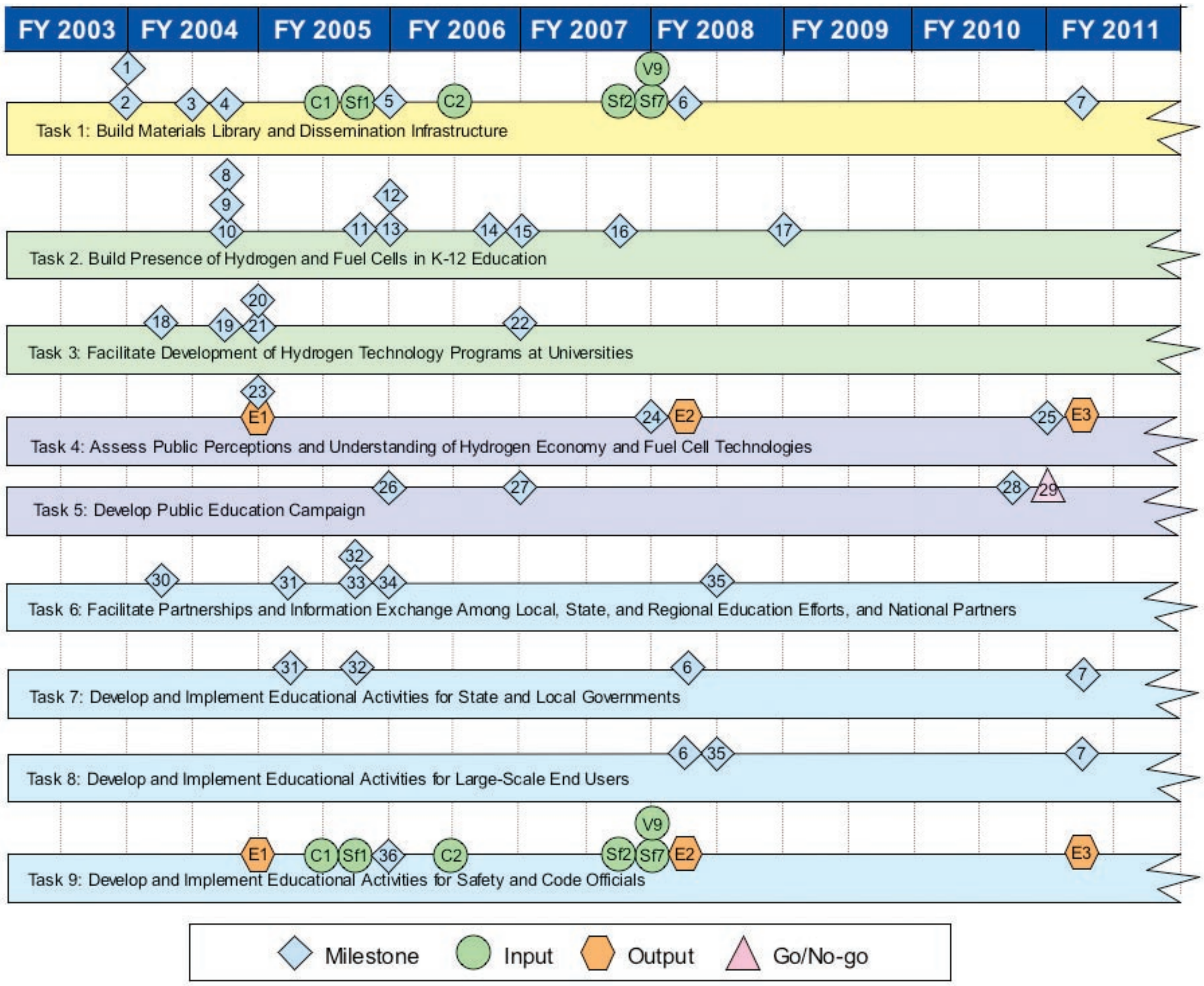
Task	Description	Barriers
1	**Build Materials Library and Dissemination Infrastructure** • Add new features to meet educational goals and address information gaps to the DOE Web site • Build visibility of education materials on the Web • Determine needs and structure for a clearinghouse; identify opportunities to tie into existing hotline/clearinghouse capabilities • Establish and promote availability of information clearinghouse • Create library of educational materials to serve the needs of multiple target audiences • Create specialized distribution plans for high visibility materials, identifying partners as necessary	Barrier A
2	**Build Presence of Hydrogen and Fuel Cells in K-12 Education** • Identify and review currently available hydrogen technology teaching materials • Evaluate opportunities to integrate hydrogen and fuel cell information into traditional and/or existing materials o Identify partners with hydrogen and education expertise and create hydrogen technology curricula and coordinated and sustainable teacher training/ professional development program for middle schools and high schools o Use secondary school experience to develop corresponding program for elementary schools	Barriers A, C, D
3	**Facilitate Development of Hydrogen Technology Programs at Universities** • Build internet-enabled database of university-level programs for hydrogen and fuel cells • Evaluate – and pursue, as appropriate – opportunities, to expand hydrogen and fuel cell focus of current DOE-sponsored university programs • Evaluate – and pursue, as appropriate – opportunities to work with industry and trade associations to engage college and university students from a variety of disciplines in the development of a hydrogen economy • Work with university partners to develop and expand hydrogen technology curricula for undergraduate and graduate students • Facilitate the development of college and university networks to extend the availability and use of hydrogen technology curricula, as appropriate and practical	Barriers A, B, C, D
4	**Assess Perceptions and Understanding of Hydrogen Economy and Fuel Cell Technologies** • In 2004, conduct a baseline knowledge assessment of key target audiences • Conduct periodic reassessments of public perceptions through 2010	Barriers A, C, D

5	**Develop Public Education Campaign** • Use knowledge assessments to identify audience education needs • Work with local and state partners to distribute general education materials to address initial education needs • Work with Technology Validation partners to implement initial public education strategies in conjunction with near-term demonstration projects • Identify partners for national-level coordinated public education campaign • Develop comprehensive plan for education campaign—develop and test messages, identify cost-effective communication mechanisms and methods for evaluating success • Implement public education campaign with partners	Barrier A
6	**Facilitate Partnerships and Information Exchange among Local, State, and Regional Education Efforts, and National Partners** • Work with DOE Regional Offices and established and emerging state and local partnerships and coalitions to facilitate information exchange and coordinate activities to maximize the reach of education efforts and avoid duplication • Create a Hydrogen Education Review Panel to facilitate coordination of education activities among partners with objectives that are national in scope	Barrier A, B, C, D
7	**Develop and Implement Educational Activities for State and Local Governments** • Provide objective information about hydrogen technology, safety, challenges to commercialization, and the role that state and local governments can play in the transition to a hydrogen economy • With DOE Regional Offices and state and local partners, develop and conduct training workshops to educate state and local governments	Barriers A, B, C
8	**Develop and Implement Educational Activities for Large-Scale End Users** • Provide objective information about the technology and hydrogen safety; share case studies, best practices, and lessons learned from the experiences of current users and, in particular, participants in Technology Validation projects • With industry and trade association partners, as well as the Safety and Technology Validation subprograms, educate potential large-scale end users and facilitate technician and employee training	Barriers A, B, C
9	**Develop and Implement Educational Activities for Safety and Code Officials** • Create coordination plan with Safety, Codes and Standards Program elements to identify opportunities and education gaps • Develop and implement training activities, as appropriate	Barriers A, B, C, D

3.8.6 Milestones

Key education achievements often involve the creation of a product. As such, Figure 3.8.4 shows the milestones and deliverables, as well as the interrelationship of these elements with the tasks and inputs from other subprograms for the Education Program element from FY 2004 through FY 2011. This information is also summarized in Table B.8 in Appendix B.

Figure 3.8.4. Hydrogen Education R&D Milestone Chart



The Education Program element is deferred to FY 2006 subject to congressional appropriation.

For chart details see next page.

Milestones

1 Complete Web site needs assessment.
2 Identify opportunities to tie into existing clearinghouse infrastructures.
3 Establish information clearinghouse.
4 Complete “phase 2” Web site upgrades and improvements (“phase 1” was initial launch, completed January 28, 2003).
5 Deliverable: Create library of materials, including, but not limited to the following: fuel cell technology fact sheets, hydrogen “basics” fact sheet (production, storage, delivery), hydrogen safety fact sheet, technology “challenges” fact sheet.
6 Deliverable: Publish data from first generation Technology Validation projects.
7 Deliverable: Publish data from second generation Technology Validation projects.
8 Identify and review existing teaching materials for grades K-12.
9 Identify and evaluate opportunities to work with traditional textbook companies to incorporate hydrogen and fuel cell information.
10 Publish middle school hydrogen activity guide to serve interim education needs.
11 Publish high school hydrogen activity guide to serve interim education needs.
12 Develop and pilot draft comprehensive middle school hydrogen technology curricula.
13 Develop draft comprehensive high school hydrogen technology curricula.
14 Publish elementary school activity guide.
15 Publish comprehensive middle school hydrogen technology curricula; launch dissemination strategy and teacher professional development.
16 Conduct local pilots and national field tests of comprehensive high school hydrogen technology curricula and teacher professional development training modules.
17 Launch national dissemination of comprehensive high school hydrogen technology curricula and teacher professional development program.
18 Launch hydrogen technology competition for university students.
19 Deliverable: Publish database of existing university programs.
20 Evaluate opportunities to expand hydrogen and fuel cell focus of current DOE-sponsored university programs.
21 Launch Hydrogen Technology Learning Center program for colleges and universities.
22 Complete development of community college hydrogen technology curriculum.
23 Establish baseline level of public awareness and perceptions.
24 Conduct follow-up public perception analysis.
25 Complete public perception assessment and results analysis.
26 Initiate national education campaign planning efforts with Controlled Hydrogen Fleet and Infrastructure Validation project partners.
27 Create plan for pilot public education campaign in conjunction with Controlled Hydrogen Fleet and Infrastructure Validation project partners.
28 Complete pilot of public education campaign strategies in conjunction with Controlled Hydrogen Fleet and Infrastructure Validation partners and in communities with ongoing technology validation activities.
29 Go-Now/Go-Later: Decision point on launch of full-scale public education campaign.
30 Complete assessment of opportunities for joint education activities with existing community partnership programs.
31 With DOE Regional Office and state and local government partners, complete first Hydrogen Learning Workshop Series to educate state and local government officials.
32 Building on first series, launch second series of Hydrogen Learning Workshops for state and local government officials.
33 Identify partners to serve on Hydrogen Education Review Panel.
34 Launch Hydrogen Education Review Panel.
35 Launch Hydrogen Learning Workshop series for potential large-scale end-users.
36 Establish a coordination plan with Safety and Codes and Standards program elements for state and local safety and code official training.

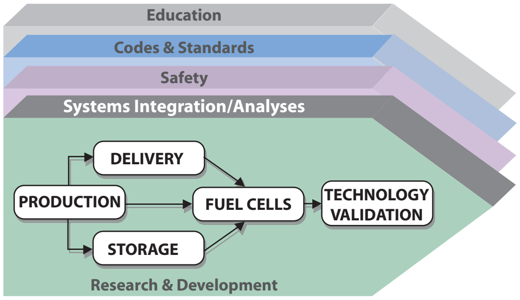
Outputs

E1 Output to Safety: Publish initial perceptions report.
E2 Output to Safety: Publish interim perceptions report.
E3 Output to Safety: Publish perceptions report.

Inputs

C1 Input from Codes and Standards: Training modules for current practices.
Sf1 Input from Safety: Report of common accident scenarios.
C2 Input from Codes and Standards: Training modules for amended practices for new technologies.
Sf2 Input from Safety: Updated report of common accident scenarios.
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
Sf7 Input from Safety: Final, peer-reviewed Best Practices Handbook.

4.0 Systems Analysis



Systems Analysis supports decision-making by providing greater understanding of the contribution of individual components to the hydrogen energy system as a whole, and the interaction of the components and their effects on the system. Analysis will be used to continually evaluate the alternatives for satisfying the functions and requirements of the future hydrogen system/economy and the Program's progress against the targets outlined in this RD&D Plan. Analysis is conducted to assess cross-cutting and overall hydrogen system issues, and to support the development of the production, delivery, storage, fuel cell and safety technologies. The Systems Analysis activities are led by the DOE Technology Analyst and are supported by the Systems Integration function, which provides analytical resources, models and tools, and independent analysis capabilities as required.

4.1 Technical Goal and Objectives

Goal

Support decision-making by evaluating existing and emerging technologies, utilizing a fact-based analytical framework to guide the selection and evaluation of RD&D projects, and providing a sound basis for estimating the potential value of research and development efforts.

Objectives

- Through analysis, continuously support the integration of the Program within a balanced, overall DOE national energy R&D effort—addressing the role of hydrogen in context of the overall energy infrastructure.

- By 2007, identify and evaluate transition scenarios consistent with developing infrastructure and hydrogen resources, including an assessment of timing and sequencing issues.

- Continuously provide and/or coordinate appropriate and timely analysis of environmental and technoeconomic issues to support decision-making tied to Program schedules, targets and milestones.

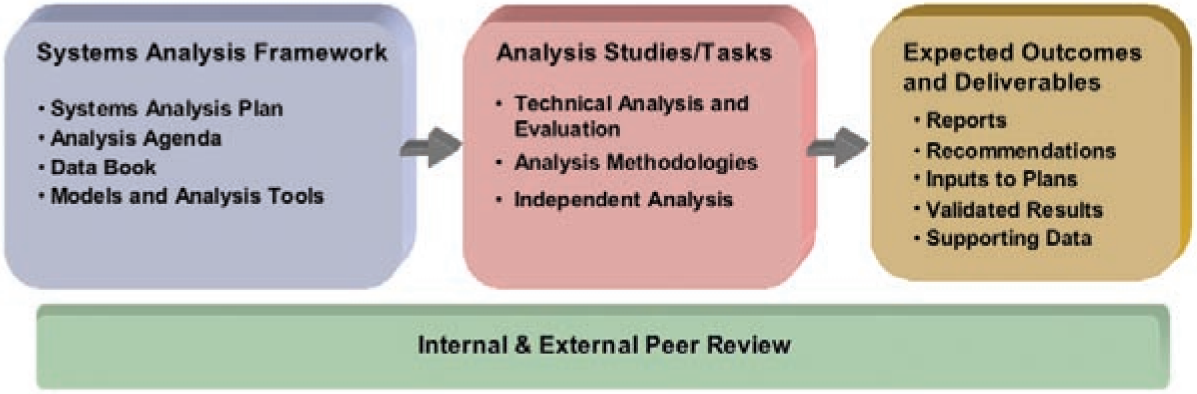
- By 2008, develop and utilize a macro-system model of the hydrogen fuel infrastructure to support transportation systems. By 2010, enhance the model to include the stationary electrical generation and infrastructure for a full hydrogen economy.

- Continuously support a spectrum of analyses, including financial and environmental assessments, across and within Program elements—from individual unit/subsystem elements to a fully integrated system and infrastructure.

4.2 Technical Approach

The overall approach to implementing a robust Systems Analysis capability is based on the need to support Program decision-making processes and milestones, provide independent analysis when required to validate decisions and/or ensure objective inputs, and respond to external review recommendations. As depicted in Figure 4.2.1, the approach provides the direction, planning, and resources/tools through the systems analysis framework, the ongoing and planned studies and tasks, and the value-added products. To ensure that the effort is properly focused, frequent, objective and effective, internal and external peer reviews are conducted.

Figure 4.2.1 Systems Analysis Approach Overview



Systems Analysis Framework

- Systems Analysis Plan
- Analysis Agenda
- Data Book
- Models and Analysis Tools

Analysis Studies/Tasks

- Technical Analysis and Evaluation
- Analysis Methodologies
- Independent Analysis

Expected Outcomes and Deliverables

- Reports
- Recommendations
- Inputs to Plans
- Validated Results
- Supporting Data

Internal & External Peer Review

4.2.1 Systems Analysis Framework

Systems Analysis Plan. A detailed Systems Analysis Plan (SAP) is being developed to lay out the overall approach, tasks and processes for the systems analysis efforts of the Program. The SAP will contain a catalog of resources, the systems analysis processes, the analysis results and supporting documentation.

Analysis Portfolio. A portfolio of technical analysis and evaluation activities will be established. The portfolio will be prioritized based on need to better understand system requirements, support Go/No-Go decisions, and evaluate progress towards the milestones and technology development goals of the program. The analysis portfolio will be updated periodically to ensure that the analytical activities provide direction, focus and support to the Program's research and development activities.

Data Book. A technical data management system will be developed to provide a consistent database, a list of assumptions, information standards and tools for capturing needed information. This repository will serve as the standard input to systems analysis, and will be used to establish the base case hydrogen system and conduct the subsequent trade-off analyses. The technical data management system will ensure consistency in analyses conducted by the Program. The database will be updated annually and made available to the community through the Web.

Models and Analysis Tools. Systems analysis tools support capturing the results of individual efforts, reviewing progress against stated objectives, and conducting ongoing evaluations that advance the Program objectives. Modeling tools will provide the basis for analyzing alternatives at the system-, technology-, or component-level in terms of their cost, performance, benefit and risk impacts on the macro system. Numerous models exist or are under development by national laboratories, industry and academia within the hydrogen system functional areas (production, delivery, storage, etc.). Systems Analysis will add a macro-system model to the current model portfolio to conduct overarching analysis and trade-off comparisons. A modeling architecture will be defined to provide consistency among the models employed for analysis, and to sustain the integrity and continuity of the outputs and results.

4.2.2 Analysis Studies/Tasks

Technical Analysis and Evaluation. The potential technology pathways for wide-scale hydrogen implementation will be modeled and analyzed from the standpoints of application requirements (targets), costs, risks, and environmental and societal impacts on a macro-system basis. Key cost and technology barriers/gaps will be identified. These results will help to further define and update the key RD&D needs and plans within each of the Program elements. Systems analysis will be used to update energy, environmental and financial impact/risk projections. To achieve these results, the analysis activities will follow a modeling methodology covering a wide spectrum of analysis needs. The types of analyses required to plan, execute and evaluate the RD&D activities are described in Table 4.2.1.

Table 4.2.1. Analysis Methodologies

Analysis Type	Description
Resource Analysis	Determines the quantity and location of resources needed to produce hydrogen. Additionally, resource analysis quantifies the cost of the resources as a function of the amount that can be available for hydrogen production. Geographic Information Systems (GIS) modeling is often used to portray and analyze resource data. GIS can also represent the spatial relationship between resources, production facilities, transportation infrastructures and demand centers.
Technology Feasibility and Cost Analysis	Determine the potential economic viability of a process or technology, and identify technologies that have the greatest likelihood of economic success. The technical feasibility assesses the basic viability of the process. The results from technology feasibility analysis provide input to balanced portfolio development and technology validation plans.
Environmental Analysis	Quantifies the environmental impacts of technologies. Specifically, life cycle assessment is used to identify and evaluate the emissions, resource consumption and energy use for all steps in the process of interest, including raw material extraction, transportation, processing and final disposal of all products and by-products. Also known as cradle-to-grave or well-to-wheels analysis, this methodology is used to better understand the full impacts of existing and developing technologies, such that efforts can be focused on mitigating negative effects.
Delivery Analysis	Identifies the most economic options for delivering hydrogen and provides a foundation for additional research on alternative storage and transportation options. Additionally, delivery analysis provides crucial information to technology feasibility analysis in determining the optimal production capacities and locations. Delivery analyses will be conducted to determine the most promising technologies, as inputs to other technical elements of the Program.
Infrastructure Development	Quantifies the total costs of scenarios for developing the hydrogen infrastructure, including production, delivery and utilization. Infrastructure development analysis can identify economical routes and financial risks for providing the lowest delivered cost of hydrogen from combinations of central and distributed production facilities. Evaluations of the costs, impacts on existing infrastructures and timelines of various scenarios for the hydrogen infrastructure will be conducted.
Macro-System Analysis	Analyzes the interrelationships within the system utilizing the tools and results from the range of analysis methodologies. Identifies critical interface issues and system optimization opportunities. Through scenario analysis, identifies the most viable routes for achieving the hydrogen future, and the costs and benefits associated with these pathways.

Independent Analysis. Independent analysis will be an integral part of Systems Analysis to ensure credibility, validate methodologies and data, and provide perspective. Independent analysis is accomplished by utilizing experts and analysts who have not been directly involved in the management, research and development, analysis, evaluation, or recommendation efforts related to the activity in question. Such outside experts often possess unique insight into particular issues that can benefit ongoing analysis activities. Independent analysts may be brought in to provide input to key program milestones, such as technology down-select decisions, and to provide recommendations on changes to major technical targets.

4.3 Analysis-Specific Roles and Responsibilities

Hydrogen Systems Analysis is the responsibility of the DOE Technology Analyst, supported by the Program's Systems Integrator. The overall team involves the Program element leads, FreedomCAR and Fuel Partnership Technical Teams, and the people and organizations that perform the analysis activities. A summary of the individual analysis responsibilities of these positions and groups is provided below:

Technology Analyst

- Accountable for analysis activities
- Provides inputs and sets priorities for the Analysis Portfolio
- Ensures communication of consistent data and information
- Coordinates analysis done in support of the Program

Systems Integrator

- Establishes priorities for the Analysis Portfolio (including technical and time pathways)
- Develops and maintains consistent data and information, and standard analysis assumptions and guidelines
- Provides independent analysis (e.g. for Go/No-Go recommendations)
- Ensures tools/models are developed, maintained, available and validated

Program Element Leads

- Provides inputs to the Analysis Portfolio
- Provides recommendations on cross-cutting analysis
- Manages analysis tasks internal to the Program element

DOE/EERE Office of Planning, Budget and Analysis (PBA)

- Provides market and benefits analysis related to hydrogen and energy infrastructure
- Reviews analysis priorities
- Coordinates activities and exchanges results with the Technology Analyst and Systems Integrator

FreedomCAR and Fuel Partnership Technical Teams

- Provides recommendations to DOE on analysis needs and issues
- Reviews studies and analysis results
- Develops technical targets based on system and customer requirements

4.4 Programmatic Status

Current Activities

Major Systems Analysis activities are listed in Table 4.4.1.

Table 4.4.1. Current Systems Analysis Activities

Topic	Approach	Organization
Resource Analysis	• Quantify location, amount and cost of resources • Develop GIS resource maps for use in infrastructure development studies	**National Renewable Energy Laboratory (NREL):** GIS studies of renewable resources for hydrogen
Technology Feasibility and Cost Analysis	• Determine potential economic viability of hydrogen technologies • Guide Program research activities by identifying cost reduction opportunities and critical development paths	**NREL, Pacific Northwest National Laboratory (PNNL), Argonne National Laboratory (ANL), Directed Technologies, TIAX, UC-Davis, Technology Insights and Parsons Engineering:** Standards and tools for consistent analysis of hydrogen technologies (H2A; details of H2A Analysis model are presented in Appendix E) **NREL:** Technoeconomic analysis of current research projects and case studies of competing and complementary production technologies
Environmental Analysis	• Conduct well-to-wheel analysis to compare existing and developing transportation technologies • Assess climate impact of the hydrogen economy • Determine environmental impacts of hydrogen technologies	**PNNL:** Incorporating hydrogen-specific technologies into long-term climate model **ANL:** Fuel cell vehicle benefits analysis using GREET and VISION models **Tellus:** Greenhouse gas impacts of transition scenarios **NREL:** Environmental analysis of hydrogen production technologies
Delivery Analysis	• Analyze systems and infrastructures for delivery of gaseous and liquid hydrogen and novel solid/liquid hydrogen carriers	**PNNL, NREL and ANL:** Components modeling; compression technology and issues; ethanol delivery infrastructure characterization; and hydrogen delivery scenario modeling **Nexant, Inc., Air Liquide, ChevronTexaco, NREL, Gas Technologies Institute, Pinnacle West, and TIAX:** Cost/environmental analyses for delivery scenarios as a function of time and demand
Infrastructure Development	• Evaluate cost impacts and timelines of various scenarios for developing hydrogen infrastructure • Identify economical routes and financial risks of hydrogen production and delivery technologies	**Oak Ridge National Laboratory (ORNL) and ANL:** HyTrans hydrogen infrastructure model to study fuel cell vehicle market penetration **NREL:** Geographic-specific hydrogen infrastructure model to study hydrogen production and its interface to the electric grid **UC-Davis and NREL:** Assessment of geographic locations for hydrogen fueling stations and infrastructure **TIAX:** Impacts of fuels choice on transportation infrastructure **RCF, ANL, Air Products, BP, Ford, WRI and University of Michigan:** Analysis of the hydrogen production and delivery infrastructure as a complex adaptive system **Direct Technologies, Inc., Sentech, H2Gen, ChevronTexaco and Teledyne:** Hydrogen production infrastructure options analysis **Energy and Environmental Analysis, BNL, Power and Energy Analytic Resources:** Impact of hydrogen production on U.S. energy markets
Market/Benefits Analysis	• Enable broad understanding of the hydrogen economy in the context of energy infrastructure • Assess the potential benefits and impacts of hydrogen and competing technologies	**EERE/PBA:** Interrelationship of the hydrogen economy to the overall energy infrastructure; market and benefits analysis of hydrogen and fuel cell vehicles

4.5 Technical Challenges

The following discussion details the various technical and programmatic barriers that must be overcome to attain the Systems Analysis goal and objectives.

Barriers

A. **Lack of Prioritized List of Analyses for Appropriate and Timely Recommendations.** Systems analysis and its resulting observations and recommendations are only of value if they address the key decisions faced by the Program and are tied to the schedules and milestones of those decision processes. Resource constraints, fluid budgets and evolving technologies impact the setting of analysis priorities.

B. **Lack of Consistent Data, Assumptions and Guidelines.** Analysis results are strongly influenced by the data sets employed, as well as the assumptions and guidelines established to frame the analytical tasks. These elements have been largely uncontrolled in the past, with individual analysts and organizations making their own value decisions. Although this does not necessarily make the results wrong, it does make it more difficult to put the results and ensuing recommendations in context with other analyses and the overall objectives of the Program. Establishing a Program-endorsed consistent set of data, assumptions and guidelines is challenging due to the large number of stakeholders involved and the breadth of technologies and system requirements.

C. **Lack of a Macro-System Model.** Although numerous models exist to analyze components and subsystems of an eventual hydrogen economy, a modeling architecture does not exist that addresses the overarching hydrogen fuel infrastructure as a "system." Such a macro-system model is critical to assessing the transition from the existing energy infrastructure to one including hydrogen. Individual models spanning a wide range of modeling platforms (operating systems, software, inputs, outputs, boundary conditions, etc.) must be integrated into a common macro-system model.

D. **Stove-Piped/Siloed Analytical Capabilities.** Analytical capabilities and resources have been largely segmented, both functionally by Program element (production, storage, fuel cells, etc.) and organizationally (laboratories, specialized teams, industry/academia, etc.). Successful systems analysis requires the integration of analysis resources across all facets of the infrastructure.

E. **Lack of Understanding of the Transition of a Hydrocarbon-Based Economy to a Hydrogen-Based Economy.** The long-term hydrogen fuel infrastructure is little understood and numerous economic, social, political and technical influences will be involved in the transition to the hydrogen economy. In addition, the overall energy infrastructure and economy into which hydrogen must fit is an ever-changing domain.

4.6 Target Setting Process

The objective of target setting is to set a realistic standard for focusing and assessing the research and development efforts. The technical targets are an essential part of the Program and key to achieving the goals and objectives of lowering cost, improving energy efficiency and ensuring reliable performance. The targets are driven by the system level and consumer requirements necessary for them to be competitive for use in light-duty vehicle transportation and stationary power markets. For example, for light-duty vehicle transportation, hydrogen fuel cell vehicles will need to compete with internal combustion engine and/or hybrid electric vehicles on a cost and performance basis. The hydrogen fuel cost target is based on the need to compete with gasoline on a cents-per-mile basis and is independent of the production pathway. The hydrogen storage and fuel cell targets reflect consumer expectations for vehicles with a range greater than 300 miles and system costs that are on parity with the convention.

While system requirement targets are set based on a top-down approach, a bottom-up approach is also used to determine if targets are realistic for specific technologies (e.g. thermodynamically feasible), to track progress towards achieving the targets, and to set priorities for cost reduction and performance improvements. As technology progresses and more is learned about the system-level requirements, the targets may be further refined.

4.7 Technical Task Descriptions

The technical task descriptions are presented in Table 4.7.1. The Systems Analysis function is in the initial stages of operation. Therefore, the tasks are currently process oriented and designed to establish the key elements required for on-going analysis.

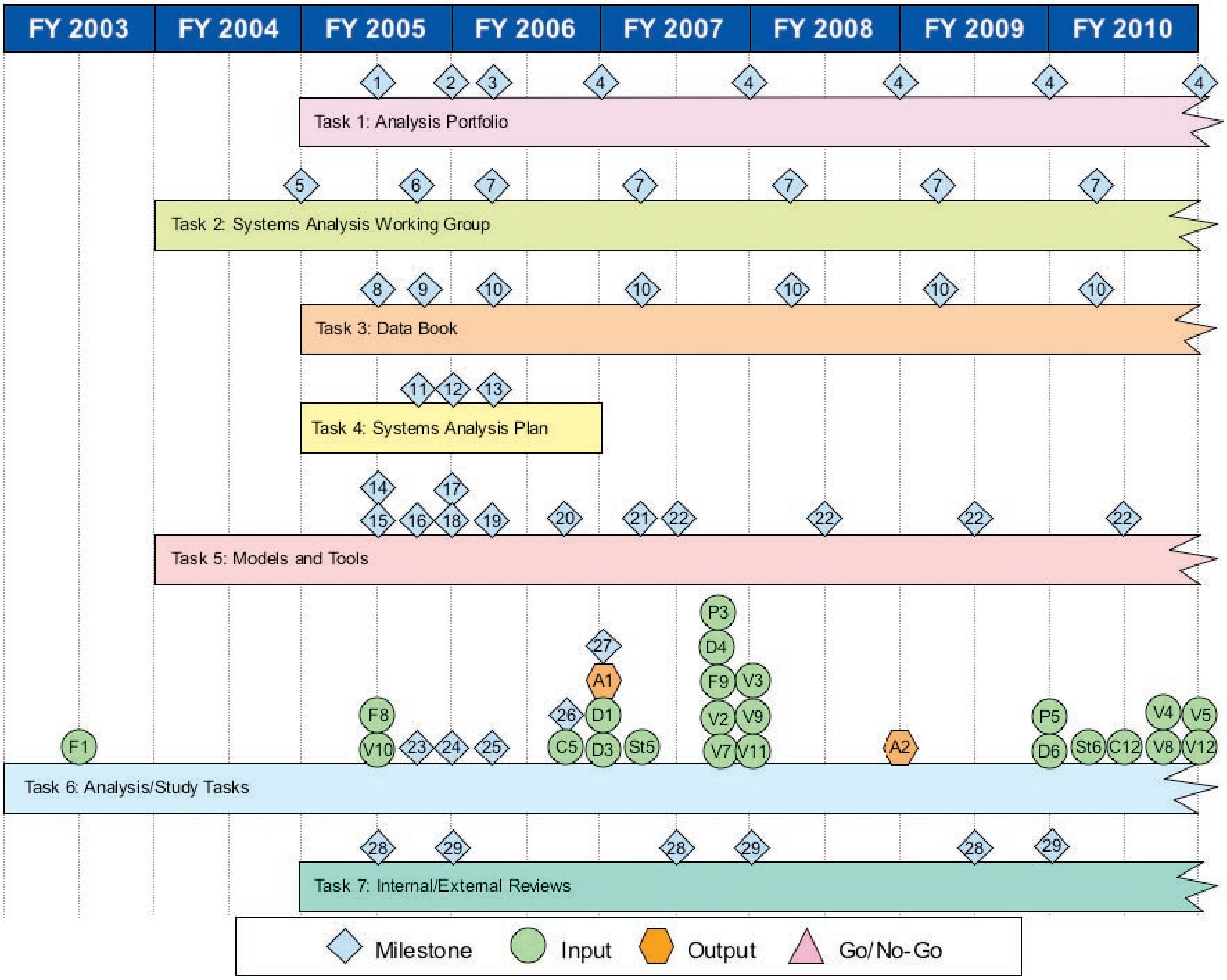
Table 4.7.1. Current Systems Analysis Activities

Task	Description	Barriers
1	**Analysis Portfolio** • Develop and maintain the Analysis Portfolio, a prioritized listing and description of the analysis tasks needed to support programmatic and technical milestones • Update the portfolio as required (at least annually to support budget preparation timelines) • Integrate the portfolio in Systems Analysis planning	A, B, C, D, E
2	**Systems Analysis Working Group** • Sponsor, establish and lead a hydrogen analysis community group to mature and coordinate systems analysis for the Program • Coordinate analysis activities with the DOE Offices of Fossil Energy and Nuclear Energy, Science and Technology • Work with the EERE Office of Planning, Budget and Analysis to integrate and coordinate market/benefits analysis with the Program needs	A, B, D, E
3	**Data Book** • Develop standard and consistent analysis data, assumptions, guidelines, and scenarios • Maintain the Data Book through a configuration managed change process • Provide access to the Data Book via a web-based interface	B
4	**Systems Analysis Plan** • Catalog current resources, systems analysis processes and analysis results, including supporting documentation • Develop an overall Systems Analysis Plan to guide the systems analysis activities of the Program, integrating input from the analysis community (Systems Analysis Working Group, Technical Teams, H2A, etc.)	A, B, C, E
5	**Models and Tools** • Complete the development of requirements for the Macro-System Model (MSM) • Develop the overall MSM architecture and choose the infrastructure hardware/software implementation • Determine standard input/output schemes for utilization within the MSM • Capture MSM requirements, description, and usage in the MSM Description Document • Develop plans for supporting models, including optimization, transition, delivery, environmental, fuel cell vehicle and combined energy	C, E
6	**Analysis/Study Tasks** • Conduct systems analysis/study tasks in key areas to support Program decisions and milestones	A, D, E
7	**Internal/External Review** • Conduct an internal review of systems analysis activities to ensure that plans and execution are in line with Program needs • Conduct an external peer review of the Systems Analysis function to measure progress	A

4.8 Milestones

Figure 4.8.1 shows the interrelationship of milestones, tasks, supporting inputs from other Program elements, and technology/analytical outputs from the Systems Analysis function from FY 2005 through FY 2010. This information is also summarized in Table B.9 in Appendix B.

Figure 4.8.1. Systems Analysis R&D Milestone Chart



For chart details see next page.

Milestones

1 Complete survey for Analysis Portfolio from all sources.
2 Complete 1st draft of prioritized Analysis Portfolio.
3 Publish Analysis Portfolio.
4 Annual update of Analysis Portfolio.
5 Establish Systems Analysis Work Group and Complete 1st Systems Analysis Workshop.
6 Complete 2nd Systems Analysis Workshop with hydrogen analysis community.
7 Annual Systems Analysis Workshop to review updated Analysis Portfolio and Data Book.
8 Survey hydrogen community for assumptions, data sets, targets and constraints for input to the database.
9 Complete "Review Version" of Data Book and issue for comment.
10 Complete 1st edition of Data Book and subsequent annual updates.
11 Complete "Review Version" of the Systems Analysis Plan.
12 Peer review the Systems Analysis Plan.
13 Complete 1st edition of the Systems Analysis Plan.
14 Complete model review for model architecture.
15 Complete transition model review.
16 Complete input/output guidelines for the Macro-System Model.
17 Select transition model for analysis and incorporate into Macro-system Model.
18 Develop initial model architecture.
19 Capture Macro-System Model requirements, description, and usage in a description document.
20 Peer review the Macro-System Model with the hydrogen modeling community.
21 Complete 1st version of the Macro-System Model.
22 Complete the integration of the Macro-System Model into the Systems Analysis and accomplish annual major model upgrades (2010 includes electricity infrastructure).
23 Complete evaluation of the factors (geographic, resource availability, existing infrastructure) that most impact transition analysis.
24 Complete baseline economic, energy efficiency and environmental targets for fossil, nuclear and renewable hydrogen production and delivery technologies.
25 Begin a coordinated study of transition analysis with H2A and Delivery models.
26 Complete study for transitioning scenarios for a hydrogen economy.
27 Complete assessment of current technologies for production and delivery pathways to meet the established targets.
28 Internal review of Systems Analysis function biennially.
29 External Peer review of Systems Analysis function biennially.

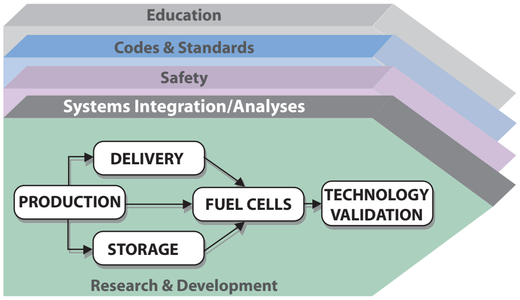
Outputs

A1 Output to Production, Delivery and Systems Integration: Complete techoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.
A2 Output to Program: Initial recommended hydrogen quality at each point in the system.

Inputs

F1 Input from Fuel Cells: Critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions and cost.
F8 Input from Fuel Cells: Preliminary hydrogen purity/impurity requirements.
V10 Input from Technology Validation: Hydrogen refueling station analysis - proposed interstate refueling station locations.
C5 Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification.
D1 Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.
D3 Input from Delivery: Hydrogen delivery infrastructure analysis results.
St5 Input from Storage: Baseline hydrogen on-board storage system analysis results (and initial down-select) including hydrogen quality needs and interface issues.
P3 Input from Production: Impact of hydrogen purity on cost and performance.
D4 Input from Delivery: Assessment of impact of hydrogen purity requirements on cost and performance of hydrogen delivery.
F9 Input from Fuel Cells: Updated hydrogen purity/impurity requirements.
V2 Input from Technology Validation: Final report for first generation vehicles and interim progress report for second generation vehicles, on performance, safety and O&M.
V7 Input from Technology Validation: Final report on infrastructure, including impact of hydrogen purity on cost and performance.
V3 Input from Technology Validation: Technology status report and re-focused R&D recommendations.
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
V11 Input from Technology Validation: Composite results of analyses & modeling from vehicle and infrastructure data collected under the learning demonstration project.
P5 Input from Production: Impact of hydrogen purity on cost and performance.
D6 Input from Delivery: Update of hydrogen purity/impurity requirements.
St6 Input from Storage: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temperature, etc.) and down-select to a primary on-board storage system candidate.
C12 Input from Codes & Standards: Final hydrogen fuel quality standard as ISO Standard.
V4 Input from Technology Validation: Final report for second generation vehicles on performance, safety and O&M.
V8 Input from Technology Validation: Final report on infrastructure, including impact of hydrogen purity on cost and performance.
V5 Input from Technology Validation: Technology status report and re-focused R&D recommendations.
V12 Input from Technology Validation: Composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.

5.0 Systems Integration



Systems Integration provides a disciplined approach to the research, design, development and validation of complex systems, ensuring that requirements are identified, verified and met, while minimizing the impact on cost and schedule of unanticipated events and interactions. Systems Integration supports the Program as it evolves and matures hydrogen production, delivery, storage, fuel cell and supporting technologies through successive stages of research and development. The desired end point is a validated technology set that enables industry commercialization decisions leading to a well-integrated hydrogen system that reliably and cost-effectively provides energy for transportation and stationary applications. The Systems Integrator provides the tools and processes to integrate and measure progress towards the goals of the Program. Tailored to the particular requirements of a robust, long-term research and development program, these tools and processes take advantage of experience and lessons learned from other parts of the federal government (e.g., DOD and NASA) as well as in industry.

5.1 Technical Goal and Objectives

Goal

Establish a disciplined approach that ensures Program requirements are identified, met and validated in the context of dynamic commercial market requirements, while minimizing the impact on cost and schedule of unanticipated events and interactions.

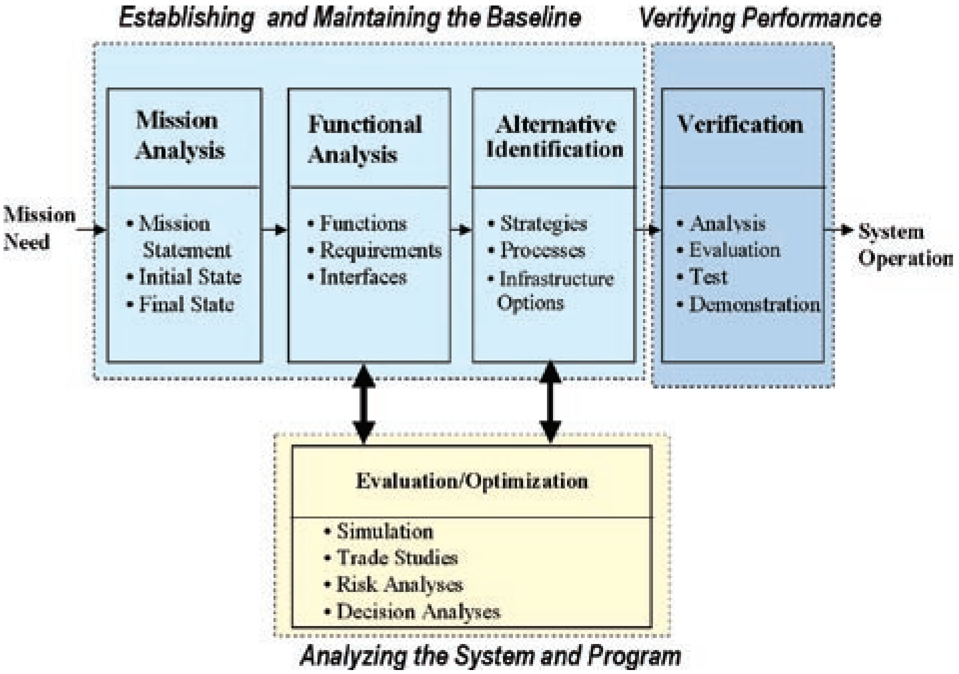
Objectives

- By 2005, establish an integrated technical and programmatic baseline, and maintain and utilize the baseline to support programmatic decisions and ensure research and development directions satisfy needs.
- Verify that the system being developed satisfies the Program requirements, projects are meeting performance and milestone objectives, and progress toward technical targets is substantiated.
- Provide analyses and recommend DOE-sponsored activities to enable the commercial sector to deploy a well-integrated hydrogen system that satisfies needs while continually monitoring system performance to identify potential improvements.

5.2 Technical Approach

Systems Integration provides technical and programmatic support to the Program by 1) establishing, validating, and maintaining the Integrated Baseline as hydrogen technologies and systems are advanced from concept to commercial adoption, 2) providing consistent and independent (when required) results of analyses to support programmatic decisions, 3) verifying that technology and system designs meet Program requirements, and 4) supporting the implementation of strong program engineering and management processes (See Figure 5.2.1).

Figure 5.2.1. Systems Integration Approach Overview

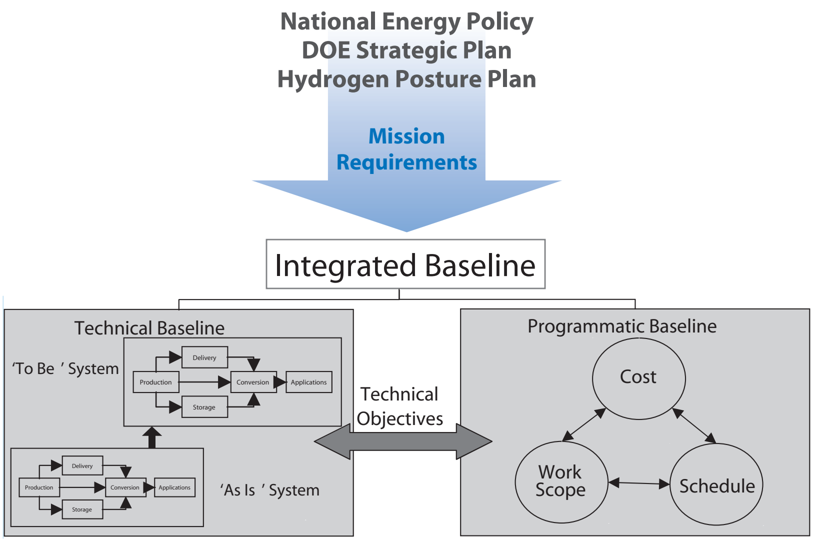


Integrated Baseline

The Integrated Baseline (IB) is a tool and process that helps manage the Program by ensuring that (1) RD&D and analysis projects are properly addressing all of the Program requirements and (2) that the cost, schedule, and performance of the Program and its projects are understood and controlled. In other words, the first ensures that the Program is "doing the right things" and the second that it is "doing things right." These two components are represented by the Technical Baseline (TB) and Programmatic Baseline (PB), respectively, which are then linked by the technical objectives of the Program to provide the "integrated" aspects of the overall baseline. As shown in Figure 5.2.2, the IB is derived from the overarching policy, strategy and planning documents associated with the President's Hydrogen Fuel Initiative. It is a representation of the entire DOE Hydrogen Program funded under that Initiative and is developed and maintained in tools that are readily available, accessible and mature.

Once the IB is approved, it becomes the control version against which the Program is assessed. The Systems Integrator supports the Program in implementing a formal process to manage and control changes to the baseline as budgets are requested and appropriated, as changes in the market or policy context are identified, or as new technical advances and information become available.

Figure 5.2.2. The Integrated Baseline



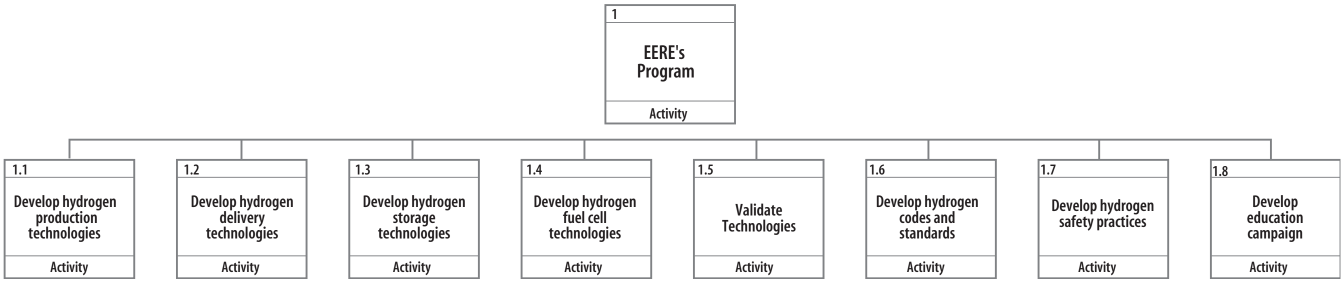
Technical Baseline. In order to ensure that the Program is "doing the right things," the TB provides a detailed mapping starting from the overall requirements, down through the objectives and barriers of the individual Program elements, and finally to the task and individual project level. Requirements for the TB are drawn from the President's Hydrogen Fuel Initiative and related announcements, FreedomCAR and Fuel Partnership Plan, National Energy Policy, National Hydrogen Vision and Roadmap, DOE Strategic Plan, individual DOE Office strategic plans, Hydrogen Posture Plan, DOE Hydrogen Program Management and Operations Plan, and individual DOE Office Multi-Year Research, Development & Demonstration Plans.

The TB includes the prioritization of activities, as well as information on the risk level of individual activities. Questions that can be addressed and answered using the TB include:

- Does the R&D portfolio properly address all the Program requirements?
- Are there gaps or weakness in coverage of technical areas?
- Are the high priority items receiving the proper level of programmatic attention?
- Are there sufficient approaches and projects in the higher risk areas to mitigate those risks?
- When funding or focus changes, in what areas should the Program redistribute, add or decrease resources?

The TB is a complete reference set of technical data describing the current ("as-is") state of the Program and hydrogen infrastructure. The CORE®[1] systems engineering tool (an example CORE graphic is shown in Figure 5.2.3) in which the TB is hosted also has the capability to represent desired ("to-be") end states, in terms of hydrogen infrastructure scenarios or expected descriptions and at different points in time over the next several decades. Using this feature, the TB can be used to identify and evaluate alternative pathways for meeting the needs/requirements or responding to a new transition period or to long-term infrastructure directions.

Figure 5.2.3. Example of TB Representation from CORE



The process of reviewing and validating requirements and aligning the Program with those requirements is recurrent to accommodate advances in R&D, as well as changes that result from the evolution of markets or policies, budget changes or programmatic focus.

Programmatic Baseline. To ensure that the Program is "doing things right," the PB provides a tool and process to track the cost, schedule, and performance of the Program down to the individually funded projects (Figure 5.2.4). The PB describes these efforts in terms of their budget, milestones, and scope, and identifies the dependencies among the activities through an integrated work breakdown structure and master schedule. Loaded with the resources necessary to accomplish the work (funding, personnel, tools, facilities, etc.), it allows assessment of shortfalls and effects of shifting priorities or funding changes. Questions that can be addressed and answered using the TB include:

- Are budgets and schedules on track – for the Program, a Program element, a task or an individual project?
- If there is a delay in a particular activity's schedule, what is the cost and schedule impact on dependent or related activities?
- If funding is reduced in an area, what is the impact to the schedule, and if resources are reallocated, how are schedules affected?
- How does the Program scope change given different funding-level scenarios?

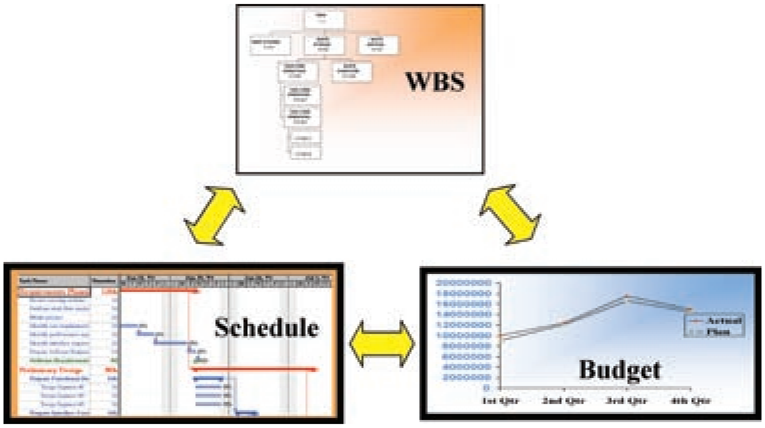
---

[1] CORE® is a registered trademark of Vitech Corporation.

Systems Analysis

Systems Integration supports the review and assessment of alternatives for satisfying the needs of the future hydrogen system/economy and the Program's progress. In addition, Systems Integration provides independent analysis, when required, to help ensure objective and substantiated decisions by the Program. For example, when key Program decision milestones are approached, Systems Integration convenes technical review panels of peer experts to provide an independent recommendation to DOE for consideration during the decision process.

Figure 5.2.4. Programmatic Baseline Concept



Technical Performance Verification

As the Program develops technologies and results, Systems Integration facilitates technical reviews at key stages to evaluate strategic fit with Program objectives, technical potential, economic/market potential, and environmental, health, and safety considerations along with the plan for further development. Verification will be accomplished through analysis, testing and/or demonstration. Criteria and approaches will vary depending on the maturity of the technology. For example, at early stages of development, information available to evaluate concepts is likely to be more general and have higher uncertainty than that available at later stages. Information stemming from these reviews will be used to re-evaluate the baseline.

The Systems Integrator works closely with the DOE Technology Development Managers to bring knowledge of system-level requirements and review criteria to planning and execution. In particular, the Systems Integrator supports reviews of the following Program activities:

- Peer review for all projects and activities
- Independent review panels for key Program milestones and Go/No-Go decisions
- Stage Gate reviews at key progress points for significant projects

Management and Technical Support

Systems Integration supports the Program by aiding implementation of several key processes, two of which are described below:

Risk Management. Systems Integration supports implementation of a risk management process to identify potential Program risks and determine actions that will mitigate the impact of those risks. A six-step risk process—risk awareness, identification, quantification, handling, impact determination, and reporting and tracking—is used. Throughout the life of the Program, the System Integrator helps identify "potential" risks, focusing on the critical areas that could affect the outcome of the Program such as:

- System Requirements
- Environment, Safety and Health
- Modeling and Simulation Accuracy
- Technology Capability
- Budget and Funding Management
- Schedule
- Stakeholder, Legal and Regulatory Issues

Configuration Management. Systems Integration manages the evolving configuration of the hydrogen system (i.e., the Technical Baseline) and continuously monitors and controls it during its life cycle. Changes to the Technical Baseline and the Programmatic Baseline (the approved work scope, schedule and cost) must both be controlled to ensure that all work being performed is consistent with the approved technical requirements and the current configuration, and that impacts throughout the Integrated Baseline are considered before actions are taken. A formal change control process has been established to ensure that the potential impacts of proposed changes to either the Technical Baseline or the Programmatic Baseline are evaluated, coordinated, controlled, reviewed, approved and documented in a manner that best serves the Program and its projects. The decision-making body within the Program for approving proposed changes is the Change Control Board. The procedures and processes will be documented in a Configuration Management Plan.

5.3 Programmatic Status

Table 5.3.1 provides the current set of Systems Integration tasks and activities.

Table 5.3.1. Current Systems Integration Activities

Activities	Description
Integrated Baseline	• Technical Baseline: Using the results of the mission and functional analyses, link and map the various levels and aspects of the Program – requirements, tasks, objectives, barriers, technical targets and projects. • Programmatic Baseline: Assemble the necessary data on subprogram and individual project cost, schedule, work scope and interdependencies.
Systems Analysis	• Develop the Systems Analysis Plan • Define requirements for the Macro-System Model • Initiate Data Book development activities • Support the Technology Analyst in technical management and monitoring of analysis projects • Coordinate cross-cutting activities and plans for critical analyses (e.g., hydrogen purity/quality)
Verification of Technical Performance	• Conduct program peer review at Annual Merit Review Meeting • Tailor stage gate review process to fit Program needs and context • Choose and acquire resources to perform independent assessment of progress on key technical targets
Management and Technical Support	• Develop the Configuration Management Plan • Develop the Risk Management Plan

5.4 Technical Challenges

The following discussion details the various technical and programmatic barriers that must be overcome to attain the DOE Hydrogen Program Systems Integration goal and objectives.

Barriers

A. Integrated Baseline Development and Utilization. The breadth and depth of the DOE Hydrogen Program make it a challenge to encompass all aspects into the Integrated Baseline. Completeness is important, because a true assessment of the sufficiency of program efforts against the requirements can only be made if the entire Program is represented. The four DOE offices (EERE, FE, NE and SC) and other programs and agencies (e.g. Department of Transportation) that are involved in work under the President's Hydrogen Fuel Initiative each have their own baselining and scheduling requirements, which must be consistent down to the individual projects. Tracking and assessing progress requires that projects have meaningful milestones, along with periodic reviews and/or reports to allow transparency in terms of accomplishments and progress. The Integrated Baseline can only provide value if it becomes an accepted and utilized tool for the planning and decision-making processes within the Program.

B. Systems Analysis. Analysis at the hydrogen system level will require modeling tools that do not currently exist. The integration of existing unique models into the Macro-System Model will require hydrogen community support and sufficient resources to develop, maintain and grow the model. For example, relating the Macro-System Model to existing national energy infrastructure models used for market and benefits analysis (e.g. NEMS and MARKAL) must be addressed.

C. Verification. The primary barrier in verification of technical performance is purely one of numbers and time/resources. For example, in FY05, the Program is funding over 200 RD&D and analysis projects to address approximately 250 technical targets. The time and resources needed to verify the progress, status and results of all these activities is a challenge.

D. Processes. Systems integration and engineering practices have typically been applied to large hardware acquisition projects, not necessarily to R&D programs. Tailoring the systems integration procedures and tools to the R&D paradigm will be a challenge, as will be gaining Program and stakeholder acceptance of these processes as value-added and important to Program element and overall Program success.

5.4.1 Expected Outcomes

Establishing standardized tools and approaches to identify, document and evaluate the complex interactions between components, systems costs, environmental impacts, societal impacts and system trade offs will enable effective management of the Program and evaluation of alternative concepts and pathways, and result in well-integrated and optimized hydrogen and fuel cell systems. Over the course of the President's Hydrogen Fuel Initiative, Systems Integration will enable the Program to:

- Establish well-documented system requirements linked to Program objectives
- Ensure that technology designs meet requirements
- Provide consistent systems-level analyses
- Make and document defensible decisions
- Identify and manage risk

5.5 Technical Task Descriptions

The technical task descriptions are presented in Table 5.5.1.

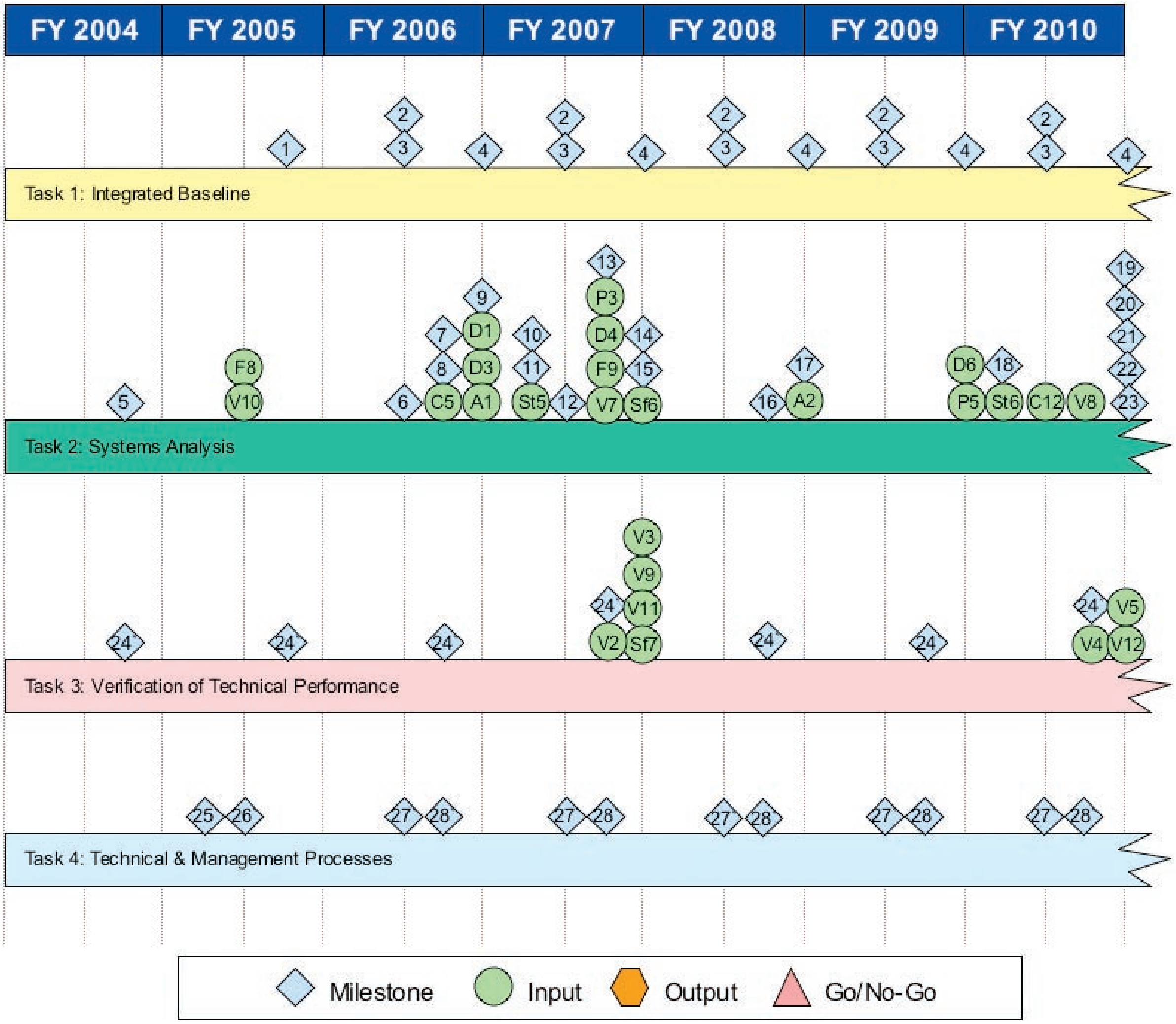
Table 5.5.1. Technical Tasks

Task	Description	Barriers
1	**Integrated Baseline** • Finalize all the inputs to the Technical Baseline and the Programmatic Baseline • Determine risks and priorities and integrate them within the key tasks and milestones of the baseline • Validate the baseline through each of the Program technical and cross-cutting elements • Complete independent quality assurance review of the baseline for accuracy and completeness • Place the Integrated Baseline under configuration management and formal change control • Produce periodic updates to the baseline as required	A
2	**Systems Analysis** • Develop the Analysis Portfolio • Develop, maintain and resolve consistent data sets/info and standard analysis assumptions and guidelines • Provide independent analysis (policy-related issues, Go/No-Go recommendations, H_2 in the context of larger energy markets, etc.) • Ensure tools/models are developed, maintained, available and validated • Provide independent review of analysis results • Support the definition of analysis scenarios	B
3	**Verification of Technical Capability** • Conduct the peer review process in conjunction with the Annual Merit Review Meeting (including EERE, FE, NE, and SC projects) • Provide independent verification of the status and progress toward key technical targets of the Program • Implement the Stage Gate review process for critical projects across the various Program elements	C
4	**Technical and Management Processes** • Complete the Configuration Management Plan and implement its processes within the Program • Support the Change Control Board • Complete the Risk Management Plan and implement its processes within the Program • Support the Risk Management Board	A, B, C, D

5.6 Milestones

Figure 5.6.1 shows the interrelationship of milestones, tasks, supporting inputs from other Program elements and outputs from the Systems Integration function from FY 2005 through FY2010. This information is also summarized in Table B.10 in Appendix B.

Figure 5.6.1. Systems Integration R&D Milestone Chart



For chart details see next page.

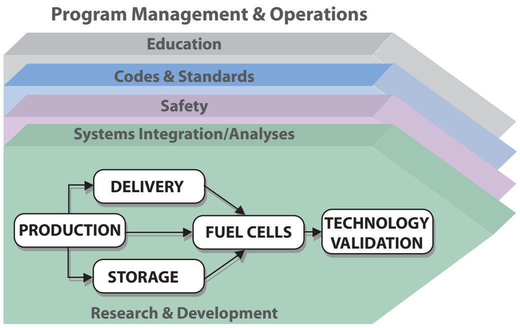
Milestones

1 Approval of initial Integrated Baseline.
2 Integrated Baseline updates based on actual FY06 through FY10 Program appropriations.
3 Integrated Baseline versions reflecting FY08 through FY12 budget requests.
4 Integrated Baseline updates based on FY07 through FY11 spend plans.
5 Independent analysis for Fuel Cells Go/No-Go decision on fuel processing R&D.
6 Independent analysis for Fuel Cells Go/No-Go decision on sensors and controls technologies.
7 Independent analysis for Fuel Cells Go/No-Go decision on MEA in single cell meeting targets.
8 Supporting analysis for Systems Analysis production and delivery task.
9 Independent analysis for Tech Val Go/No-Go decision on purchase of additional vehicles .
10 Independent analysis for Storage Go/No-Go decision on compressed and cryogenic tank technologies for on-board.
11 Independent analysis for Storage Go/No-Go decision on carbon nanotubes.
12 Independent analysis for Production Go/No-Go decision on continued high-temperature steam electrolysis R&D.
13 Independent analysis for Fuel Cells Go/No-Go decision on air management and thermal management technologies.
14 Independent analysis for Production Go/No-Go decision on membrane separation technology.
15 Independent analysis for Fuel Cells Go/No-Go decision on scale up precious metal reclamation process.
16 Supporting analysis for Systems Analysis hydrogen purity task.
17 Independent analysis for Fuel Cells Go/No-Go decision on auxiliary power, portable power and off-road R&D.
18 Independent analysis for Storage Go/No-Go decision on advanced carbon-based materials.
19 Independent analysis for Storage Go/No-Go decision on continuation of on-board reversible metal hydride R&D.
20 Independent analysis for Storage Go/No-Go decision on chemical storage R&D for 2015 targets.
21 Independent analysis for Fuel Cells Go/No-Go decision on stationary fuel cell systems.
22 Independent for Production Go/No-Go decision for transparent H_2-impermeable material.
23 Independent analysis for Production Go/No-Go decision on high-temperature solar-driven thermochemical cycles.
24 Conduct peer review of projects at Annual Merit Review.
25 Formal configuration management plan approved and processes implemented.
26 Formal risk management plan approved and processes implemented.
27 Change Control Boards periodically each fiscal year.
28 Risk Management Boards periodically each fiscal year.

Inputs

F1 Input from Fuel Cells: Critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions, and cost.
F8 Input from Fuel Cells: Preliminary hydrogen purity/impurity requirements.
V10 Input from Technology Validation: Hydrogen refueling station analysis - proposed interstate refueling station locations.
C5 Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.
D1 Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.
D3 Input from Delivery: Hydrogen delivery infrastructure analysis results.
A1 Input from Systems Analysis: Complete technoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.
St5 Input from Storage: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.
P3 Input from Production: Impact of hydrogen purity on cost and performance.
D4 Input from Delivery: Assessment of impact of hydrogen purity requirements on cost and performance of hydrogen delivery.
F9 Input from Fuel Cells: Updated hydrogen purity/impurity requirements.
V7 Input from Technology Validation: Final report on infrastructure and hydrogen quality for first generation vehicles.
Sf6 Input from Safety: Sensor meeting technical targets.
A2 Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.
P5 Input from Production: Impact of hydrogen purity on cost and performance.
D6 Input from Delivery: Update of hydrogen purity/impurity requirements.
St6 Input from Storage: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary on-board storage system candidate.
C12 Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.
V8 Input from Technology Validation: Final report on infrastructure, including impact of hydrogen quality for second generation vehicles.
V2 Input from Technology Validation: Final report for first generation vehicles and interim progress report for second generation vehicles, on performance, safety, and O&M.
V3 Input from Technology Validation: Technology Status Report & re-focused R&D recommendations.
V9 Input from Technology Validation: Final report on safety and O&M of three refueling stations.
V11 Input from Technology Validation: Composite results of analyses & modeling from vehicle and infrastructure data collected under the learning demonstration project.
Sf7 Input from Safety: Final peer reviewed Best Practices Handbook.
V4 Input from Technology Validation: Final report for second generation vehicles on performance, safety, and O&M.
V5 Input from Technology Validation: Technology Status Report & re-focused R&D recommendations.
V12 Input from Technology Validation: Final composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.

6.0 Program Management and Operations



The DOE Hydrogen Program is comprised of activities within the Offices of Energy Efficiency and Renewable Energy (EERE); Fossil Energy (FE); Nuclear Energy, Science and Technology (NE); and Science (SC). EERE's Hydrogen, Fuel Cells & Infrastructure Technologies Program represents a major component of this effort. Each office manages those activities within its mission area, but because of the complexity involved in transitioning to a hydrogen-based economy, the DOE Hydrogen Program is being managed through a single Program Manager located within EERE. This allows for clear lines of communication and authority, and integrates the many participating offices, agencies, laboratories, and contractors.

DOE's Hydrogen Program includes RD&D, systems integration, safety, codes and standards, and education activities, requiring the integrated efforts of Washington, D.C. offices, field offices, laboratories, and contractors spread across the country. Thousands of individuals will take part in the Program through partnerships with automotive and power equipment manufacturers, energy and chemical companies, electric and natural gas utilities, building designers, diverse component suppliers, other federal agencies, state government agencies, universities, national laboratories, and other stakeholder organizations. This complexity requires a Program management and operations approach based on a uniform set of requirements, assumptions, expectations, and procedures.

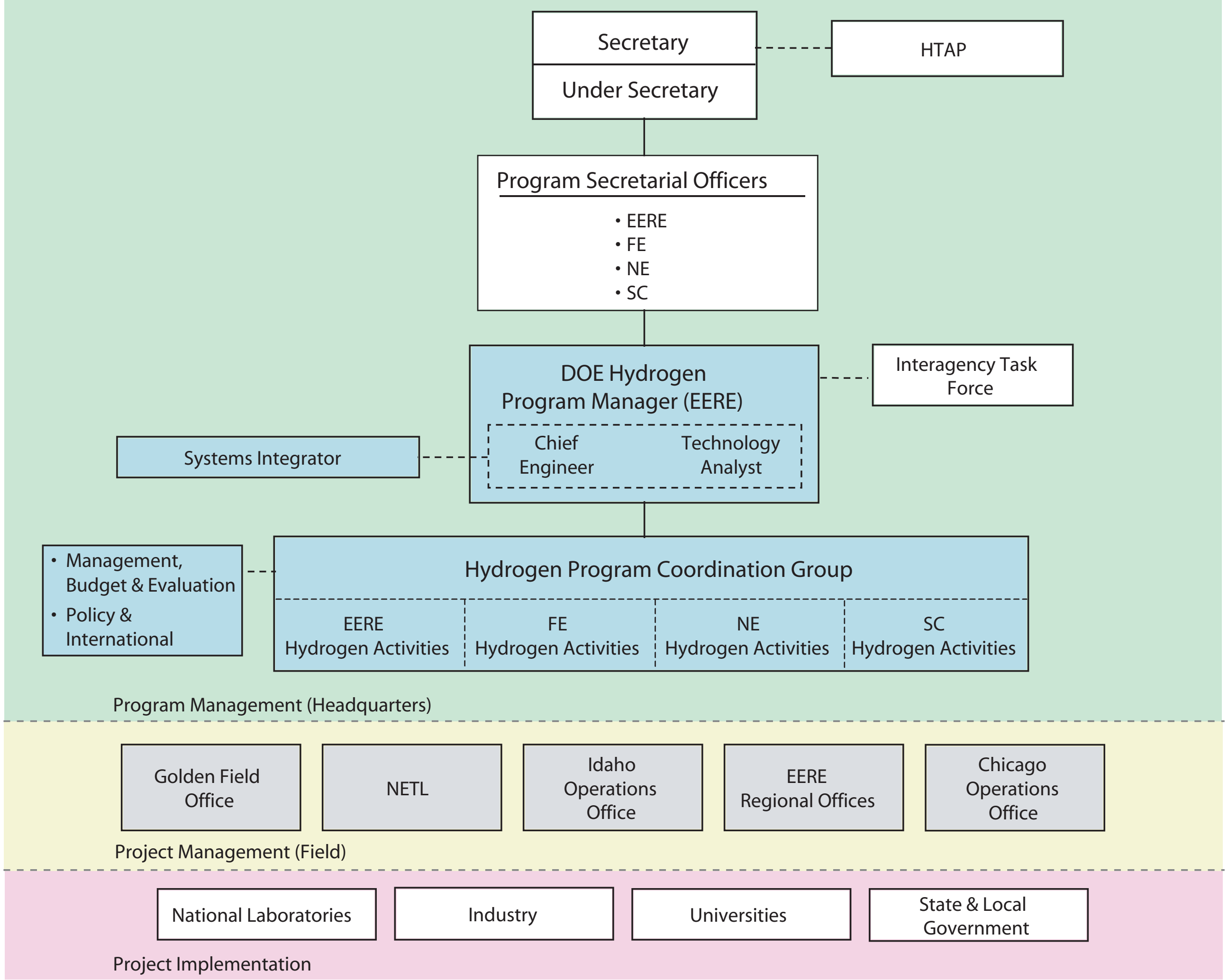
6.1 Program Organization

The organizational structure of the DOE Hydrogen Program is shown in Figure 6.1.1. Program management takes place at DOE Headquarters in Washington, D.C. Project management is conducted in field locations, namely the Golden Field Office, EERE Regional Offices, the National Energy Technology Laboratory (NETL), Idaho Operations Office, and the Chicago Operations Office. Project implementation is carried out at the national laboratories, with industry and universities, and through coalitions with state and local government agencies.

The management approach is grounded in the following results-oriented management principles:

- A vertical organization with clear lines of responsibility and authority
- Top-down Program (to project) planning from conception to technology validation, and time-phased technical, cost and schedule baselines
- Centralization of key functions to ensure effective integration of the Program's projects
- Independent Program control systems ensuring maximum visibility/transparency

Figure 6.1.1. DOE Hydrogen Program Organization Chart



Advisory Groups

The DOE Hydrogen Program utilizes outside experts to advise management on all aspects of the transition to the hydrogen economy. The Program draws upon the best available information from experts in a variety of fields such as chemistry and chemical engineering, materials science, environmental sciences, biology, physics, mechanical engineering, and systems engineering. Since the creation of the DOE Hydrogen Program, a variety of groups have been identified or created to oversee, review, or advise Program activities. Two examples of DOE Hydrogen Program advisory groups include:

National Academies. At DOE's request, the National Academies' National Research Council and the National Academy of Engineering appointed a committee in September 2002 to conduct a study of Alternatives and Strategies for Future Hydrogen Production and Use. The study evaluated the cost and status of technologies for production, delivery, storage and end-use of hydrogen, and reviewed DOE's hydrogen research, development and demonstration strategy. The final report is available at http://books.nap.edu/books/0309091632/html/index.html. In addition, the National Academies have been asked by DOE to do periodic assessments of the Program.

Hydrogen Technical Advisory Panel (HTAP). Legislation called for the establishment of HTAP to advise the Secretary of Energy on DOE's Hydrogen Program activities. HTAP is comprised of between 12 and 25 members. The Secretary appoints members to represent domestic industry, academia, professional societies, government agencies, and financial, environmental, and other appropriate organizations to provide the range of technical expertise and other experience required.

HTAP reviews and makes recommendations to the Secretary in a biennial report on:
- The implementation and conduct of programs and activities
- The safety, economical, environmental and other consequences of technologies for the production, distribution, delivery, storage and use of hydrogen
- Means for resolving barriers to implementing hydrogen and fuel cell technologies

The Secretary considers, but is not required to adopt, any recommendations of HTAP. The Secretary either describes the implementation of each recommendation made in the biennial report, or provides an explanation to Congress of the reasons that a recommendation is not to be implemented. The Secretary also provides the resources necessary for HTAP to carry out its responsibilities.

Public-Private Partnerships

Through cooperative partnerships, the DOE Hydrogen Program is leveraging the vast capabilities and experience of stakeholders in industry, state and local governments, and international organizations. The roles of these groups vary, as does the nature of their collaboration with DOE. In broad terms, the roles that these stakeholder groups play are:

- **State and Local Governments.** Partnerships in codes and standards, field validation and education
- **Industry.** Partnerships in developing, validating and demonstrating advanced fuel cell and hydrogen energy technologies
- **International**. Partnerships in R&D, validation, codes and standards and safety

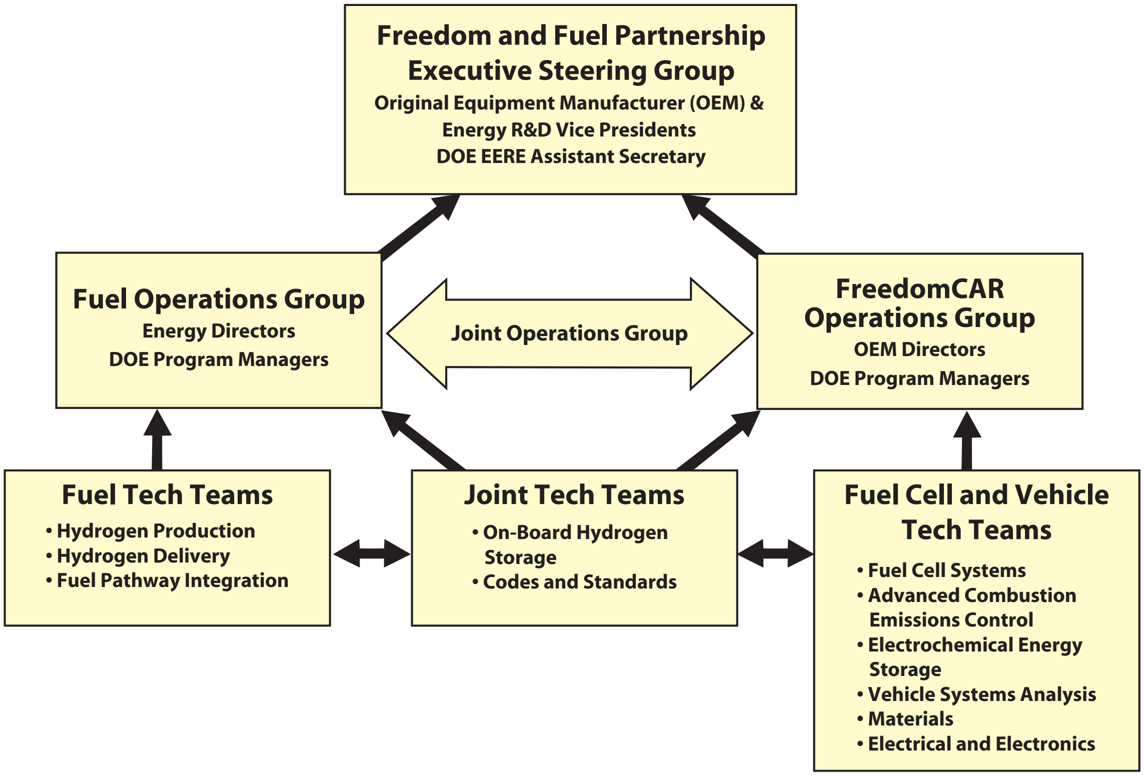
State and Local Governments. The California Fuel Cell Partnership is a unique collaboration of auto manufacturers, energy companies, fuel cell technology companies and government agencies that is placing fuel cell vehicles on the roads in California. This partnership is showcasing new vehicle technology that could move the world toward practical and affordable environmental solutions. The other government partners include the California Air Resources Board, the California Energy Commission, the South Coast Air Quality Management District, DOT and EPA.

The state and local partnerships that take place through the Regional Offices are the primary vehicle through which DOE meets the needs of individual citizens, cities, counties and states across the nation. The Program will coordinate with the Regional Offices to:
- Work with states and communities to promote the Program
- Identify and engage community and state partners
- Integrate the Program with public and private sector activities

Industry. The FreedomCAR and Fuel Partnership includes the Department of Energy, USCAR and five energy companies to develop the technologies and the infrastructure for hydrogen fuel cell vehicles to emerge in the transportation sector. The Executive Steering Group (ESG) provides governance and management of the Partnership (see Figure 6.1.2). The ESG is comprised of the DOE Assistant Secretary for EERE and a senior executive responsible for R&D from each of the partnership member companies.

The Operations Groups are responsible for operations oversight of partnership activities and serve as primary information channels to the ESG. Both operations groups include the DOE Program Managers for the Hydrogen, Fuel Cells & Infrastructure Technologies Program and the FreedomCAR and Vehicle Technologies Program. The FreedomCAR Operations Group also includes the senior technical managers from the automotive companies, while the Fuel Operations Group includes senior level technical directors from energy companies. The operations groups are responsible for identifying and managing their respective technical teams.

Figure 6.1.2. FreedomCAR and Fuel Partnership Executive Steering Group



The technical teams consist of scientists and engineers with technology-specific expertise from the automotive and energy partner companies, DOE, the national laboratories, and other sources on an as-needed basis such as the supplier community and other government agencies. The primary purpose of the technical teams is to identify and recommend comprehensive technical goals and evaluate progress and the achievement of technical milestones. Each of the partners will consider the information developed by the technical teams in implementing its respective R&D programs.

Coordination

Interagency Task Force. The Hydrogen Research and Development (R&D) Interagency Task Force was established shortly after the President's announcement of the Hydrogen Fuel Initiative in early 2003. It serves as the key mechanism for collaboration among the eight federal agencies that fund hydrogen-related research and development. The task force has developed an extensive hydrogen research taxonomy of past, present and potential future hydrogen activities of the federal government; provided guidance for agency research directions; identified key areas for interagency collaboration; and established subgroups to develop and implement a 10-year Interagency Coordination Plan. The subgroups coordinate focused efforts in three areas:

- Fundamental Research (led by DOE's Office of Science)
- Hydrogen Production, Distribution and Storage Technologies (led by DOE's Office of Energy Efficiency and Renewable Energy)
- Hydrogen Conversion Technologies (led by the U.S. Department of Commerce's National Institute of Standards and Technology).

The task force is co-chaired by the White House Office of Science and Technology Policy (OSTP) and the Department of Energy (DOE), and includes the Department of Transportation; Department of Defense; Department of Agriculture; Department of Commerce; Environmental Protection Agency; National Aeronautics and Space Administration; National Science Foundation; and, from the Executive Office of the President, OSTP, Office of Management and Budget, and Council on Environmental Quality.

International. On April 23, 2003, Secretary Abraham called for an "International Partnership for the Hydrogen Economy." As a result of the Secretary's vision, efforts have been initiated with 15 countries and the European Commission in the areas of codes and standards, PEM fuel cells, hydrogen production, hydrogen storage, and economic modeling.

The Secretary's call for an international partnership builds on the efforts of the last several years in which DOE has coordinated international activities to advance hydrogen and fuel cell technologies. DOE is taking a leadership role in the International Energy Agency Hydrogen Implementing Agreement and Advanced Fuel Cell Implementing Agreement (see Table 6.1.1).

Table 6.1.1. International Energy Agency Hydrogen and Advanced Fuel Cell Implementing Agreement Tasks

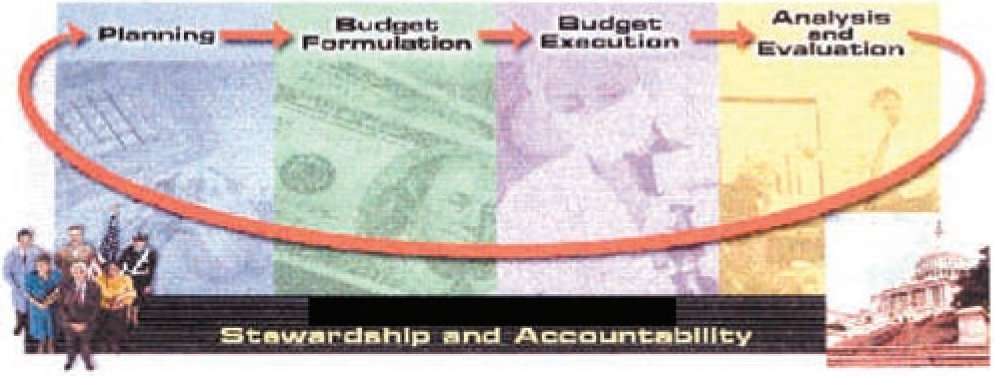
Hydrogen	Fuel Cells
• Photobiological Production • Hydrogen from Carbon-Containing Materials • Solid and Liquid State Storage • Integrated Systems Evaluation • Hydrogen Safety • Water Photolysis	• Polymer Electrolyte Fuel Cells • MCFC Towards Demonstration • Solid Oxide Fuel Cells • Fuel Cells for Stationary Applications • Fuel Cell Systems for Transportation • Fuel Cells for Portable Applications

In addition, the Program is working with international groups, such as the ICC and the ISO to develop a comprehensive set of codes and standards, which will facilitate the global demonstration and commercialization of hydrogen and fuel cell technologies.

6.2 Program Management Approach

The overall management of the DOE Hydrogen Program consists of a performance-based planning, budgeting, execution, and evaluation system as shown in Figure 6.2.1.

Figure 6.2.1. The Four Phases of Program Management



Program Planning

The National Energy Policy and the President's Hydrogen Fuel Initiative provide the planning foundation for the DOE Hydrogen Program. The Program integrates the hydrogen planning in EERE, SC, FE, and NE. Each year, these offices will collaborate to integrate each office's fiscal year planning and budgeting into the DOE Hydrogen Posture Plan, which will reflect the prior year's appropriations and the budget requested of Congress in the upcoming fiscal year. Individual office research plans supporting the Posture Plan will be provided to the DOE Hydrogen Program Manager for concurrence to ensure consistency in planning.

Program Budgeting

The budget for DOE's Hydrogen Program falls under the jurisdiction of two separate Congressional appropriations subcommittees. The key activities by DOE office are shown in Table 6.2.2.

Budget Execution

Table 6.2.2. DOE Hydrogen Program Key Activities by Budget Appropriation

Energy and Water Development	Interior and Related Agencies
• EERE – Hydrogen Technology ○ Hydrogen Production and Delivery ○ Hydrogen Storage ○ Hydrogen Infrastructure Validation** ○ Safety, Codes and Standards ○ Systems Analysis and Education • Office of Nuclear Energy, Science and Technology – Generation IV Nuclear Systems Initiative* – Nuclear Hydrogen Initiative • Office of Science – Chemical Science, Geoscience, and Energy Science – Materials Science and Engineering	• EERE – Fuel Cell Technology – Transportation Systems – Distributed Generation Systems – Fuel Processing – Stack Components – Technology Validation** – Technical/Program Support • Office of Fossil Energy – Fuels, Hydrogen from Coal – Carbon Sequestration* – Pipeline Infrastructure*

* The appropriations indicated by an asterisk support the President's Hydrogen Initiative, but are not directly a part of it, and would be funded even without it.

** Resources appropriated in Infrastructure Validation under the Hydrogen Technology subprogram and Technology Validation under the Fuel Cell Technology subprogram are planned, executed and evaluated as one project.

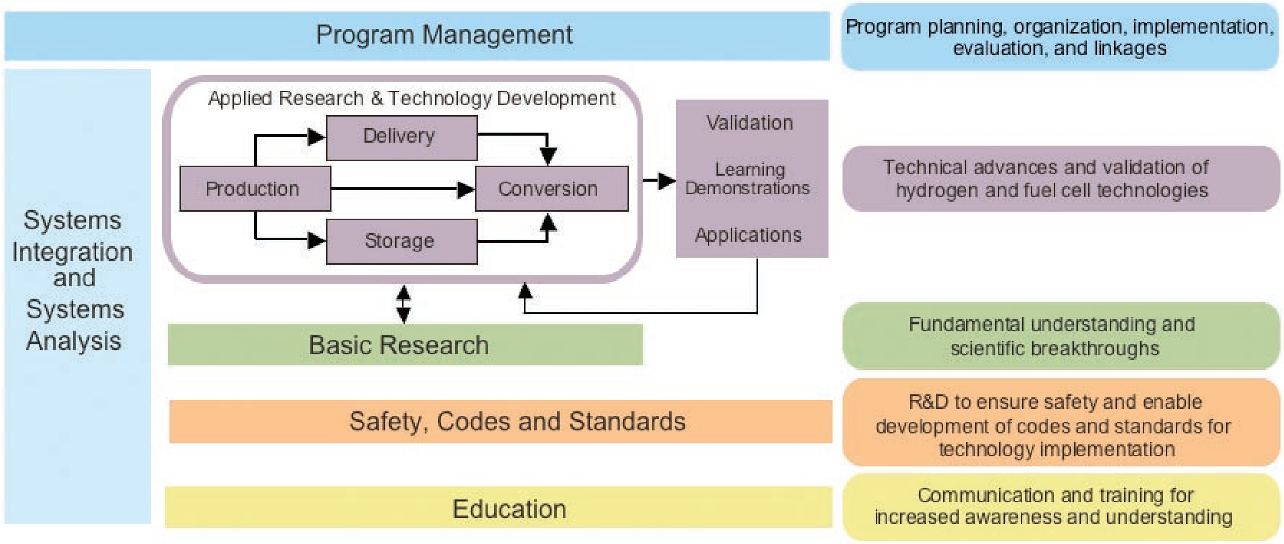
Analysis and Evaluation

Program budget performance is regularly evaluated by OMB, in consultation with the Office of Science and Technology Policy. The OMB evaluation includes both the OMB R&D Investment Criteria and the OMB Program Assessment Rating Tool (PART) process. The criteria are used to guide Program budget planning, management review, and performance goals and targets. Each year, the Program reports the current status against pre-established Program goals. In addition, projects are evaluated through the Program's Annual Merit Review and Peer Evaluation, and through FreedomCar and Fuel Partnership Tech Team review.

6.3 Program Elements

Achieving the hydrogen economy will require successfully addressing technical RD&D challenges including lowering the cost of hydrogen production, delivery, storage, conversion (e.g., fuel cells), and end-use applications; establishing effective codes and equipment standards to address safety issues; and instituting outreach and education campaigns to raise awareness, accelerate technology transfer, and increase public understanding of hydrogen energy systems. To ensure the success of the hydrogen economy, DOE's Hydrogen Program has identified the Program elements that are shown in Figure 6.3.1. The complex interdependencies of these elements and technology options need to be understood and their interfaces managed to achieve overall Program objectives. Consequently, as research provides new insights and as markets and policies evolve, the Program will continuously reexamine its understanding of hydrogen system developments and refine Program elements accordingly (the role of the Systems Integration function). To provide this research feedback loop effectively, it is essential that a continuum of basic and applied research, technology development, and learning demonstrations constitute the Program's portfolio.

Figure 6.3.1. DOE's Hydrogen Program Elements



6.4 Program Implementation

The implementation strategy for the DOE Hydrogen Program has three functions:

- **Linking the RD&D and Education Efforts to Policies, Requirements, and the Process for Selecting Options.** The development of an implementation strategy ensures that activities and procedures are consistent with the rationale and analysis underlying the Program.
- **Organizing the Program.** The implementation strategy includes an organizational structure, procedures, budget and schedule for carrying out the Program, and ensures the clear assignment of responsibility and accountability.
- **Managing and Monitoring the Program.** The implementation strategy includes monitoring the Program so that technological, cost, and scheduling issues can be addressed when they arise.

To carry out these functions, the DOE Hydrogen Program implementation strategy consists of the following components:

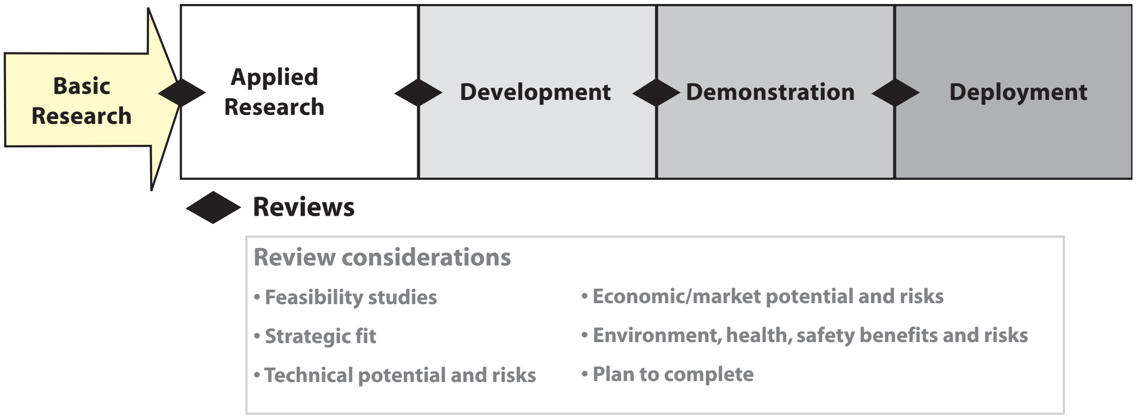
- Program Management Approach
- Organization Plan
- Acquisition Strategy
- Technical Management Strategy
- Safety, Quality Assurance, Environmental Compliance and Security Strategies
- Program Schedule, Cost and Staffing Plan

6.5 Decision Making

A systematic decision process based on sound analytics and technical evaluation standards will provide a credible and transparent basis for key Program decisions. A modified Stage-Gate™[1] process will be used to manage investments in development projects. The Stage-Gate™ process (represented conceptually in Figure 6.5.1) is a disciplined approach for evaluating projects at key points (gates). For the DOE Hydrogen Program, this decision framework will account for evolving markets and government policies.

At the beginning of each stage is a gate, or a Go/No-Go decision point, that must be passed before work on the next stage can begin. Reviews held at these key stages ensure that a project has met its objectives and that the plan for proceeding will satisfy the criteria for the next gate. Reviewers may include individuals from the government, national laboratories and the private sector.

Figure 6.5.1. Stage-Gate™ Decision Process



---

[1] Professor Robert Cooper of McMaster University, Ontario, Canada has written and consulted extensively on this process and has trademarked the term.

The general types of criteria used at each stage are shown in the figure, with the specific criteria becoming more rigorous as the project advances toward commercialization. At each gate, decisions are made to either:

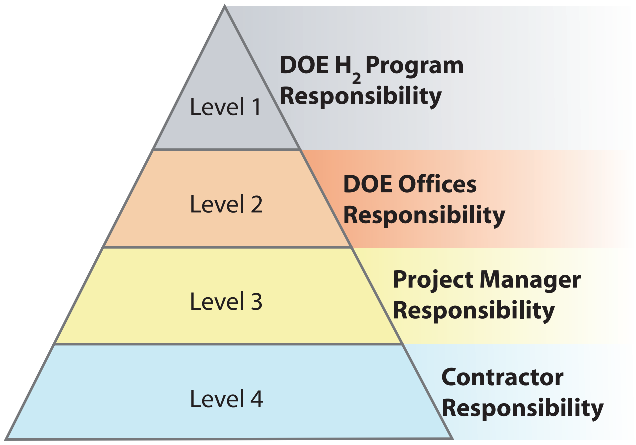
- Advance the project to the next stage
- Continue the current effort because not all goals have been met
- Place the project on hold because the need appears to have gone away, but could re-emerge
- Stop the project because it is unlikely to meet its goals or the need for the effort has permanently disappeared

Each of the gate reviews is conducted in the context of changing external conditions, with consideration of new knowledge and insights that are gained within the Program, and with a focus on the impact of decisions on overall Program outcomes.

6.6 Program Schedule

The schedules and milestones supporting the DOE Hydrogen Program are divided into a multi-tier hierarchical structure consisting of the Program master schedule, Program summary schedules, project intermediate schedules, and project detailed schedules. This structure, shown in Figure 6.6.1, provides the framework for vertical and horizontal integration among organizations, participants, and technologies.

Figure 6.6.1. DOE Hydrogen Program Schedule Hierarchy



At this time, all of the schedules and milestones are based on available cost estimates and projected budget appropriations. Because most of the first phase of the Program (through 2015) focuses on RD&D, it is not currently known which technologies will be winners or losers, and therefore schedules and budgets will be continually adjusting to accommodate the results of Program activities.

6.7 Program Control

To ensure that the DOE Hydrogen Program remains on schedule and within cost, a Program control system is being instituted with the following objectives:

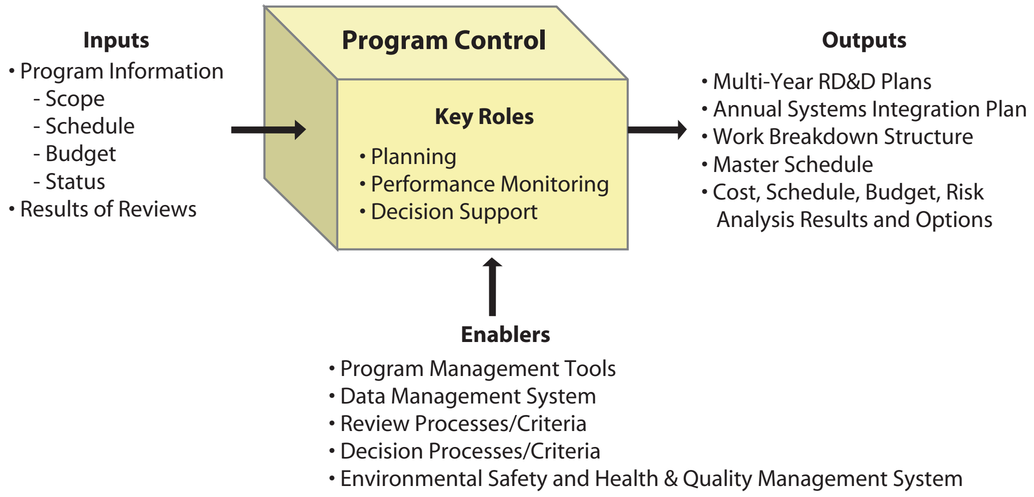
- Provide assurance that all work has been planned and considered in developing the Program cost and schedule baselines
- Identify the necessary procedures and organizational measures required for effective, timely management of the effort
- Ensure that these measures are implemented and that the resulting information accurately reflects the status of the Program
- Establish a review and decision-making process that addresses Program dynamics

Under the Program control system, integrated cost, schedule, and supporting baselines are developed. The performance of the DOE Hydrogen Program offices and supporting organizations (contractors, national laboratories, etc.) in completing tasks is measured against these baselines and reported to their organizations, so that action can be taken if baselines and actual performance diverge significantly.

Responsibilities for Program Control Implementation. The Chief Engineer is responsible for Program control. The Systems Integrator—in support of the Chief Engineer—gathers, integrates, and analyzes information on the scope, schedule, and budget of elements. Element plans and schedules are integrated into a Program plan, work breakdown structure, and master schedule. Together these plans comprise the programmatic baseline that is associated with a specific version of the technical baseline. The Systems Integrator analyzes this information to ensure that all technical requirements are addressed and consistent, and to identify critical-paths, milestones, and decision points. The Systems Integrator provides tools and information to support DOE in monitoring performance against schedule and budget and in identifying risk.

Implementation of Program Control. Figure 6.7.1 provides an overview of the DOE Hydrogen Program's Program control process. The primary inputs to Program control include the integrated baseline (see Section 5), budget guidance, and results of prior Program reviews.

Figure 6.7.1. Program Control Process



Inputs
- Program Information
  - Scope
  - Schedule
  - Budget
  - Status
- Results of Reviews

Program Control

Key Roles
- Planning
- Performance Monitoring
- Decision Support

Outputs
- Multi-Year RD&D Plans
- Annual Systems Integration Plan
- Work Breakdown Structure
- Master Schedule
- Cost, Schedule, Budget, Risk Analysis Results and Options

Enablers
- Program Management Tools
- Data Management System
- Review Processes/Criteria
- Decision Processes/Criteria
- Environmental Safety and Health & Quality Management System

Appendix A – Budgetary Information

The schedule for completing the milestones and achieving the targets and R&D priorities outlined in this plan is based on expected funding levels, the current stage of development of different technologies, and the perceived difficulty in attaining the targets. Deviation from the expected funding levels may alter the schedule for completion of the tasks and milestones. For example, if funding falls short of expected levels, the target dates for completion of certain milestones may be extended to later dates. If additional funding is made available over the expected amount, the rate of technology development could be accelerated in key research areas.

Funding Profile:

The funding profile for the Hydrogen, Fuel Cells & Infrastructure Technologies Program is shown in Table A.1. Consistent with the National Energy Policy, there has been a steady increase in funding from FY 2001 through FY 2005. To reach its targets, the Hydrogen, Fuel Cells & Infrastructure Technologies Program expects funding to be provided at the level projected within internal DOE planning documents. If funding deviates from these projections, priorities have been established to reallocate funds.

Table A.1. Fiscal Year Funding (2003-2005)[1] (Millions of Dollars)

Major Activity	FY 2003	FY 2004		FY 2005	
	Funding	Request	Funding	Request	Funding
Hydrogen Technology					
Hydrogen Production & Delivery	6.4	23.0	10.3	25.3	14.4
Hydrogen Storage	10.8	30.0	14.0	30.0	23.8
Infrastructure Validation	3.0	13.2	5.9	15.0	9.6
Safety, Codes & Standards, Utilization	2.6	16.0	5.9	18.0	6.1
Education and Cross-cutting Analysis	1.9	5.8	3.9	7.0	3.4[2]
Congressionally-directed Projects	13.4	--	42.0	--	37.3
Subtotal, Hydrogen Technology	**38.1[3]**	**88.0**	**82.0[3]**	**95.3**	**94.6[3]**
Fuel Cell Technology					
Transportation Systems	6.1	7.6	7.5	7.6	7.5
Distributed Energy Systems	7.3	7.5	7.4	7.5	6.9
Fuel Processing	23.5	19.0	14.8	13.9	9.7
Stack Components	14.8	28.0	25.2	30.0	32.5
Technology Validation	1.8	15.0	9.9	18.0	17.8
Technical and Program Support	0.4	0.4	0.4	0.5	0.5
Subtotal, Fuel Cell Technology	**53.9**	**77.5**	**65.2**	**77.5**	**74.9**
TOTAL, Hydrogen and Fuel Cells	**92.0[3]**	**165.5**	**147.2[3]**	**172.8**	**169.5[3]**

[1] Funding for EERE only. Does not reflect other participants in the Hydrogen Fuel Initiative (FE, NE, SC, DOT).
[2] Funding for Education activities was not appropriated in FY 2005.
[3] The amount appropriated by Congress; distribution among key activities (production, storage, etc.) is determined by DOE based on Program priorities.

Appendix B – Milestones

Table B.1. Hydrogen Production

Task	Milestone	Description	Date (FY)
1	*1*	Down-select research for distributed natural gas-to-hydrogen production.	3Q, 2006
1	*2*	Select advanced shift catalysts that are more efficient and impurity tolerant.	4Q, 2007
1	*3*	Verify feasibility of achieving $1.50/gge (delivered) from distributed natural gas.	4Q, 2010
2	*4*	Verify feasibility of achieving $3.60/gge for renewable liquids distributed reforming.	4Q, 2010
2	*5*	Down-select research for distributed production from bio-derived renewable liquid fuels.	4Q, 2012
3	*6*	Go/No-Go: Decision on continued high-temperature steam electrolysis R&D based on a complete technoeconomic analysis and laboratory-scale research results.	2Q, 2007
3	*7*	Verify feasibility of achieving $2.85/gge (delivered) from electrolysis.	4Q, 2010
4	*8*	Go/No-Go: Determine if membrane separation technology can be applied to natural gas distributed reforming during the transition to a hydrogen economy.	4Q, 2008
4	*9*	Down-select separation technology for development in distributed natural gas reforming.	4Q, 2008
4	*10*	Demonstrate pilot-scale use of integrated separation (membrane) reactor system for natural gas.	4Q, 2009
4	*11*	Down-select separation technology for distributed bio-derived renewable liquid feedstocks reforming.	4Q, 2010
4	*12*	Demonstrate pilot-scale use of integrated separation (membrane) reactor system for renewable feedstocks.	1Q, 2012
5	*13*	Down-select to a primary technology and configuration for biomass gasification/pyrolysis clean–up, reforming, shift, separation and purification.	4Q, 2008
5	*14*	Verify a projected cost for biomass gasification/pyrolysis of $1.75/gge at plant gate.	4Q, 2010
5	*15*	Down-select to 1-2 primary novel technologies for biomass gasification/pyrolysis clean up, reforming, shift, separation and purification.	4Q, 2010
6	*16*	Identify or generate an Fe-hydrogenase with a half-life of 5 min in air for photolytic hydrogen production.	4Q, 2008

6	17	Produce one cyanobacterial recombinant evolving H_2 through an O_2-tolerant NiFe-hydrogenase.	4Q, 2008
6	18	Increase the duration of H_2 production by immobilized, sulfur-deprived algal cultures to 40 days.	4Q, 2008
6	19	Complete research to develop a photosynthetically efficient green alga/ cyanobacterial system in which the P/R ratio is ≤ 2.	4Q, 2009
6	20	For photolytic hydrogen production, achieve 15% primary utilization efficiency of incident solar light energy (E0*E1), 2% efficiency of incident light energy to H_2 from water (E0*E1*E2), and 30 min (O_2 tolerant system) duration of continuous photoproduction.	4Q, 2010
6	21	Identify or generate an Fe-hydrogenase with a half life of 30 min in air for photolytic hydrogen production.	4Q, 2012
7	22	Go/No-Go: Identify cost-effective (based on analysis) transparent H_2 -impermeable material for use in photobiological H_2-production system.	4Q, 2010
8	23	Complete research to generate photosynthetic bacteria that have 50% smaller (compared to wild-type) Bchl antenna size and display increased sunlight conversion efficiency.	4Q, 2009
8	24	Complete research to engineer photosynthetic bacteria with a 30% expression level of a functional nitrogenase/hydrogenase at elevated nitrogen-carbon ratios (expression level is defined relative to that detected at low N:C ratios).	4Q, 2009
8,9,10	25	Complete research to inactivate competitive uptake of H_2 by hydrogenase.	4Q, 2009
8	26	For photosynthetic bacterial hydrogen production, achieve 3% efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, and 50% of maximum molar yield of carbon conversion to H_2 (depends on nature of organic substrate).	4Q, 2010
10	27	For dark fermentative hydrogen production, achieve 4 molar yield of H_2 production from glucose.	4Q, 2010
9	28	Complete research to determine the efficacy of green algae/ cyanobacteria and photosynthetic bacteria to metabolize carbon substrates ($C \leq 4$) and produce H_2 in co-cultivation.	4Q, 2009
13,14,15	29	Update technoeconomic analysis on the projected technology.	3Q, 2006
13	30	Complete structure and initial data population of a photoelectrochemical materials database.	4Q, 2006
13	31	Establish standard cell and testing protocols for PEC materials for validation efficiencies.	4Q, 2006
13	32	Install testing laboratory for the standard cell and testing protocol for PEC materials.	4Q, 2007
13,14,15	33	Update technoeconomic analysis on the projected technology.	4Q, 2010

13,14,15	**34**	Identify materials/systems with a 2.3 eV useable semiconductor bandgap, 8% plant solar-to-hydrogen efficiency, and projected durability of 1,000 hours.	4Q, 2010
13,14,15	**35**	Build a consensus, lab-scale PEC panel based on best available 2010 technology to validate technoeconomic analysis.	4Q, 2012
15	**36**	Go/No-Go: Identify cost-effective (based on analysis) transparent hydrogen-impermeable material for use in photoelectrochemical hydrogen production system.	4Q, 2010
16	**37**	Down-select to 2-4 promising high temperature solar driven thermochemical cylcles for R&D based on analysis and initial laboratory work of potential cycles.	4Q, 2007
16	**38**	Go/No-Go: Verify the feasibility of an effective integrated high-temperature solar-driven thermochemical cycle for hydrogen projected to meet the 2010 cost goal of $6/gge.	4Q, 2010
16	**39**	Verify the successful continuous operation of a promising integrated high temperature solar-driven thermochemical cycle at a scale of >10 kg/hr. of hydrogen production.	4Q, 2012
16	**40**	Down-select to 1-2 promising high-temperature solar-driven thermochemical cycles for development..	4Q, 2012
Milestones Beyond 2012			
6		Complete research to develop a photosynthetically efficient green alga/ cyanobacterial system in which the P/R ratio is ~ 1.	4Q, 2014
6		Demonstrate H_2 production in air in a cyanobacterial recombinant.	4Q, 2015
6,7,12		Go/No-Go: For photolytic hydrogen production, achieve 20% primary utilization efficiency of incident solar light energy (E0*E1), 5% efficiency of incident light energy to H_2 from water (E0*E1*E2), 4 h (O_2 tolerant) duration of continuous photoproduction, and 2 h O_2 tolerance (half≠ life in air) at a projected hydrogen production cost of less than $4/kg, with projected research improvements that will achieve costs that are competitive with traditional fuels for transportation applications and with other non-biological technologies for central hydrogen production.	4Q, 2015
8		Complete research to generate photosynthetic bacteria that have 70% smaller (compared to wild-type) Bchl antenna size and display increased sunlight conversion efficiency.	4Q, 2014
8		Complete research to engineer photosynthetic bacteria with a 60% expression level of a functional nitrogenase/hydrogenase at elevated nitrogen-carbon ratios (expression level is defined relative to that at low N:C ratios).	4Q, 2014
8		Complete research to inactivate the photosynthetic bacterial metabolic pathway leading to polymer accumulation that competes with H_2 production.	4Q, 2014

8,9,12		Go/No-Go: For photosynthetic bacterial hydrogen production, achieve 4.5% efficiency of incident solar light energy to H_2 (E0*E1*E2) from organic acids, and 65% of maximum molar yield of carbon conversion to H_2 (depends on nature of organic substrate) at a projected hydrogen production cost of less than $4/kg, with projected research improvements that will achieve costs that are competitive with traditional fuels for transportation applications and with other non-biological technologies for central hydrogen production.	4Q, 2015
10,11,12		Go/No-Go: For dark fermentative hydrogen production, achieve 6 molar yield of H_2 production from glucose at a projected hydrogen production cost of less than $4/kg, with projected research improvements that will achieve costs that are competitive with traditional fuels for transportation applications and with other non-biological technologies for central hydrogen production.	4Q, 2015
12		Complete research to regulate growth/competition between different organisms in co-cultivation (e.g., to maintain optimal Chl/Bchl ratios).	4Q, 2014
12		Complete research to identify cell-growth inhibitors and eliminate transfer of such compounds from bacterial fermentors to photoreactors.	4Q, 2014
13,14,15		Go/No-Go: Identify materials/systems with 12% chemical conversion process efficiency, 10% plant solar-to-hydrogen efficiency, projected durability of 5,000 hours and cost of hydrogen of $50/gge.	4Q, 2015
Outputs			
1	***P1***	Output to Fuel Cells and Technology Validation: Hydrogen production technology for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2005
1,2,3,4,5	***P2***	Output to Delivery, Storage and Fuel Cells: Assessment of fuel contaminant composition.	4Q, 2006
1,2,3	***P3***	Output to Systems Analysis and Systems Integration: Impact of hydrogen purity on cost and performance.	3Q, 2007
1	***P4***	Output to Fuel Cells and Technology Validation: Hydrogen production technology for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2007
1,2,3	***P5***	Output to Systems Analysis and Systems Integration: Impact of hydrogen purity on cost and performance.	4Q, 2009

2,3,4,5	***P6***	Output to Delivery, Storage and Fuel Cells: Assessment of fuel contaminant composition.	4Q, 2009
1	***P7***	Output to Fuel Cells and Technology Validation: Hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2010
3	***P8***	Output to Technology Validation: Down-select of high-temperature electrolysis technology based on research results.	2Q, 2007
3	***P9***	Output to Technology Validation: Electrolysis system making hydrogen for $2.85/gge delivered.	4Q, 2010
5	***P10***	Output to Technology Validation: Hydrogen production system making hydrogen for $1.90/gge from biomass at the plant gate.	4Q, 2005
Inputs			
1,2,3	***C3***	Input from Codes and Standards: Preliminary assessment of Safety, Codes and Standards requirements for the hydrogen delivery infrastructure.	2Q, 2005
1,2,3	***Sf3***	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2005
1,2,3	***C5***	Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
1,2,3,5	***A1***	Input from Systems Analysis: Complete technoeconomic analysis on production and delivery technologies currently being researched to meet overall program hydrogen fuel objective.	4Q, 2006
1,2	***F2***	Input from Fuel Cells: Research results of advanced reformer development.	4Q, 2007
1,2,3	***V9***	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007
1,2,3,5	***A2***	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008
1,2,3,5	***C12***	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010
1,2,3	***Sf5***	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2010

Table B.2. Hydrogen Delivery

Milestones

Task	Milestone	Description	Date (FY)
1	1	Characterize the current cost and energy efficiency of the components and complete pathways for gaseous and liquid hydrogen delivery and the cost boundaries of potential novel solid and liquid carrier systems.	4Q, 2005
1	2	Identify cost-effective options for hydrogen delivery infrastructure to support the introduction and long-term use of hydrogen for transportation and stationary power.	4Q, 2006
2	3	Down select to 2-3 most promising compression technologies for hydrogen transmission, refueling, and other needs in delivery.	4Q, 2008
2	4	Verify 2010 targeted costs and performance for hydrogen compression (transmission and forecourt).	4Q, 2010
2,5,6	5	Verify achieving a refueling station cost contribution for compression, storage and dispensing of $0.80/gge of hydrogen.	4Q, 2010
3	6	Down-select to most promising 1-2 liquefaction technologies.	4Q, 2008
3	7	Verify 2010 targeted cost and performance for hydrogen liquefaction.	4Q, 2010
4	8	Research identifies fundamental mechanism of hydrogen embrittlement and permeation in steel pipelines and identifies promising cost effective measures to mitigate these issues.	4Q, 2007
4	9	Down-select on materials and/or coatings for pipelines including the potential use of natural gas pipelines for mixtures of natural gas and hydrogen, or hydrogen alone.	4Q, 2008
4	10	Verify 2010 targeted cost and performance for hydrogen pipelines.	4Q, 2010
5	11	Go/No-Go: Initial down-select for potential solid or liquid carrier systems for hydrogen delivery based on cost boundary analysis and initial research efforts.	4Q, 2007
5	12	Go/No-Go: Verify the feasibility of a hydrogen carrier system to meet the 2010 carrier targets.	4Q, 2010
6	13	Complete baseline analyses of off-board storage options at refueling stations and throughout the delivery infrastructure.	4Q, 2006
6	14	Complete the research to establish the feasibility and define the cost for geologic hydrogen storage.	4Q, 2010
6	15	Down-select to the most promising 1-2 technologies for off-board storage.	4Q, 2010
6	16	Verify the feasibility of achieving the 2010 refueling station storage cost targets.	4Q, 2010

Outputs			
1	***D1***	Output to Storage, Systems Analysis and Systems Integration: Assessment of cost and performance requirements for off-board storage systems.	4Q, 2006
1,2,3,4,5,6	***D2***	Output to Storage and Fuel Cells: Hydrogen contaminant composition and issues.	4Q, 2006
1	***D3***	Output to Technology Validation, Systems Analysis and Systems Integration: Hydrogen delivery infrastructure analysis results.	4Q, 2006
2,3,4,5,6	***D4***	Output to Systems Analysis and Systems Integration: Assessment of impact of hydrogen purity requirements on cost and performance of hydrogen delivery.	3Q, 2007
2	***D5***	Output to Technology Validation: Compression technology recommended for validation.	2Q, 2009
2,3,4,5,6	***D6***	Output to Systems Analysis and Systems Integration: Update of hydrogen purity/impurity requirements.	4Q, 2009
3	***D7***	Output to Technology Validation: Recommended liquefaction technology for potential validation.	2Q, 2009
4	***D8***	Output to Technology Validation: Recommended pipeline technology for validation.	2Q, 2009
6	***D9***	Output to Storage and Technology Validation: Recommended off-board storage technology for validation.	2Q, 2009
Inputs			
1,2,3,4,5,6	***C3***	Input from Codes and Standards: Preliminary assessment of Safety, Codes and Standards for the hydrogen delivery infrastructure.	2Q. 2005
1,2,5,6	***Sf3***	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2005
1,2,3,4,5,6	***C5***	Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
1,3,5,6	***C6***	Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.	3Q, 2006
1,2,5,6	***C8***	Input from Codes and Standards: Draft standards (balloting) for refueling stations (NFPA).	4Q, 2006
2,3,4,5,6	***A1***	Input from Systems Analysis: Selected production and delivery technologies identified to meet the program targets.	4Q, 2006
2,5,6	***C7***	Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).	4Q, 2006
2,3,4,5,6	***V9***	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007

2,3,4,5,6	**A2**	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008
2,3,4,5,6	**C11**	Input from Codes and Standards: Codes and Standards for the delivery infrastructure complete.	2Q, 2010
2,3,4,5,6	**C12**	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010
2,5,6	**Sf5**	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2010
4,5	**P2**	Input from Production: Assessment of fuel contaminant composition.	4Q, 2006
4,6	**C9**	Input from Codes and Standards: Materials compatibility technical reference	2Q, 2008
4,5	**P6**	Input from Production: Assessment of fuel contaminant composition.	4Q, 2009
5,6	**St4**	Input from Storage: Full-cycle integrated chemical hydrogen system meeting 2010 targets.	4Q, 2010
6	**St5**	Input from Hydrogen Storage: Baseline hydrogen on-board storage system analysis results including hydrogen quality and refueling interface needs.	1Q, 2007
6	**St6**	Input from Hydrogen Storage: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temperature, etc.) and down-select to a primary on-board storage system candidate.	1Q, 2010

Table B.3. Hydrogen Storage

Milestones

Task	Milestone	Description	Date (FY)
1	**1**	Complete feasibility study of hybrid tank concepts.	4Q, 2005
1	**2**	Go/No-Go: Decision on compressed and cryogenic tank technologies for on-board vehicular applications.	4Q, 2006
3	**3**	Complete construction of materials test facility.	4Q, 2004
3	**4**	Complete verification of test facility.	2Q, 2005
3	**5**	Reproducibly demonstrate 4wt% material capacity on carbon nanotubes.	4Q, 2005
3	**6**	Complete prototype complex hydride integrated system meeting 2005 targets.	2Q, 2006
3	**7**	Go/No-Go: Decision point on carbon nanotubes.	4Q, 2006

4	**8**	Down-select on-board reversible metal hydride materials.	4Q, 2007
4	**9**	Go/No-Go: Decision point on advanced carbon-based materials.	4Q, 2009
5	**10**	Complete prototype complex hydride integrated system meeting 2010 targets.	4Q, 2010
5	**11**	Go/No-Go: Decision on continuation of on-board reversible metal hydride R&D.	4Q, 2010
6	**12**	Complete preliminary estimates of efficiency for off-board regeneration.	1Q, 2006
7	**13**	Down-select from chemical hydrogen regeneration processes.	4Q, 2007
7	**14**	Demonstrate efficient chemical hydrogen regeneration laboratory process.	4Q, 2008
7	**15**	Complete chemical hydrogen storage life-cycle analyses.	1Q, 2009
7	**16**	Down-select from chemical hydrogen storage approaches for 2010 targets.	2Q, 2009
7	**17**	Complete prototype chemical hydrogen storage integrated system.	4Q, 2009
8	**18**	Demonstrate scaled-up chemical hydrogen regeneration process.	4Q, 2010
8	**19**	Identify advanced chemical hydrogen regeneration laboratory process with potential to meet 2015 targets.	4Q, 2010
8	**20**	Go/No-Go: Decision point on chemical storage R&D for 2015 targets.	4Q, 2010
10	**21**	Down-select from new material concepts to meet 2010 targets.	4Q, 2007
11	**22**	Down-select the most promising new material concepts for continued Development.	4Q, 2010
12	**23**	Complete baseline analyses of on-board storage options for 2010 targets.	4Q, 2006
12	**24**	Update on-board storage targets.	4Q, 2007
12	**25**	Complete analyses of on-board storage options for 2010 and 2015 targets.	4Q, 2009

Outputs			
1	St1	Output to Fuel Cells and Technology Validation: Compressed and cryogenic liquid storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.	3Q, 2006
2	St2	Output to Fuel Cells and Technology Validation: Advanced compressed/ cryogenic tank technologies.	4Q, 2009
3	St3	Output to Technology Validation and Fuel Cells: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.	3Q, 2006
8	St4	Output to Delivery, Technology Validation and Fuel Cells: Full-cycle, integrated chemical hydrogen system meeting 2010 targets.	4Q, 2010
12	St5	Output to Delivery, Systems Analysis and Systems Integration: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.	1Q, 2007
12	St6	Output to Delivery, Systems Analysis and Systems Integration: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc.) and down-select to a primary on-board storage system candidate.	1Q, 2010
Inputs			
12	Sf3	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2005
12	C4	Input from Codes and Standards: Standards for compressed gaseous on-board storage.	4Q, 2005
12	Sf4	Input from Safety: Safety requirements for on-board storage.	4Q, 2005
12	C5	Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
12	C6	Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.	3Q, 2006
12	P2	Input from Production: Assessment of fuel contaminant composition.	4Q, 2006
12	D1	Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.	4Q, 2006
12	D2	Input from Delivery: Hydrogen contaminant composition and issues.	4Q, 2006
12	C7	Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).	4Q, 2006
12	V9	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007
12	C9	Input from Codes and Standards: Materials compatibility technical Reference.	2Q, 2008
12	A2	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008

12	**D9**	Input from Delivery: Off-board storage technology.	2Q, 2009
12	**P6**	Input from Production: Assessment of fuel contaminant composition.	4Q, 2009
12	**C12**	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO standard.	2Q, 2010
12	**Sf5**	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2010

Table B.4. Fuel Cells

Milestones

Task	Milestone	Description	Date (FY)
1	**1**	Complete development and testing of low-cost, high-sensitivity sensors.	1Q, 2006
1	**2**	Go/No-Go: The status of sensors and controls technologies will be assessed and compared with the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.	1Q, 2006
2	**3**	Develop laboratory-scale physical and chemical sensors with improved response time and lower cost.	4Q, 2008
2	**4**	Develop physical and chemical sensors meeting 2010 targets.	4Q, 2010
3	**5**	Deliver model of FCV system.	4Q, 2003
3	**6**	Complete modeling of the availability and economics of platinum group metals.	1Q, 2004
3	**7**	Complete initial evaluation of 25-50-kW advanced integration, atmospheric gasoline reformed system.	1Q, 2005
3	**8**	Quantify fuel cell power system emissions.	2Q, 2005
3	**9**	Evaluate progress towards meeting FY2005 fuel cell cost target.	3Q, 2005
3	**10**	Complete analysis of overall and specific component costs for transportation fuel cell systems.	4Q, 2005
3	**11**	Evaluate progress towards meeting FY2010 fuel cell cost target.	3Q, 2006
3	**12**	Evaluate progress towards meeting FY2010 fuel cell cost target.	3Q, 2007
3	**13**	Evaluate progress towards meeting FY2010 fuel cell cost target.	3Q, 2008
3	**14**	Evaluate progress towards meeting FY2010 fuel cell cost target.	3Q, 2009
4	**15**	Complete development of heat rejection technologies (compact humidifiers, heat exchangers, and radiators).	1Q, 2006
4	**16**	Complete development and testing of low-cost, high-efficiency, lubrication-free compressors, expanders, blowers, motors, and motor controllers.	4Q, 2006

4	*17*	Go/No-Go: The status of air management and thermal management technologies will be assessed and compared to the established technical and cost targets. Based on the assessment and the degree of success, the technologies will be released for use, more development will be indicated, or effort will be terminated.	3Q, 2007
5	*18*	Complete development of compressor, expander motor, blower and motor controller meeting 2010 targets.	3Q, 2010
6	*19*	Identify main routes of DMFC performance degradation.	4Q, 2003
6	*20*	Go/No-Go: Decision to discontinue DMFC R&D for transportation applications.	4Q, 2003
6	*21*	Down-select design scenarios for vehicular fuel cell APUs for further study.	4Q, 2003
7	*22*	Complete evaluation of fuel cell system designs for APUs.	1Q, 2006
7	*23*	Complete design of filtration unit for off-road applications.	1Q, 2007
7	*24*	Evaluate 3-10 kW APU system towards meeting 80 W/kg and 80 W/L targets.	1Q, 2008
7	*25*	Evaluate 20-50 W portable power fuel cell system towards meeting 2006 targets.	2Q, 2008
7	*26*	Portable power fuel cell technology available for industry evaluation.	3Q, 2008
7	*27*	Go/No-Go: Decision on whether to continue auxiliary power, portable power and off-road R&D based on the progress towards meeting 2010	4Q, 2008
8	*28*	Complete testing on 50 kW stationary beta module system.	2Q, 2006
8	*29*	Complete economic analysis report.	4Q, 2006
8	*30*	Demonstrate prototype back up power system.	1Q, 2007
8	*31*	Complete 15,000 hour, stationary fuel cell system test.	3Q, 2007
9	*32*	Demonstrate the effective utilization of fuel cell thermal energy for heating to meet combined heat and power (CHP) efficiency targets.	1Q, 2008
9	*33*	Go/No-Go: Decision on whether to continue stationary fuel cell system based on progress towards meeting durability, cost and electrical efficiency simultaneously.	4Q, 2010
10	*34*	Demonstrate performance (600 mV at 400 mA/cm^2) of an ultra-thin membrane (< 75 μm) in an MEA under atmospheric conditions at 120°C in a 30-cm^2 cell.	3Q, 2003
10	*35*	Complete full-scale MEA evaluation in short stack.	4Q, 2006
11	*36*	Demonstrate fuel-flexible fuel processor meeting year 2005 targets for efficiency, power density and specific power. Measure start-up capability.	2Q, 2003

11	*37*	Verify quick-start concept in brass-board prototype system demonstrating capability to meet 2010 startup technical target..	4Q, 2003
11	*38*	Verify small scale, microchannel reformer.	4Q, 2003
11	*39*	Fabricate prototype ion transport membrane module.	1Q, 2004
11	*40*	Go/No-Go: Decision to discontinue fuel processing R&D.	3Q, 2004
12	*41*	Verify fuel processing subsystem performance for distributed generation towards meeting 2010 targets.	1Q, 2007
12	*42*	Absorption-enhanced natural gas reformer start-up/shut down cycle, transient and durability testing.	2Q, 2007
12	*43*	Develop base metal shift catalysts that enhance conversion to hydrogen and reduce conversion to methane (<1% methane).	2Q, 2008
12	*44*	Develop tolerance of reforming catalysts to fuel containing 1 ppm sulfur.	4Q, 2010
13	*45*	Evaluate 120°C membrane in MEA/single cell.	1Q, 2005
13	*46*	Evaluate 120°C MEA in <10 kW stack.	1Q, 2006
13	*47*	Demonstrate MEA in single cell meeting 2005 platinum loading and performance targets.	2Q, 2006
13	*48*	Evaluate first generation 150°C membrane in MEA/single cell.	1Q, 2007
14	*49*	Evaluate reproducibility (physical and performance) of full-size bipolar plates in high-rate manufacturing processes.	1Q, 2004
14	*50*	Evaluate reproducibility (physical and performance) of MEAs in high-rate manufacturing processes.	1Q, 2005
15	*51*	Initiate 2,000-hour test with advanced membrane & standard GDL.	4Q, 2005
15	*52*	Develop 120°C membrane for operation at < 25% RH.	1Q, 2007
15	*53*	Complete 2,000 hour durability test of advanced MEA for stationary fuel cell application.	3Q, 2007
15	*54*	Go/No-Go: Evaluate precious metal reclamation processes to determine whether to scale-up or terminate.	4Q, 2007
15	*55*	Develop technology for platinum group metal recycling.	4Q, 2008
15	*56*	Evaluate a MEA running on re-manufactured catalyst coated membranes.	4Q, 2008

17	*57*	Develop a method for cleaning sulfur-poisoned platinum catalyst layers in stacks, with minimum interruption of fuel cell operation.	1Q, 2007
17	*58*	Develop a method for cleaning sulfur- and nitrogen-oxide poisoned platinum catalyst layers in stacks, with minimum interruption of fuel cell operation.	1Q, 2010
Outputs			
3	*F1*	Output to Systems Analysis and System Integration: Develop a critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions, and cost.	2Q, 2003
12	*F2*	Output to Production: Research results of advanced reformer development.	4Q, 2007
15	*F3*	Output to Technology Validation: Laboratory PEM technology with 2,000 hours durability.	4Q, 2006
15	*F4*	Output to Technology Validation: Complete 4,000 hour testing of advanced MEA for stationary and transportation applications.	4Q, 2007
15	*F5*	Output to Technology Validation: Laboratory PEM technology with 5,000 hours durability.	2Q, 2010
16	*F6*	Output to Technology Validation: Verify cold-start in 60 s of short stack.	1Q, 2008
16	*F7*	Output to Technology Validation: Technology short stack survivability at-40°C.	1Q, 2010
17	*F8*	Output to Systems Analysis and Systems Integration: Develop preliminary hydrogen purity/impurity requirements.	2Q, 2005
17	*F9*	Output to Systems Analysis and Systems Integration: Updated hydrogen purity/impurity requirements.	3Q, 2007
Inputs			
3	*V1*	Input from Technology Validation: Validate maximum fuel cell system efficiency.	4Q, 2005
3	*V9*	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007
4	*St1*	Input from Storage: Compressed and cryogenic liquid storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.	3Q, 2006
4	*St3*	Input from Storage: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kW/L.	3Q, 2006
4	*St2*	Input from Storage: Advanced compressed/cryogenic tank technologies.	4Q, 2009
4	*St4*	Input from Storage: Full-cycle, integrated chemical hydride system meeting 2010 targets.	4Q, 2010
7	*C10*	Input from Codes and Standards: Final draft standard (balloting) for portable fuel cells (UL).	4Q, 2008
12	*P1*	Input from Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration, assuming 100s of units of production per year.	4Q, 2005

12	***P4***	Input from Production: Hydrogen production technologies for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2007
12	***P7***	Input from Production: Hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2010
16	***V6***	Input from Technology Validation: Validate cold start-up capability (in a vehicle with an 8-hour soak) meeting 2005 requirements (specific cold-start energy).	3Q, 2011
17	***C5***	Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
17	***P2***	Input from Production: Assessment of fuel contaminant composition.	4Q, 2006
17	***D2***	Input from Delivery: Hydrogen contaminant composition and issues.	4Q, 2006
17	***A2***	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008
17	***P6***	Input from Production: Assessment of fuel contaminant composition.	4Q, 2009
17	***C12***	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010

Table B.5. Technology Validation

Milestones

Task	Milestone	Description	Date (FY)
1,2	*1*	Make awards to start fuel cell vehicle/infrastructure demonstration activity and for hydrogen co-production infrastructure facilities.	4Q, 2004
1	*2*	Demonstrate FCVs that achieve 50% higher fuel economy than gasoline vehicles.	3Q, 2005
1	*3*	Demonstrate (on a vehicle) compressed and cryogenic storage tanks achieving the 2005 energy and mass density targets.	4Q, 2006
1	*4*	Go/No-Go: Decision for purchase of additional vehicles based on projected vehicle performance and durability, and hydrogen cost criteria	4Q, 2006
1	*5*	Validate fuel cell demonstration vehicle range of ~ 200 miles and durability of ~ 1,000 hours.	4Q, 2006
1	*6*	Validate vehicle refueling time of 5 minutes or less.	4Q, 2006
1	*7*	Test results from student-designed hybrid fuel cell and internal combustion engine vehicles.	3Q, 2007
1	*8*	Validate (on a vehicle) 2.0 kWh/kg and 1.2 kWh/L compressed gas tank.	1Q, 2008
1,2	*9*	Validate FCVs with 250-mile range, 2,000-hour fuel cell durability, and a hydrogen cost of $3/gge (based on volume production).	3Q, 2009
1	*10*	Validate refueling time and durability for reversible complex hydride storage.	4Q, 2010
2.3	*11*	Validate cost of producing hydrogen in quantity of $3.00/gge untaxed.	1Q, 2006
2	*12*	Five stations and two maintenance facilities constructed with advanced sensor systems and operating procedures.	4Q, 2006
2	*13*	Total of eight stations and four maintenance facilities constructed with advanced sensor systems and operating procedures.	1Q, 2008
2,3	*14*	Validate $2.50/gge hydrogen cost.	4Q, 2008
4	*15*	Validate co-production system using 50 kW PEM fuel cell; hydrogen produced at $3.60/gge and electricity at 8 cents/kWhr.	4Q, 2005
4	*16*	Demonstrate prototype energy station for 6 months; projected durability >40,000 hours; electrical energy efficiency >40%; availability >0.80.	1Q, 2008
4	*17*	Validate prototype energy station for 12 months; projected durability >40,000 hours; electrical energy efficiency >40%; availability >0.85.	4Q, 2008
5	*18*	Demonstrate pyrolysis system for waste biomass.	1Q, 2005
5	*19*	Complete Power Park demonstrations and make recommendations for business case economics.	2Q, 2007
5	*20*	Validate $2.85/gge hydrogen cost from biomass/wind (untaxed and unpressurized) at the plant gate.	4Q, 2011

Milestones Beyond 2012			
1		Validate short-stack survivability at -40°C.	1Q, 2013
1		Validate chemical storage on vehicle at 1.5 kWh/L and 2.0 kWh/kg.	4Q, 2013
Outputs			
1	***V1***	Output to Fuel Cells: Validate maximum fuel cell system efficiency.	4Q, 2005
1	***V2***	Output to Systems Analysis and Systems Integration: Final report for first generation vehicles, interim progress report for second generation vehicles on performance, safety, and O&M.	3Q, 2007
1,2	***V3***	Output to Systems Analysis and Systems Integration: Technology Status Report and re-focused R&D recommendations.	4Q, 2007
1	***V4***	Output to Systems Analysis and Systems Integration: Final report for second generation vehicles on performance, safety, and O&M.	3Q, 2010
1,2	***V5***	Output to Systems Analysis and Systems Integration: Technology Status Report and re-focused R&D recommendations.	4Q, 2010
1	***V6***	Output to Fuel Cells: Validate cold start-up capability (in a vehicle with an 8-hour soak) meeting 2005 requirements (specify cold-start energy).	3Q, 2011
2	***V7***	Output to Systems Analysis and Systems Integration: Final Report on infrastructure and hydrogen quality for first generation vehicles.	3Q, 2007
2	***V8***	Output to Systems Analysis and Systems Integration: Final Report on infrastructure, including impact of hydrogen quality for second generation vehicles.	3Q, 2010
3	***V9***	Output to Program: Final report on safety and O&M of three refueling stations.	4Q, 2007
6	***V10***	Output to Systems Analysis and Systems Integration: Hydrogen refueling station analysis - proposed interstate refueling station locations.	2Q, 2005
6	***V11***	Output to Systems Analysis and Systems Integration: Composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.	4Q, 2007
6	***V12***	Output to Systems Analysis and Systems Integration: Final composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.	4Q, 2010
Inputs			
1,2	***Sf3***	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2005
1	***Sf4***	Input from Safety: Safety requirements for on-board storage.	4Q, 2005
1	***St1***	Input from Storage: Compressed and cryogenic storage tanks achieving 1.5 kWh/kg and 1.2 kWh/L.	3Q, 2006
1,2	***St3***	Input from Storage: Complex hydride integrated system achieving 1.5 kWh/kg and 1.2 kWh/L.	3Q, 2006

1,2	***C5***	Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
1,2	***C6***	Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage.	3Q, 2006
1	***F3***	Input from Fuel Cells: Laboratory PEM technology with 2,000 hours durability.	4Q, 2006
1,2,3	***C7***	Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (NFPA).	4Q, 2006
1	***F4***	Input from Fuel Cells: Complete 4,000 hour testing of advanced MEA for stationary and transportation applications.	4Q, 2007
1,2	***Sf6***	Input from Safety: Sensor meeting technical targets.	4Q, 2007
1,2	***Sf7***	Input from Safety: Final peer reviewed Best Practices Handbook.	4Q, 2007
1	***F6***	Input from Fuel Cells: Verify cold start in 60 s of short stack.	1Q, 2008
1,2	***A2***	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008
1	***St2***	Input from Storage: Advanced compressed/cryogenic tank technologies.	4Q, 2009
1	***F7***	Input from Fuel Cells: Technology with short-stack survivability at -40°C.	1Q, 2010
1	***F5***	Input from Fuel Cells: Laboratory PEM technology with 5,000 hours durability.	2Q, 2010
1,2	***C12***	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010
1,2	***Sf5***	Input from Safety: Safety requirements and protocols for refueling.	2Q, 2010
1	***St4***	Input from Storage: Full-cycle, integrated chemical hydride system meeting 2010 targets	4Q, 2010
2,3	***P1***	Input from Production: Verify hydrogen production technologies for distributed systems using natural gas with projected cost of $3.00/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2004
2,3	***C8***	Input from Codes and Standards: Draft standards (balloting) for refueling stations (NFPA).	4Q, 2006
2,3	***P4***	Input from Production: Hydrogen production technologies for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2007
2,3	***D5***	Input from Delivery: Compression technology recommended for validation.	2Q, 2009

2	***D7***	Input from Delivery: Recommendations liquefaction technology for potential validation.	2Q, 2009
2	***D8***	Input from Delivery: Recommended pipeline technology for validation.	2Q, 2009
2,3	***D9***	Input from Delivery: Off-board storage technology.	2Q, 2009
3	***P7***	Input from Production: Verify hydrogen production technologies for distributed systems using natural gas with projected cost of $1.50/gge hydrogen at the pump, untaxed, no carbon sequestration assuming 100s of units of production per year.	4Q, 2010
2,5	***P9***	Input from Production: Electrolysis system making hydrogen for $2.85/gge delivered.	4Q, 2010
5	***P8***	Input from Production: Down-select of high-temperature electrolysis technology based on research results.	2Q, 2007
5	***P10***	Input from Production: Verify hydrogen production system making hydrogen for $1.90/gge from biomass at the plant gate.	4Q, 2009
6	***D3***	Input from Delivery: Hydrogen delivery infrastructure analysis results.	4Q, 2006

Table B.6. Codes and Standards

Milestones

Task	Milestone	Description	Date (FY)
1	1	Produce a curriculum for training modules.	3Q, 2003
1	2	Collaborate with ICC and NFPA to develop first- order continuing education for code officials.	2Q, 2004
1	3	Coordination plan with Education Program element for state and local official training established.	4Q, 2005
2	4	Coordination Committee for hydrogen technical experts to support the code development process established.	4Q, 2003
2	5	Complete analytical experiments and data collection for hydrogen release scenarios as needed to support code development (Phase 1).	4Q, 2006
3	6	Generic licensing agreement drafted and estimated licensing costs established.	4Q, 2003
3	7	Final generic licensing agreement, schedule of critical licensing agreements, and budget requirements developed for FY05 and beyond.	2Q, 2005
4	8	Workshop to identify and develop critical research objectives that impact model codes held.	4Q, 2003
4	9	Initiate experimental validation of large hydrogen releases and jet flame tests completed.	1Q, 2005
4	10	Final code changes that incorporate underground storage of liquid hydrogen and canopy-top storage of gaseous hydrogen for fueling stations (NFPC, ICC) completed.	2Q, 2005
4	11	Perform tests of walled hydrogen storage systems.	3Q, 2005
4	12	Complete detailed scenario analysis risk assessments.	4Q, 2005
4	13	Draft standards for dispensing systems (dispenser, hoses, hose assemblies, temperature compensating devices, breakaway devices, etc.) available (CSA America).	4Q, 2005
4	14	Draft standards for compressed gaseous on-board storage available (CSA HGV-2).	4Q, 2005
4	15	Draft standards for sensors and leak detection equipment developed (UL).	1Q, 2006
4	16	Draft standards for portable fuel cells completed (UL).	2Q, 2006
4	17	Develop small leak characterization for building releases and pressure release devices (PRD).	3Q, 2006

4	**18**	Technical assessment of metallic and composite bulk storage containers completed (ASME).	3Q, 2006
4	**19**	Draft standards for refueling stations completed (NFPA).	3Q, 2006
4	**20**	Implement research program to support new technical committees for the key standards including fueling interface, and fuel storage.	4Q, 2006
4	**21**	Templates of commercially viable footprints for fueling stations that incorporate advanced technologies developed.	1Q, 2007
4	**22**	Complete Model unintended release in complex metal hydrides.	2Q, 2007
4	**23**	Final draft standard (balloting) for sensors and leak detection equipment developed (UL).	1Q, 2008
4	**24**	Final draft standards completed for transportable composite containers for balloting (ASME).	1Q, 2008
4	**25**	Materials compatibility technical reference updated.	2Q, 2008
5	**26**	Negotiate agreement with DOT/NHTSA at Working Party on Pollution and Energy meeting.	3Q, 2003
5	**27**	Mechanism to support appropriate U.S. Technical Advisory Groups (TAG) through CSA America and CGA in place.	3Q, 2003
5	**28**	Initiate the development of the next generation Sourcebook to include Japan, Europe, Canada and the U.S. (PATH).	1Q, 2004
5	**29**	Roadmap for global technical regulations (GTR) published.	2Q, 2005
5	**30**	General licensing agreement for ISO standards in place.	4Q, 2008
5	**31**	Draft regulation for comprehensive hydrogen fuel cell vehicle requirements as a GTR approved (UN Global Technical Regulation).	4Q, 2010
Outputs			
1	**C1**	Output to Education: Training modules for current practices.	2Q, 2005
1	**C2**	Output to Education: Training modules for amended practices for new technologies.	2Q, 2006
4	**C3**	Output to Production and Delivery: Preliminary assessment of Safety, Codes and Standards requirements for the hydrogen delivery infrastructure.	2Q, 2005
4	**C4**	Output to Storage: Standards for compressed gaseous on-board storage.	4Q, 2005
4	**C5**	Output to Program: Completed hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
4	**C6**	Output to Delivery, Storage and Technology Validation: Technical assessment of Standards requirements for metallic and composite bulk storage tanks.	3Q, 2006
4	**C7**	Output to Delivery, Storage and Technology Validation: Final standards (balloting) for fuel dispensing systems (CSA America).	4Q, 2006

4	***C8***	Output to Technical Validation and Delivery: Draft standards (balloting) for refueling stations (NFPA).	4Q, 2006
4	***C9***	Output to Delivery and Storage: Materials compatibility technical reference.	2Q, 2008
4	***C10***	Output to Fuel Cells: Final draft standard (balloting) for portable fuel cells (UL).	4Q, 2008
4	***C11***	Output to Delivery: Codes and Standards for delivery infrastructure complete.	2Q, 2010
4	***C12***	Output to Program: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010
Inputs			
4	***V9***	Input from Technology Validation: Submit final report on safety and O&M of three refueling stations.	4Q, 2007
4	***A2***	Input from Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008

Table B.7. Safety

Milestones

Task	Milestone	Description	Date (FY)
2	1	Prepare draft failure modes and risk mitigation protocol.	4Q, 2005
2	2	Conduct workshop to review draft protocol.	4Q, 2005
2	3	Release consensus protocol.	1Q, 2006
3	4	Initiate collaboration with NASA, DOT, and other agencies to establish and publish an interagency plan on the cooperation of hydrogen safety R&D.	1Q, 2004
3	5	Review existing data and hydrogen classification.	4Q, 2005
3	6	Develop design protocol that employs passive system or holistic design techniques.	1Q, 2006
3	7	Convene hydrogen safety workshops to communicate research findings and disseminate information to safety stakeholders.	2Q, 2008
3	8	Conduct research as needed to fill data gaps on hydrogen properties and behaviors.	2Q, 2010
4	9	Conduct workshop to identify key performance parameters for hydrogen sensors and leak detection devices.	3Q, 2005
5	10	Assemble panel of experts in hydrogen safety to provide expert technical guidance to funded projects.	4Q, 2003
6	11	Identify user needs for Safety database.	3Q, 2006
6	12	Publish Safety database.	4Q, 2007
7	13	Safety Review Panel to prepare draft of Best Management Practices Handbook.	2Q, 2007
7	14	Complete final peer-reviewed Handbook.	4Q, 2007
8	15	Kickoff meeting between HAMMER, DOE and national laboratory staff.	1Q, 2004
8	16	Consensus 5-Year Plan for HAMMER released.	2Q, 2005
8	17	First hydrogen safety class (non-prop) offered at HAMMER.	3Q, 2005
8	18	First hands-on training prop completed.	1Q, 2007
9	19	Develop guidelines for hydrogen safety planning and inclusion in procurements.	2Q, 2003
9	20	Publish guidelines for safety plans.	4Q, 2004
10	21	First DOE annual review incorporating new emphasis on safety.	3Q, 2004
10	22	Establish annual review criteria for safety.	2Q, 2005
10	23	Publish final annual review criteria for safety on DOE Web site.	3Q, 2005

Outputs			
1	***Sf1***	Output to Education: Report of common accident scenarios.	3Q, 2005
1	***Sf2***	Output to Education: Updated report of common accident scenarios.	3Q, 2007
3	***Sf3***	Output to Production, Delivery, Storage and Technology Validation: Safety requirements and protocols for refueling.	2Q, 2005
3	***Sf4***	Output to Storage and Technology Validation: Safety requirements for on-board storage.	4Q, 2005
3	***Sf5***	Output to Production, Delivery, Storage and Technology Validation: Safety requirements and protocols for refueling.	2Q, 2010
4	***Sf6***	Output to Technology Validation and Systems Integration: Sensor meeting technical targets.	4Q, 2007
7	***Sf7***	Output to Technology Validation, Education and Systems Integration: Final peer reviewed Best Practices Handbook.	4Q, 2007
Inputs			
3	***V9***	Input from Technology Validation: Submit final report on safety and O&M of three refueling stations.	4Q, 2007
7	***E1***	Input from Education: Published initial perceptions report.	4Q, 2004
7	***E2***	Input from Education: Interim perceptions report.	1Q, 2008
7	***E3***	Input from Education: Final perceptions report.	1Q, 2011

Table B.8. Education

Milestones

Task	Milestone	Description	Date (FY)
1	1	Complete Web site needs assessment.	4Q, 2003
1	2	Identify opportunities to tie into existing clearinghouse infrastructures.	4Q, 2003
1	3	Establish information clearinghouse.	2Q, 2004
1	4	Complete "phase 2" Web site upgrades and improvements ("phase 1" was initial launch, completed January 28, 2003).	3Q, 2004
1	5	Deliverable: Create library of materials, including, but not limited to the following: fuel cell technology fact sheets, hydrogen "basics" fact sheet (production, storage, delivery), hydrogen safety fact sheet, technology "challenges" fact sheet.	4Q, 2005
1,7,8	6	Deliverable: Publish data from first generation Technology Validation Projects.	1Q, 2008
1,7,8	7	Deliverable: Publish data from second generation Technology Validation projects.	1Q, 2011
2	8	Identify and review existing teaching materials for grades K-12.	3Q, 2004
2	9	Identify and evaluate opportunities to work with traditional textbook companies to incorporate hydrogen and fuel cell information.	3Q, 2004
2	10	Publish middle school hydrogen activity guide to serve interim education needs.	3Q, 2004
2	11	Publish high school hydrogen activity guide to serve interim education needs.	3Q, 2005
2	12	Develop and pilot draft comprehensive middle school hydrogen technology curricula.	4Q, 2005
2	13	Develop draft comprehensive high school hydrogen technology curricula.	4Q, 2005
2	14	Publish elementary school activity guide.	3Q, 2006
2	15	Publish comprehensive middle school hydrogen technology curricula; launch dissemination strategy and teacher professional development.	4Q, 2006
2	16	Conduct local pilots and national field tests of comprehensive high school hydrogen technology curricula and teacher professional development training modules.	3Q, 2007
2	17	Launch national dissemination of comprehensive high school hydrogen technology curricula and teacher professional development program.	4Q, 2008
3	18	Launch hydrogen technology competition for university students.	1Q, 2004
3	19	Deliverable: Publish database of existing university programs.	3Q, 2004

3	20	Evaluate opportunities to expand hydrogen and fuel cell focus of current DOE-sponsored university programs.	4Q, 2004
3	21	Launch Hydrogen Technology Learning Center program for colleges and universities.	4Q, 2004
3	22	Complete development of community college hydrogen technology curriculum.	4Q, 2006
4	23	Establish baseline level of public awareness and perceptions.	4Q, 2004
4	24	Conduct follow-up public perception analysis.	4Q, 2007
4	25	Complete public perception assessment and results analysis.	4Q, 2010
5	26	Initiate national education campaign planning efforts with Controlled Hydrogen Fleet and Infrastructure Validation project partners.	4Q, 2005
5	27	Create plan for pilot public education campaign in conjunction with Controlled Hydrogen Fleet and Infrastructure Validation project partners.	4Q, 2006
5	28	Complete pilot of public education campaign strategies in conjunction with Controlled Hydrogen Fleet and Infrastructure Validation partners and in communities with ongoing technology validation activities.	3Q, 2010
5	29	Go-Now/Go-Later: Decision point on launch of full-scale public education campaign.	4Q, 2010
6	30	Complete assessment of opportunities for joint education activities with existing community partnership programs.	1Q, 2004
6,7	31	With DOE Regional Office and state and local government partners, complete first Hydrogen Learning Workshop Series to educate state and local government officials.	1Q, 2005
6,7	32	Building on first series, launch second series of Hydrogen Learning Workshops for state and local government officials.	3Q, 2005
6	33	Identify partners to serve on Hydrogen Education Review Panel.	3Q, 2005
6	34	Launch Hydrogen Education Review Panel.	4Q, 2005
6,8	35	Launch Hydrogen Learning Workshop series for potential large-scale end-users.	2Q, 2008
9	36	Establish a coordination plan with Safety and Codes and Standards Program elements for state and local safety and code official training.	4Q, 2005
Outputs			
4,9	E1	Output to Safety: Publish initial perceptions report.	4Q, 2004
4,9	E2	Output to Safety: Publish interim perceptions report.	1Q, 2008
4,9	E3	Output to Safety: Publish perceptions report.	1Q, 2011

Inputs			
1,9	***C1***	Input from Codes and Standards: Training modules for current practices.	2Q, 2005
1,9	***Sf1***	Input from Safety: Report of common accident scenarios.	3Q, 2005
1,9	***C2***	Input from Codes and Standards: Training modules for amended practices for new technologies.	2Q, 2006
1,9	***Sf2***	Input from Safety: Updated report of common accident scenarios.	3Q, 2007
1,9	***V9***	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007
1,9	***Sf7***	Input from Safety: Final, peer-reviewed Best Practices Handbook.	4Q, 2007

Table B.9. Systems Analysis

Milestones

Task	Milestone	Description	Date (FY)
1	***1***	Complete survey for Analysis Portfolio from all sources.	2Q, 2005
1	***2***	Complete 1st draft of prioritized Analysis Portfolio.	4Q, 2005
1	***3***	Publish Analysis Portfolio.	1Q, 2006
1	***4***	Annual update of Analysis Portfolio.	4Q, 2006 through 4Q, 2010
2	***5***	Establish Systems Analysis Work Group and Complete 1st Systems Analysis Workshop.	4Q, 2004
2	***6***	Complete 2nd Systems Analysis Workshop with hydrogen analysis community.	3Q, 2005
2	***7***	Annual Systems Analysis Workshop to review updated Analysis Portfolio and Data Book.	1Q, 2006 through 1Q, 2010
3	***8***	Survey hydrogen community for assumptions, data sets, targets and constraints for input to the database.	2Q, 2005
3	***9***	Complete “Review Version” of Data Book and issue for comment.	3Q, 2005
3	***10***	Complete 1st edition of Data Book and subsequent annual updates.	1Q, 2006 through 1Q, 2010
4	***11***	Complete “Review Version” of the Systems Analysis Plan.	3Q, 2005
4	***12***	Peer review the Systems Analysis Plan.	4Q, 2005
4	***13***	Complete 1st edition of the Systems Analysis Plan.	1Q, 2006
5	***14***	Complete system model and model architecture.	2Q, 2005

5	*15*	Complete transition model review.	2Q, 2005
5	*16*	Complete input/output guidelines for the Macro-System Model.	3Q, 2005
5	*17*	Select transition model for analysis and incorporate into Macro-System Model.	4Q, 2005
5	*18*	Develop initial model architecture.	4Q, 2005
5	*19*	Capture Macro-System Model requirements, description, and usage in a description document.	1Q, 2006
5	*20*	Peer review the Macro-System Model with the hydrogen modeling community.	3Q, 2006
5	*21*	Complete 1st version of the Macro-System Model.	1Q, 2007
5	*22*	Complete the integration of the Macro-System Model into the Systems Analysis and accomplish annual major model upgrades (2010 includes electricity infrastructure).	2Q, 2007 through 2Q, 2010
6	*23*	Complete evaluation of the factors (geographic, resource availability, existing infrastructure) that most impact transition analysis.	3Q, 2005
6	*24*	Complete baseline economic, energy efficiency and environmental targets for fossil, nuclear and renewable hydrogen production and delivery technologies.	4Q, 2005
6	*25*	Begin a coordinated study of transition analysis with H2A and Delivery models.	1Q, 2006
6	*26*	Complete study for transitioning scenarios for a hydrogen economy.	3Q, 2006
6	*27*	Complete assessment of current technologies for production and delivery pathways to meet the established targets.	4Q, 2006
7	*28*	Internal review of Systems Analysis function biennially.	2Q, 2005; 2Q, 2007; 2Q, 2009
7	*29*	External Peer review of Systems Analysis function biennially.	4Q, 2005; 4Q, 2007; 4Q, 2009
Outputs			
6	*A1*	Output to Production, Delivery and Systems Integration: Complete techoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.	4Q, 2006
6	*A2*	Output to Program: Initial recommended hydrogen quality at each point in the system.	4Q, 2008

Inputs			
6	**F1**	Input from Fuel Cells: Critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions and cost.	2Q, 2003
6	**F8**	Input from Fuel Cells: Preliminary hydrogen purity/impurity requirements.	2Q, 2005
6	**V10**	Input from Technology Validation: Hydrogen refueling station analysis - proposed interstate refueling station locations.	2Q, 2005
6	**C5**	Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
6	**D1**	Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.	4Q, 2006
6	**D3**	Input from Delivery: Hydrogen delivery infrastructure analysis results.	4Q, 2006
6	**St5**	Input from Storage: Baseline hydrogen on-board storage system analysis results (and initial down-select) including hydrogen quality needs and interface issues.	1Q, 2007
6	**P3**	Input from Production: Impact of hydrogen purity on cost and performance.	3Q, 2007
6	**D4**	Input from Delivery: Assessment of impact of hydrogen purity requirements on cost and performance of hydrogen delivery.	3Q, 2007
6	**F9**	Input from Fuel Cells: Updated hydrogen purity/impurity requirements.	3Q, 2007
6	**V2**	Input from Technology Validation: Final report for first generation vehicles and interim progress report for second generation vehicles, on performance, safety and O&M.	3Q, 2007
6	**V7**	Input from Technology Validation: Final report on infrastructure, including impact of hydrogen purity on cost and performance.	3Q, 2007
6	**V3**	Input from Technology Validation: Technology status report and re-focused R&D recommendations.	4Q, 2007
6	**V9**	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007
6	**V11**	Input from Technology Validation: Composite results of analyses and modeling from vehicle and infrastructure data collected under the learning demonstration project.	4Q, 2007
6	**P5**	Input from Production: Impact of hydrogen purity on cost and performance.	4Q, 2009
6	**D6**	Input from Delivery: Update of hydrogen purity/impurity requirements.	4Q, 2009
6	**St6**	Input from Storage: Final On-board hydrogen storage system analysis results of cost and performance (including pressure, temperature, etc.) and down-select to a primary on-board storage system candidate.	1Q, 2010

6	C12	Input from Codes & Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010
6	V4	Input from Technology Validation: Final report for second generation vehicles on performance, safety and O&M.	3Q, 2010
6	V8	Input from Technology Validation: Final report on infrastructure, including impact of hydrogen purity on cost and performance.	3Q, 2010
6	V5	Input from Technology Validation: Technology status report and refocused R&D recommendations.	4Q, 2010
6	V12	Input from Technology Validation: Composite results of analyses and modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.	4Q, 2010

Table B.10. Systems Integration

Milestones

Task	Milestone	Description	Date (FY)
1	1	Approval of initial Integrated Baseline.	3Q, 2005
1	2	Integrated Baseline updates based on actual FY06 through FY10 Program appropriations.	2Q, 2006 through 2Q, 2010
1	3	Integrated Baseline versions reflecting FY08 through FY12 budget requests.	2Q, 2006 through 2Q, 2010
1	4	Integrated Baseline updates based on FY07 through FY11 spend plans.	4Q, 2006 through 4Q, 2010
2	5	Independent analysis for Fuel Cells Go/No-Go decision on fuel processing R&D.	3Q, 2004
2	6	Independent analysis for Fuel Cells Go/No-Go decision on sensors and controls technologies.	2Q, 2006
2	7	Independent analysis for Fuel Cells Go/No-Go decision on MEA in single cell meeting targets.	3Q, 2006
2	8	Supporting analysis for Systems Analysis production and delivery task.	3Q, 2006
2	9	Independent analysis for Technology Validation Go/No-Go decision on purchase of additional vehicles.	4Q, 2006
2	10	Independent analysis for Storage Go/No-Go decision on compressed and cryogenic tank technologies for on-board.	1Q, 2007
2	11	Independent analysis for Storage Go/No-Go decision on carbon nanotubes.	1Q, 2007

2	**12**	Independent analysis for Production Go/No-Go decision on continued high-temperature steam electrolysis R&D.	2Q, 2007
2	**13**	Independent analysis for Fuel Cells Go/No-Go decision on air management and thermal management technologies.	3Q, 2007
2	**14**	Independent analysis for Production Go/No-Go decision on membrane separation technology.	4Q, 2007
2	**15**	Independent analysis for Fuel Cells Go/No-Go decision on scale up precious metal reclamation process.	4Q, 2007
2	**16**	Supporting analysis for Systems Analysis hydrogen purity task.	3Q, 2008
2	**17**	Independent analysis for Fuel Cells Go/No-Go decision on auxiliary power, portable power and off-road R&D.	4Q, 2008
2	**18**	Independent analysis for Storage Go/No-Go decision on advanced carbon-based materials.	1Q, 2010
2	**19**	Independent analysis for Storage Go/No-Go decision on continuation of on-board reversible metal hydride R&D.	4Q, 2010
2	**20**	Independent analysis for Storage Go/No-Go decision on chemical storage R&D for 2015 targets.	4Q, 2010
2	**21**	Independent analysis for Fuel Cells Go/No-Go decision on stationary fuel cell systems.	4Q, 2010
2	**22**	Independent for Production Go/No-Go decision for transparent H_2-impermeable material.	4Q, 2010
2	**23**	Independent analysis for Production Go/No-Go decision on high-temperature solar-driven thermochemical cycles.	4Q, 2010
3	**24**	Conduct peer review of projects at Annual Merit Review.	3Q, 2004 through 3Q, 2010
4	**25**	Formal configuration management plan approved and processes implemented.	1Q, 2005
4	**26**	Formal risk management plan approved and processes implemented.	2Q, 2005
4	**27**	Change Control Boards periodically each fiscal year.	2Q, 2006 through 2Q, 2010
4	**28**	Risk Management Boards periodically each fiscal year.	3Q, 2006 through 3Q, 2010

Inputs			
2	***F1***	Input from Fuel Cells: Critical analysis of well-to-wheels studies of fuel cell system performance, efficiency, greenhouse gas emissions, and cost.	2Q, 2003
2	***F8***	Input from Fuel Cells: Preliminary hydrogen purity/impurity requirements.	2Q, 2005
2	***V10***	Input from Technology Validation: Hydrogen refueling station analysis - proposed interstate refueling station locations.	2Q, 2005
2	***C5***	Input from Codes and Standards: Completed hydrogen fuel quality standard as ISO Technical Specification.	3Q, 2006
2	***D1***	Input from Delivery: Assessment of cost and performance requirements for off-board storage systems.	4Q, 2006
2	***D3***	Input from Delivery: Hydrogen delivery infrastructure analysis results.	4Q, 2006
2	***A1***	Input from Systems Analysis: Complete technoeconomic analysis on production and delivery technologies currently being researched to meet overall Program hydrogen fuel objective.	4Q, 2006
2	***St5***	Input from Storage: Baseline hydrogen on-board storage system analysis results including hydrogen quality needs and interface issues.	1Q, 2007
2	***P3***	Input from Production: Impact of hydrogen purity on cost and performance.	3Q, 2007
2	***D4***	Input from Delivery: Assessment of impact of hydrogen purity requirements on cost and performance of hydrogen delivery.	3Q, 2007
2	***F9***	Input from Fuel Cells: Updated hydrogen purity/impurity requirements.	3Q, 2007
2	***V7***	Input from Technology Validation: Final report on infrastructure and hydrogen quality for first generation vehicles.	3Q, 2007
2	***Sf6***	Input from Safety: Sensor meeting technical targets.	4Q, 2007
2	***A2***	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q, 2008
2	***D6***	Input from Delivery: Update of hydrogen purity/impurity requirements.	4Q, 2009
2	***P5***	Input from Production: Impact of hydrogen purity on cost and performance.	4Q, 2009
2	***St6***	Input from Storage: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary on-board storage system candidate.	1Q, 2010
2	***C12***	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q, 2010

2	***V8***	Input from Technology Validation: Final report on infrastructure, including impact of hydrogen quality for second generation vehicles.	3Q, 2010
3	***V2***	Input from Technology Validation: Final report for first generation vehicles and interim progress report for second generation vehicles, on performance, safety, and O&M.	3Q, 2007
3	***V3***	Input from Technology Validation: Technology Status Report & re-focused R&D recommendations.	4Q, 2007
3	***V9***	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q, 2007
3	***V11***	Input from Technology Validation: Composite results of analyses & modeling from vehicle and infrastructure data collected under the learning demonstration project.	4Q, 2007
3	***Sf7***	Input from Safety: Final peer reviewed Best Practices Handbook.	4Q, 2007
3	***V4***	Input from Technology Validation: Final report for second generation vehicles on performance, safety, and O&M.	3Q, 2010
3	***V5***	Input from Technology Validation: Technology Status Report & re-focused R&D recommendations.	4Q, 2010
3	***V12***	Input from Technology Validation: Final composite results of analyses & modeling from vehicle and infrastructure data collected under the Learning Demonstration Project.	4Q, 2010

Appendix C – Benefits Assumptions

This appendix has been added to provide additional information related to Program Benefits (see section 2.0).

References

Ahlbrandt, T.S., R.R. Charpentier, T.R. Klett, J.W. Schmoker and C.J. Schenk , "Chapter AR: Analysis of Assessment Results," *U.S. Geological Survey World Petroleum Assessment 2000 – Description and Results*, U.S. Department of the Interior, U.S. Geological Survey (2000). http://greenwood.cr.usgs.gov/energy/WorldEnergy/DDS-60/

American Petroleum Institute, *API Monthly Statistical Report* (September 2004). http://api-ec.api.org/media/index.cfm?objectid=C5363301-9941-498B-B9BE2515D7100686&method=display_body&er=1&bitmask=001007001000000000

Davis, S.C. and S.W. Diegel, *Transportation Energy Data Book: Edition 22*, Oak Ridge National Laboratory Report ORNL-6967, (September 2002).

Fulton, G.A., S.P. McAlinden, D.R. Grimes, L.G. Schmidt, and B.C. Richardson, *Contribution of the Automotive Industry to the U.S. Economy in 1998: The Nation and Its Fifty States*, The University of Michigan Institute for Labor and Industrial Relations, The University of Michigan Transportation Research Institute, Office for the Study of Automotive Transportation, and the Center for Automotive Research (Winter 2001).

National Academies' National Research Council and National Academy of Engineering, T*he Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*, National Academies Press, Washington (c2004).

Santini, D.J., "Interactions Among Transportation Fuel Substitution, Vehicle Quantity Growth and National Economic Growth," *Transportation Research A*, 23(3): 183-207 (May 1989).

U.S. Department of Commerce, Bureau of Economic Analysis, *National Income and Product Accounts (NIPA): Table 2.3.5. Personal Consumption Expenditures by Major Type of Product* (2003). http://www.bea.doc.gov/bea/dn/nipaweb/TableView.asp?SelectedTable=65&FirstYear=2002&LastYear=2004&Freq=Qtr

U.S. Department of Commerce, *Bureau of the Census, Historical National Population Estimates: July 1, 1900 to July 1, 1999* (June 28, 2000). http://www.census.gov/popest/archives/1990s/popclockest.txt

U.S. Department of Commerce, Bureau of the Census, *World Population Profile, 1998* (March 1999). http://www.census.gov/ipc/www/wp98.html

U.S. Department of Energy, "Table 7: Transportation Oil Consumption by Mode to 2025,"Annual Energy Outlook With Projections to 2025," Energy Information Administration, Report DOE/EIA-0383 (2003). To estimate transportation oil consumption for 2026-2040, AEO 2003 projections were extended using the average annual growth rate during 2020-2025.

U.S. Department of Transportation, Federal Highway Administration, "Table MV-200: State Motor Vehicle Registrations by Year, 1900-1995,"*Highway Statistics Summary to 1995*. http://www.fhwa.dot.gov/ohim/summary95/section2.html

U.S. Department of Transportation, Federal Highway Administration, “Table VM-1: Annual Vehicle Distance Traveled in Miles and Related Data, 2001,”*Highway Statistics 2001*.
http://www.fhwa.dot.gov/ohim/hs01/re.htm

Wang, M., “Fuel Choices for Fuel Cell Vehicles: Well-to-Wheels Energy and Emissions Impacts,” *Journal of Power Sources,* 112: 307-321 (2002). Data presented here has been updated for 2003 data.

Ward’s Communications, Ward’s World Motor Vehicle Data, Southfield, MI. http://wardsauto.com/home/index.htm

Modeling of the Fuel Cycle Analysis

The total fuel cycle analysis including the environmental analysis was conducted using the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model, developed by the Center for Transportation Research at Argonne National Laboratory for the U.S. Department of Energy (see http://www.transportation.anl.gov/greet/index.html).

Modeling of the Oil Savings Benefit from Fuel Cell Vehicles

The President’s Hydrogen Fuel Initiative states that light duty fuel cell vehicles (FCVs) could save over 11 million barrels of oil per day (mmb/d) by 2040. This reduction in oil demand is relative to the oil that light duty conventional vehicles (CVs) might otherwise consume in 2040. The estimate was developed using the VISION model. This model was developed by DOE to provide estimates of the potential energy use, oil use and carbon emission impacts through 2050 of advanced light- and heavy-duty highway vehicle technologies and alternative fuels. VISION was used instead of the Energy Information Administration’s (EIA’s) National Energy Modeling System (NEMS) in part because NEMS only provides such estimates to 2025. Further, NEMS market penetration estimates themselves require projections of fuel prices, vehicle costs, and vehicle attributes. The prediction of fuel prices beyond 2025 is extremely uncertain, while predictions of H_2 FCV vehicle cost and attributes would be premature this early in the program, since yet to be discovered technical and cost breakthroughs are the goal of the program.

The VISION model consists of two Excel workbooks: one a Base Case of US highway fuel use and carbon emissions to 2050 and another a copy of the Base Case which can be modified to reflect alternative assumptions about advanced vehicle and alternative fuel market penetration. Oil savings estimates that are derived using this model are thus based on a number of assumptions about advanced vehicle (e.g., FCV) penetration, energy efficiency and resource fuel as well as assumptions about Base Case vehicle oil use which in turn is dependent on vehicle fuel, efficiency and travel.

A number of key modeling assumptions lead to the oil savings estimate calculated. They are as follows:

1) VISION uses EIA projections as much as possible in its Base Case. At this time, VISION uses the projections contained in EIA’s Annual Energy Outlook (AEO) 2002. EIA has subsequently released AEO 2003 that actually implies higher oil use by light-duty vehicles (LDVs). VISION is being updated to incorporate these latter estimates, but the VISION results discussed here are based on AEO 2002 estimates.

2) The certification test fuel economy of new gasoline-fueled CVs in the Base Case is fixed at 28.5 MPG for cars and 21.2 MPG for light trucks throughout the analysis period. This assumption differs from EIA’s latest projections of slight improvements in the fuel economy of gasoline-fueled CVs. In AEO 2003 EIA projects an 8% increase (total) in new gasoline light truck mpg between 2002 and 2025 and a 4% increase for new gasoline cars. VISION uses a fixed MPG Base Case because many analyses want to evaluate the effects of new technology penetration relative to existing technology.

3) All of the CVs in the Base Case are gasoline-fueled. Again this differs from EIA's AEO 2003 projections. By 2025, EIA projects that 17% of all LDVs sold in that year will be in a category defined by EIA as alternative fuel vehicles (AFVs). Though present hybrid electric vehicles run on gasoline and most, if not all, future hybrid electric vehicles will likely also run on gasoline, EIA nevertheless includes hybrid vehicles in its accounting of AFVs. Over 90% of EIA's AFVs will be hybrid electric and ethanol flex fuel vehicles, both of which will or can use gasoline (or diesel in the case of diesel hybrids). Only 0.04% would be FCVs. Again, the Base Case in VISION assumes 100% gasoline CVs in the future in order to evaluate the effects of new technology penetration relative to the predominant existing technology.

4) VISION includes Class 2b trucks (8,500 –10,000 lbs GVW) in its estimates of LDV fuel use. EIA does not.

5) The annual VMT per LDV in VISION is based on EIA's AEO 2002 vehicle-miles traveled (VMT) estimates extended to 2050. In VISION, average LDV VMT rises from 12,200 in 2002 to 13,859 in 2020, then to 14,737 in 2040, and finally to 15,000 by 2050. Cars and light trucks are used differently but by 2030 their average annual VMT is quite similar. EIA's AEO 2003 VMT estimates differ from its AEO 2002 estimates.

6) The energy efficiency of FCVs relative to current technology CVs is substantial, but also much debated. A future FCV is likely to be two to three times as energy efficient as a current technology CV. In the VISION run used to develop the oil savings estimate for the FreedomCAR and Fuel Partnership, the relative energy efficiency of FCVs was assumed to a) be 2.25 in 2018 through 2020, b) increase linearly to 2.5 by 2030 and c) remain there until 2040. We assumed that a FCV's relative energy efficiency would eventually reach 3.0, but not until post-2040.

7) When FCVs might be mass marketed is not known. But in this case it is assumed that FCVs would begin to be sold in substantial numbers in 2018 and reach 52.2% of LDV sales in 2025. The specific penetration rates that were assumed are 4% in 2018, 27% in 2020, 52% in 2025, 78% in 2030 and 100% in 2038, with linear interpolation generally used for intervening years. Hydrogen supplies are assumed to be available to facilitate this market penetration level.

8) The FCVs do not use petroleum (i.e., on-board reforming of gasoline is not assumed). The H_2 used by the FCVs is produced from natural gas or zero-carbon fuels.

Given the assumptions listed above, use of H_2 FCVs was estimated with the VISION model to generate an oil savings of 11.6 mmb/d in the light-duty transportation sector in 2040. Such a substantial savings in oil consumption would likely lead to lower oil prices than would otherwise occur. If world oil supplies are depleted within the time frame of the scenario, the hydrogen switch might be timely in preventing very high oil prices. If oil is abundant in that time frame, then energy security would be provided for the U.S., but oil might be used to a greater extent elsewhere in the world. VISION does not in any way evaluate interactions of world oil prices and oil demand.

Appendix D – 2004 Annual Program Review Project Evaluation Form

SESSION: __Mon __Tues __Wed __Thu __a.m. __p.m.

REVIEWER : ____

TITLE OF PROJECT:____

Project # ________________

PRESENTER NAME:____

Using the following criteria, rate the work presented in the context of the program objectives and provide **specific, concise** comments to support your evaluation. -- Write/print **clearly** please. --

1. **Relevance** to overall DOE objectives – the degree to which the project supports the President's Hydrogen Fuel Initiative and the goals and objectives of the HFCIT Multi-Year RD&D plan.

4-Outstanding. The project is critical to the President's Hydrogen Fuel Initiative and fully supports the RD&D plan objectives.		Specific Comments:
3-Good. Most aspects of the project align with the President's Hydrogen Fuel Initiative and support the RD&D plan objectives.		
2-Fair. The project partially supports the President's Hydrogen Fuel Initiative and the RD&D plan objectives.		
1.-Poor. The project provides little support to the President's Hydrogen Fuel Initiative and the RD&D plan objectives.		

2. **Approach** to performing the R&D – the degree to which technical barriers are addressed, the project is well-designed, technically feasible, and integrated with other research.

4-Outstanding. The project is sharply focused on one or more key technical barriers to development of the hydrogen or fuel cell technologies. Difficult for the approach to be improved significantly.		Specific Comments:
3-Good. The approach is generally well thought out and effective but could be improved in a few areas. Most aspects of the project will contribute to progress in overcoming the barriers.		
2-Fair. Some aspects of the project may lead to progress in overcoming some barriers, but the approach has significant weaknesses.		
1.-Poor. The approach is not responsive to project objectives and unlikely to make significant contributions to overcoming the barriers.		

3. **Technical Accomplishments and Progress** toward overall project and DOE goals – the degree to which research progress is measured against performance indicators and to which the project elicits improved performance (effectiveness, efficiency, cost, and benefits).

4-Outstanding. The project has made excellent progress toward objectives and overcoming one or more key technical barriers. Progress to date suggests that the barrier(s) will be overcome.		Specific Comments:
3-Good. The project has shown significant progress toward its objectives and toward overcoming one or more technical barriers.		
2-Fair. The project has shown modest progress in overcoming barriers, and the rate of progress has been slow.		
1.-Poor. The project has demonstrated little or no progress towards its objectives or toward overcoming any barriers.		

4. **Technology Transfer/Collaborations** with industry/universities/other laboratories – the degree to which the project interacts, interfaces, or coordinates with other institutions and projects.

4-Outstanding. The project is fully integrated with relevant hydrogen and fuel cell R&D activities conducted through industry, universities and other laboratories.		Specific Comments:
3-Good. The project is carried out in close coordination with relevant hydrogen and fuel cell R&D activities conducted through industry, universities and other laboratories.		
2-Fair. The project makes a modest effort to coordinate its efforts with hydrogen and fuel cell R&D activities conducted through industry, universities and other laboratories.		
1.-Poor. The project makes little to no effort to coordinate with hydrogen and fuel cell R&D activities conducted through industry, universities and other laboratories.		

5. **Proposed Future Research** approach and relevance – the degree to which the project has effectively planned its future, considered contingencies, built in optional paths or off ramps, etc.

4-Outstanding. The future work plan clearly builds on past progress and is sharply focused on one or more key technical barriers in a timely manner.		Specific Comments:
3-Good. Future work plans build on past progress and generally address removing or diminishing barriers in a reasonable period.		
2-Fair. The future work plan may lead to improvements, but should be better focused on removing/diminishing key barriers in a reasonable timeframe.		
1.-Poor. Future work plans have little relevance or benefit toward eliminating barriers or advancing the program.		

Strengths

Weaknesses

Recommendations for Additions/Deletions to Project Scope

Appendix E – H2A Hydrogen Analysis Model

Introduction

The H2A model, which stands for Hydrogen Analysis model, was developed as a collaborative effort of the Department of Energy, national laboratories and key industry analysts to provide consistent analysis of hydrogen production and delivery technologies and systems to guide research and development efforts. The objective of H2A is to improve the transparency and consistency of the analysis approaches, enable technologies to be compared on a "level playing field" and seek better validation of analysis studies by industry. To meet this objective, H2A has developed models to assess the economics of hydrogen production and delivery scenarios.

Approach

The H2A Production Cost Analysis Tool

To address the need for transparent reporting and consistent methodology, the H2A production modeling tool was developed to assess the hydrogen cost for central and distributed hydrogen production technologies. The user defines the characteristics of the process being studied, including process design, capacity, capacity factor, efficiency, feedstock requirements and capital and operating costs. The tool includes agreed upon H2A reference values for all key economic and financial parameters but users can vary these parameters for their own purpose. These parameters include: internal rate of return, plant life, feedstock costs, tax rates and depreciation schedules. The calculation part of the tool uses a standard discounted cash flow rate of return analysis methodology to determine hydrogen cost for the desired internal rate of return (10% is the H2A reference value).

Assumptions and data from each case studied using the H2A production modeling tool will be transparent and easily accessed. The tool is programmed into a standardized Excel spreadsheet (Summary Workbook Spreadsheet) that documents the following:

- Original source(s) of data (i.e., report title, authors, etc.)
- Basic process information (feedstock and energy inputs, size of plant, co-products produced, etc.)
- Process flowsheet and stream summary (flowrate, temperature, pressure, composition of each stream)
- Technology performance assumptions (e.g., process efficiency and hydrogen product conditions)
- Economic assumptions (discount rate, depreciation schedule, plant lifetime, income tax rate, capacity factor, etc.)
- Capital and operating costs
- Calculation of the discounted cash flow (the calculation procedure will be built into the standardized spreadsheet so that all technologies use the same methodology)
- Results (plant-gate hydrogen selling price and cost contributions in \$/kg H_2, operating efficiency, total fuel and feedstock consumption, and emissions)
- Sensitivity of the results to assumptions (e.g., feedstock cost, co-product selling price, capital cost, operating costs, internal rate of return, conversion efficiencies, etc.)

This production modeling tool also will facilitate the explanation of any differences between the final results of this effort and previously published results.

Technologies can be characterized at various future points in time, with the assumption that the performance and cost will change in the future. The tool includes projected costs for various potential feedstocks and utilities from 2000-2070 based on EIA and other analysis projections.

The tool allows the analysis to be done on a well-to-gate basis for central-plant technologies and a well-to-pump basis for distributed technologies. In other words, the performance characteristics of the technology (cost, energy consumption, emissions) include all upstream activities associated with the plant. This is straightforward relative to costs (because the cost of upstream activities are included in the price of inputs to the plant). It is less straightforward for energy use, efficiency and emissions. To help assess the energy and environmental impacts of the upstream activities, the H2A effort will use a model developed by Argonne National Laboratory called GREET, which contains a large database of environmental and energy data for characterizing the total lifecycle energy and emissions of various transportation processes (see: http://www.transportation.anl.gov/greet/index.html).

The H2A Production Model will be available for public use in the first quarter of 2005 and will be accessed from the Program's Web site (http://www.eere.energy.gov/hydrogenandfuelcells).

Delivery Analysis

H2A delivery models are in the development stage. Once completed, this part of the H2A effort will provide analysis fundamentals for increased understanding of delivery component costs and full delivery infrastructure costs. Three modes of hydrogen transport will be included in the initial models: compressed gas truck, liquid hydrogen truck and gas pipeline.

The H2A Delivery Component Model has information on and calculates the cost contribution of the various components of hydrogen delivery infrastructure. These include:

- Compressed hydrogen gas truck (tube trailer)
- Liquid hydrogen truck
- Hydrogen compression
- Hydrogen pipelines
- Liquefiers
- Liquid hydrogen storage tanks
- Gaseous hydrogen storage tanks
- Compressed hydrogen gas truck terminal
- Liquid hydrogen truck terminal
- Gaseous hydrogen underground geological storage

In addition to the H2A Delivery Component Model, a Delivery Scenario Model is being developed. This model will have the capability of laying out a full hydrogen delivery infrastructure for particular hydrogen delivery scenarios. One such scenario might be the delivery infrastructure from a central plant to a large city of a million people with a certain hydrogen fuel cell vehicle market share. The model will provide a discounted cash flow analysis to calculate the cost of hydrogen delivery for that scenario. There will be a wide choice of delivery scenarios when the model is fully developed.

All of the H2A tools will be compatible and consistent. They will contain the same analysis approach that utilizes consistent data and financial parameter default values.

A Strong Energy Portfolio for a Strong America

Energy efficiency and clean, renewable energy will mean a stronger economy, a cleaner environment, and greater energy independence for America. Working with a wide array of state, community, industry, and university partners, the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy invests in a diverse portfolio of energy technologies.

President Bush Launches the Hydrogen Fuel Initiative

"Tonight I am proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles.

"A simple chemical reaction between hydrogen and oxygen generates energy, which can be used to power a car producing only water, not exhaust fumes.

"With a new national commitment our scientists and engineers will overcome obstacles to taking these cars from laboratory to showroom so that the first car driven by a child born today could be powered by hydrogen, and pollution free.

"Join me in this important innovation to make our air significantly cleaner, and our country much less dependent on foreign sources of energy."

– 2003 State of the Union Address
January 28, 2003

U.S. Department of Energy
Energy Efficiency and Renewable Energy
Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Hydrogen, Fuel Cells & Infrastructure Technologies Program
DOE/GO-102005-1741
March 2005