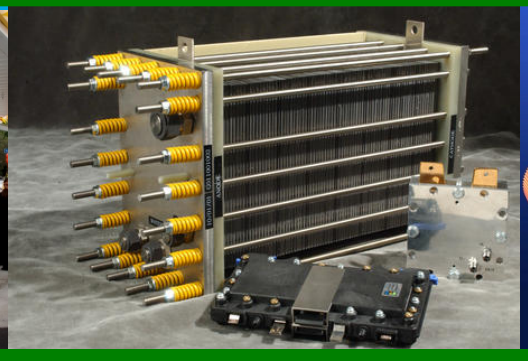
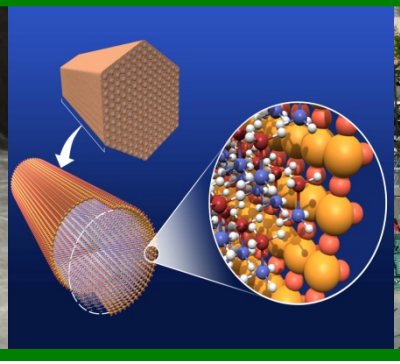
U.S. DEPARTMENT OF ENERGY

Electrolytic Hydrogen Production Workshop

Sara Dillich

U.S Department of Energy
Office of Energy Efficiency & Renewable Energy
Fuel Cell Technologies Office

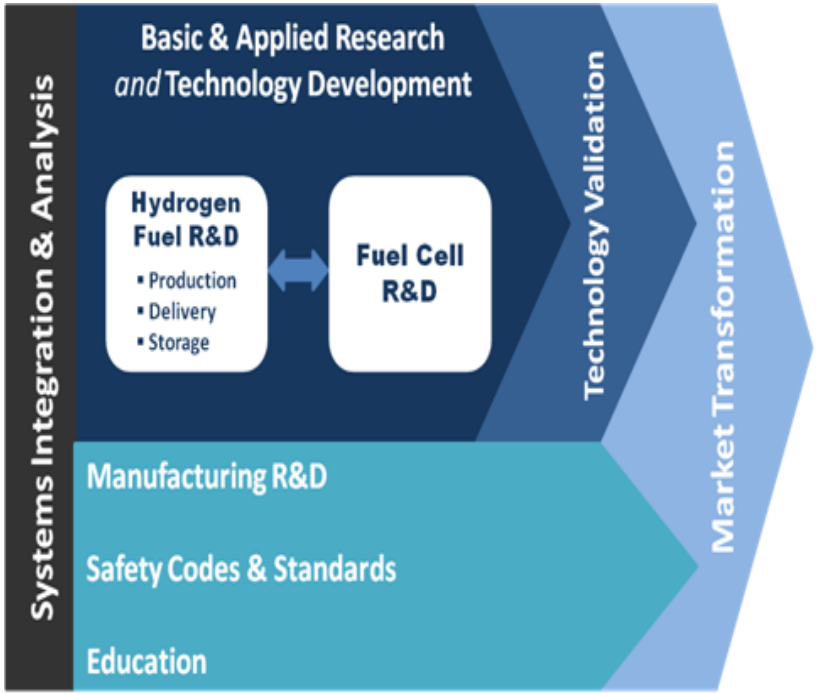
National Renewable Energy Laboratory
Golden, Colorado
February 27, 2014

Hydrogen and Fuel Cells Program Overview

U.S. DEPARTMENT OF ENERGY

Mission: Enable widespread commercialization of a portfolio of hydrogen and fuel cell technologies through applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges.

Key Goals : Develop hydrogen and fuel cell technologies for early markets (stationary power, lift trucks, portable power), mid-term markets (CHP, APUs, fleets and buses), and long-term markets (light duty vehicles).



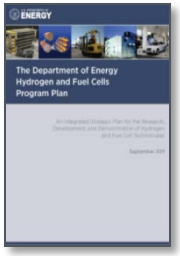
WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power

Examples of Key Targets

- **Fuel Cells:**
  - **Transportation: $30/kW, 5K hours**
  - **Stationary: $1,500/kW, 60-80K hours**
- **Hydrogen: <$4/gge**

DOE H_2 and Fuel Cell Program includes: EERE (Fuel Cell Technologies Office), and DOE Offices of Science, Fossil Energy and Nuclear Energy



EERE Multi-year RD&D Plan updated

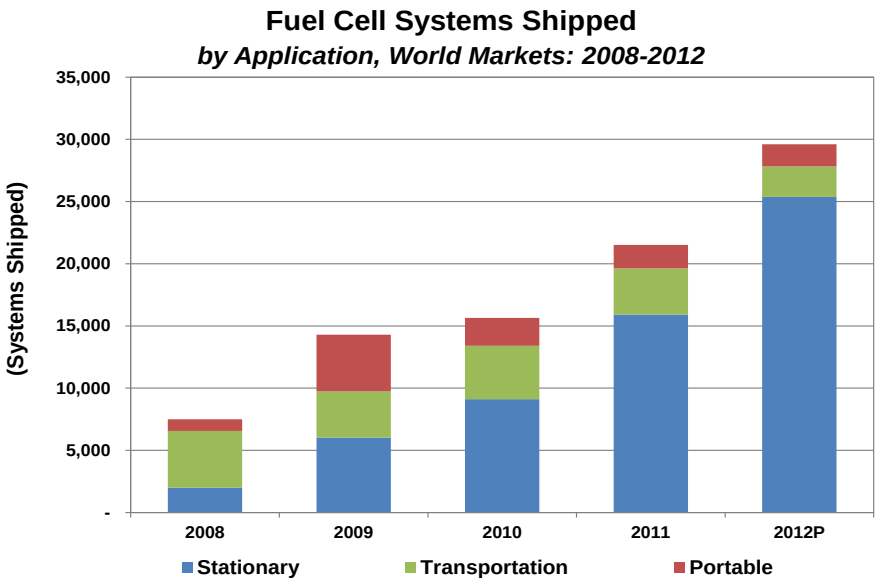
Nearly 300 projects currently funded at companies, national labs, and universities/institutes

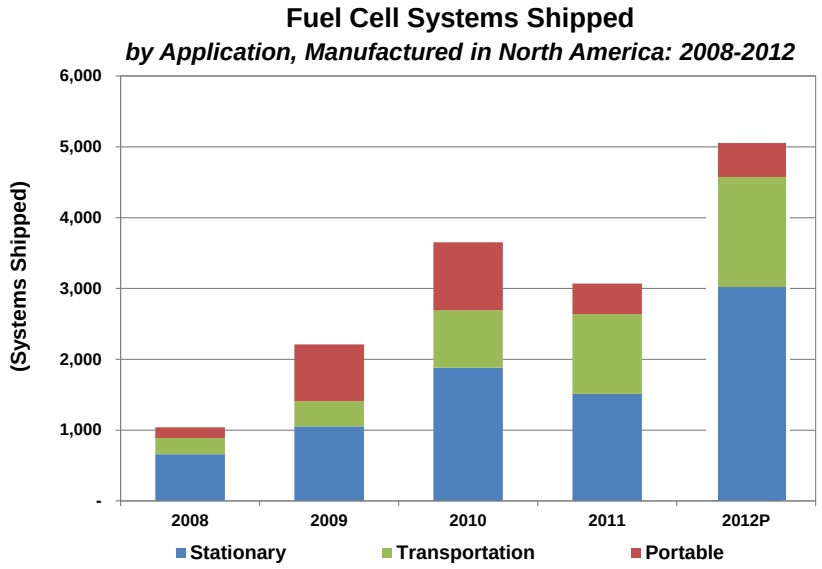
Program Plan at: http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf

Basic research conducted thru Office of Science; Applied RD&D conducted through EERE, FE, NE

Fuel Cell Market Overview

U.S. DEPARTMENT OF ENERGY





Source: Navigant Research

Market Growth

Fuel cell markets continue to grow

- **48% increase in global MWs shipped**
- **62% increase in North American systems shipped in the last year**

The Market Potential

Independent analyses show global markets could mature over the next 10–20 years, producing revenues of:

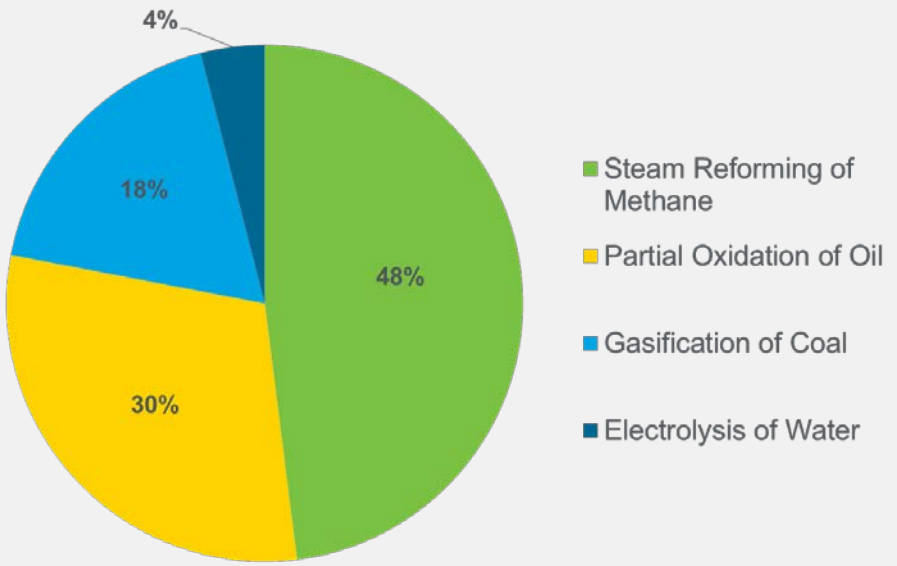
- **$14 – $31 billion/year for stationary power**
- **$11 billion/year for portable power**
- **$18 – $97 billion/year for transportation**

Several automakers have announced commercial FCEVs in the 2015-2017 timeframe.

For further details and sources see: *DOE Hydrogen and Fuel Cells Program Plan,* http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf; FuelCells 2000, Fuel Cell Today, Navigant Research

Hydrogen Production & Applications

U.S. DEPARTMENT OF ENERGY

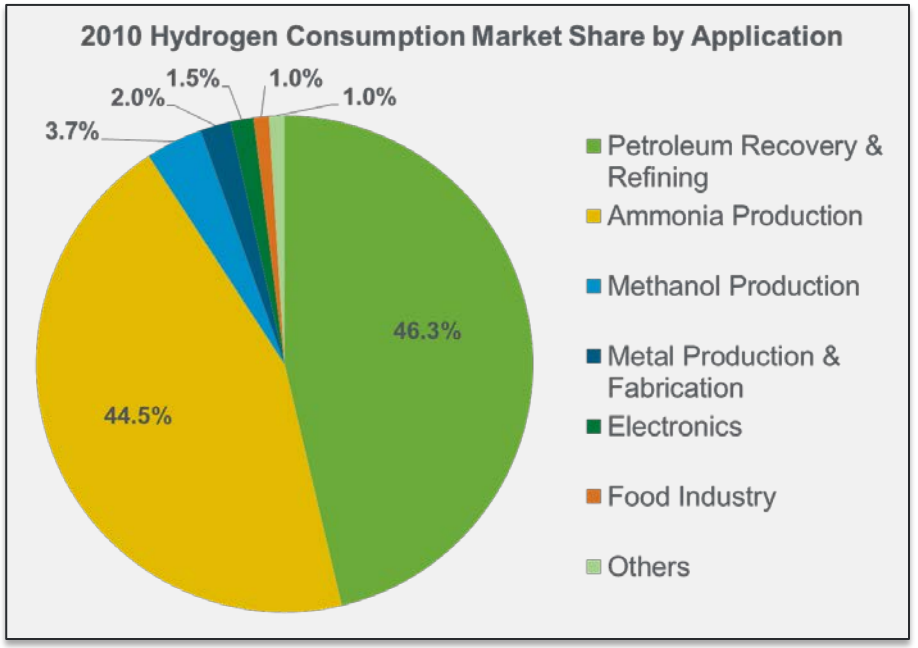


Hydrogen is produced through a variety of technologies, though ~95% of U.S. hydrogen production comes from SMR.

Hydrogen is used in a broad range of applications including electronics and metal production and fabrication in addition to its traditional role in refinery operations and ammonia production.

Major merchant suppliers

- Air Products and Chemicals, Inc.
- Airgas, Inc.
- Air Liquide
- BOC India Limited
- Linde AG
- Praxair Inc.
- Taiyo Nippon Sanso Corp.



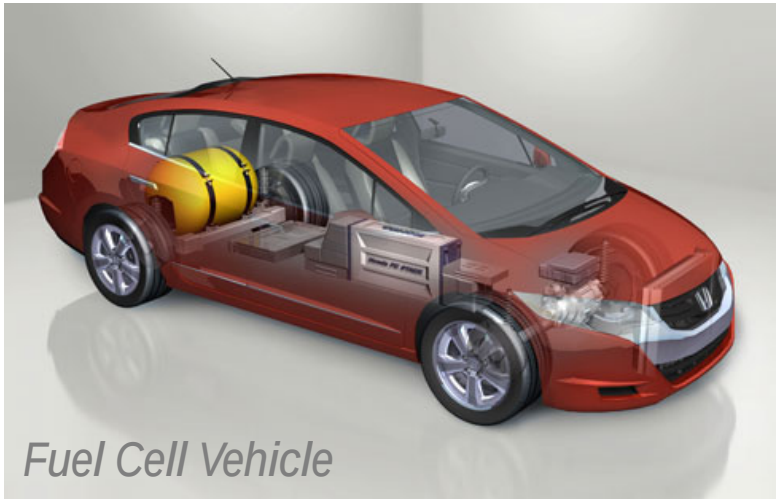
H2 Targets Relate to Auto Market Needs

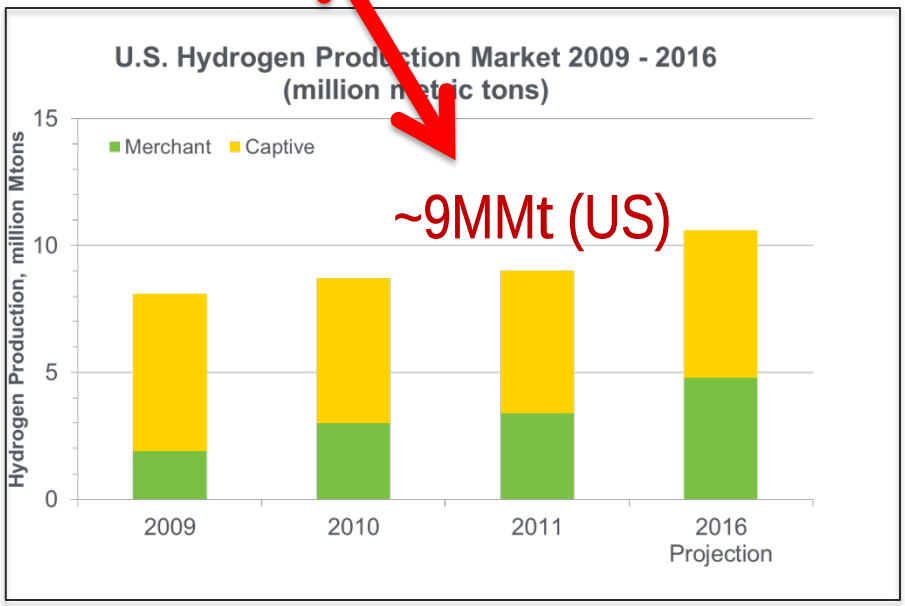
U.S. DEPARTMENT OF ENERGY

Number of Fuel Cell Cars Served	Hydrogen Demand (metric tons per day)[1]	Hydrogen Demand (million metric tons per year)
1 million	700	**0.25 (<<9)**
250 million	175,000	**~64 (>>9)**

early deployment

~# cars on US roads



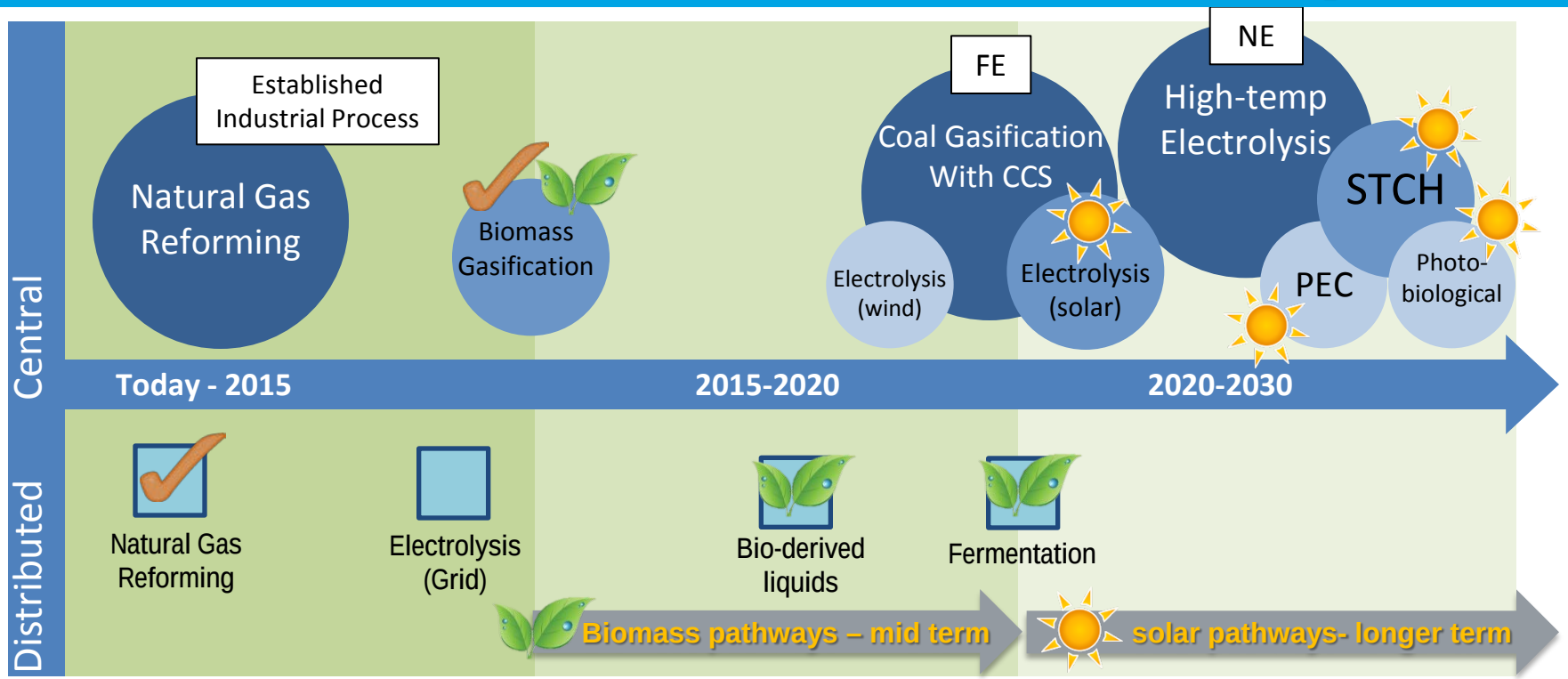


[1]Based on "Transitions to Alternate Transportation Technology- A Focus on Hydrogen. National Research Council of National Academies. 2008"

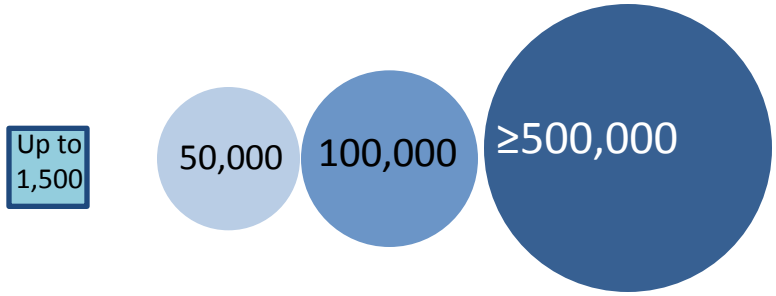
Technology Readiness of DOE Funded Production Pathways

U.S. DEPARTMENT OF ENERGY

Objective: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of $2-$4/kg H_2 by 2020



Estimated Plant Capacity (kg/day)



P&D Subprogram R&D efforts successfully concluded

FE, NE: R&D efforts in DOE Offices of Fossil and Nuclear Energy, respectively

FCTO Electrolysis Projects - 2014

U.S. DEPARTMENT OF ENERGY

Year Ending	Organization	Project
SBIR Phase II		
FY15	Giner Electrochemical Systems	High-Performance, Long-Lifetime Catalysts for PEM Electrolysis
FY15	Proton On-Site	Low Noble Metal Content Catalysts/Electrodes for Electrolysis
FY15	Proton On-Site	High Efficiency Electrocatalysts for Alkaline Membrane Electrolysis
SBIR Phase I *		
FY14	Giner Electrochemical Systems	High Temperature, High Efficiency PEM Electrolysis
FY14	Tetramer Technologies, LLC	New Approaches to Improved PEM Electrolyzer Ion Exchange Membranes
FY14	Amsen Technologies, LLC	High Performance Proton Exchange Membranes for Electrolysis Cells

**Electrolyzer membrane projects recently selected for negotiation from BES topic*

NREL Wind to Hydrogen

U.S. DEPARTMENT OF ENERGY

Renewable Electrolysis Integrated System Development & Testing
(Co-funded with FCTO Technology Validation Program)

Approach

- Provide independent testing of state-of-the-art electrolyzer stacks and systems
- Quantify stack and system integration with renewable power systems
- Develop and optimize electrolyzer sub-systems, power conversion and test equipment for renewable hydrogen

2013:

- Demonstrated PEM Electrolyzer efficiency for 200 hours of operation
- Completed 10,000 hour performance comparison between variable wind power and constant power operation.

Progress: H_2 Station Data Collection

U.S. DEPARTMENT OF ENERGY

DOE Awarded $2.4M for Hydrogen Station Evaluations and Advanced Refueling Components in 2013

350 bar and 700 bar fast-fill capability at all stations.

California State University—Los Angeles (CSULA)

- **Station Location:** Los Angeles, CA (on CSULA campus).
- **Station Characteristics:** Electrolyzer; 30-60 kg H_2/day.

Proton Energy (Proton OnSite)

- **Station Locations:** Wallingford, CT (SunHydro #1) and Braintree, MA (SunHydro #2).
- **Station Characteristics:** 65 kg H_2/day, advanced 57 bar PEM electrolyzer (at SunHydro #1 station); co-located PV array.

California Air Resources Board (CARB)

- **Station Location:** Newport Beach, CA.
- **Station Characteristics:** 100 kg H_2/day; natural gas reforming.

Gas Technology Institute (GTI)

- **Station Locations:** California (North: San Mateo, Cupertino, Mountainview, West Sacramento) & (South: Laguna Niguel, San Juan Capistrano).
- **Station Characteristics:** new 900 bar ionic compression; gaseous or liquid delivered hydrogen.

KEY METRICS

Location/Capacity/Utilization:

Station usage patterns and geographic locations.

Fueling:

Fueling rates, times, amounts, back-to-back fills, communication.

Maintenance/Availability:

Maintenance patterns, reliability and availability of stations.

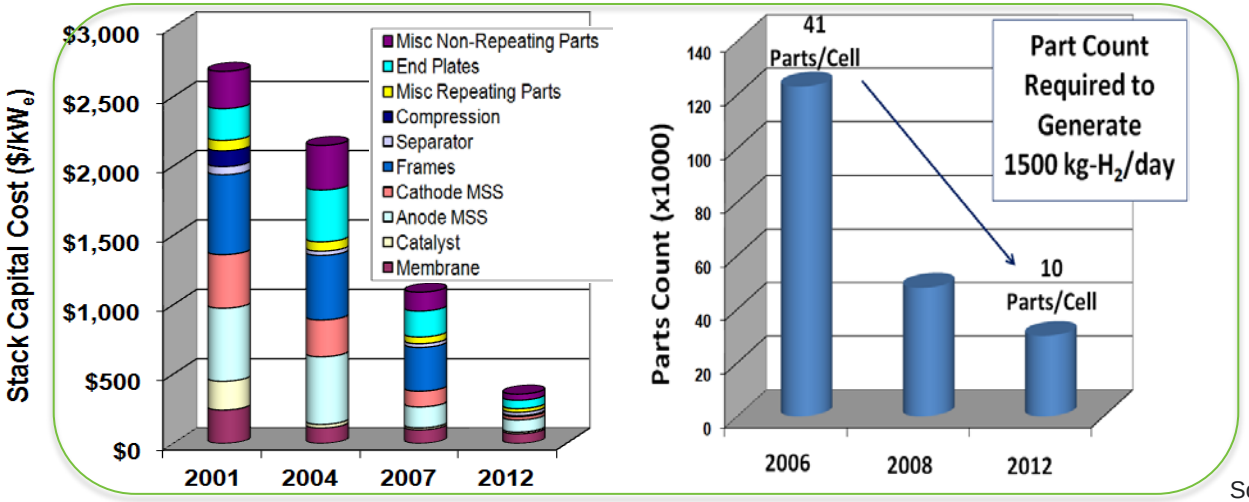
Cost:

Energy cost, maintenance cost.

Station Timing:

Permitting time, building time, commissioning time.

Current Status: Electrolytic H_2 Production

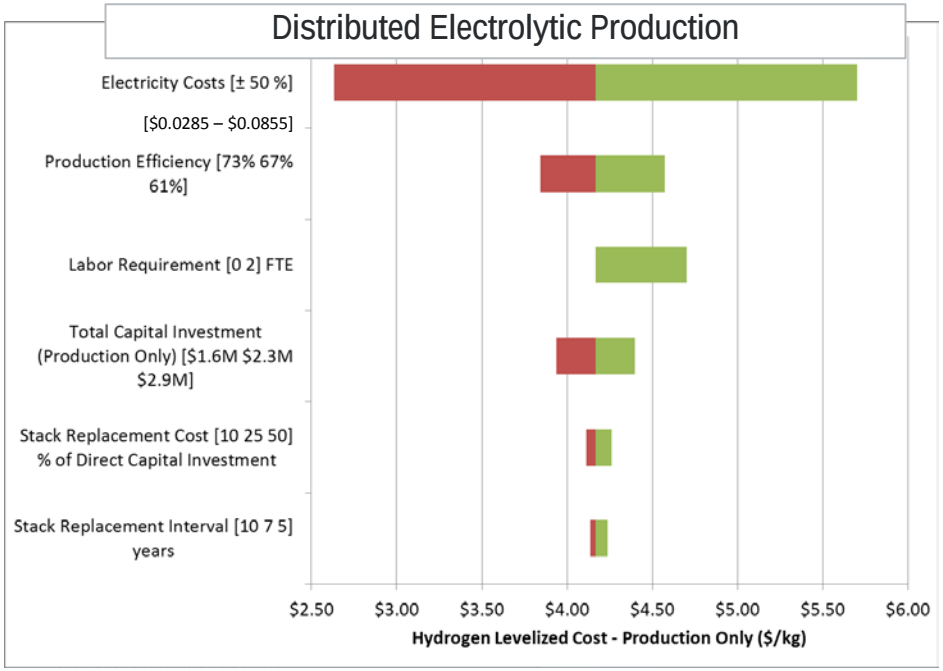


Innovations continue with 3 active SBIR Phase II projects. Three Phase I projects recently selected

Source: Giner, Inc.; 2013 Annual Merit Review
http://www.hydrogen.energy.gov/annual_progress13.html

Key Accomplishments:

- >80% reduction in stack cost since 2001 to less than $400/kW . >60% reduction in since 2007
- >75% reduction in stack part count since 2006 with 50% reduction in manufacturing labor.
- >10,000 hours of successful reliability testing on wind power profiles independently performed and validated by NREL



Critical Challenges in H2 Production

U.S. DEPARTMENT OF ENERGY

broad challenge to maintain broad R&D portfolio of near- to longer-term pathways

Bio-Derived Liquids Reforming

- High capital costs
- High operation and maintenance costs
- Design for manufacturing
- Feedstock availability, quality, and cost

Coal and Biomass Gasification

- High capital costs
- System efficiency
- Feedstock cost and purity
- Carbon capture and storage

Water Electrolysis

- Low system efficiency and high capital costs
- Integration with renewable energy sources
- Design for manufacturing
- Electricity costs

➢ **Meeting H_2 production cost threshold for all near- and longer-term pathways requires improvements in materials efficiency and durability, and reductions in overall capital costs**

Solar Thermochemical

- Cost-effective reactor and system
- Effective and durable reaction and construction materials

Photo-electrochemical

- Efficient and durable photocatalyst materials
- Innovative integrated devices

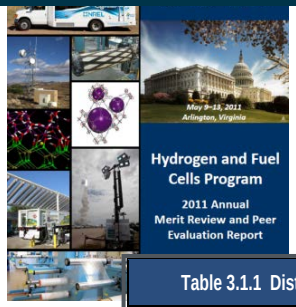
Biological

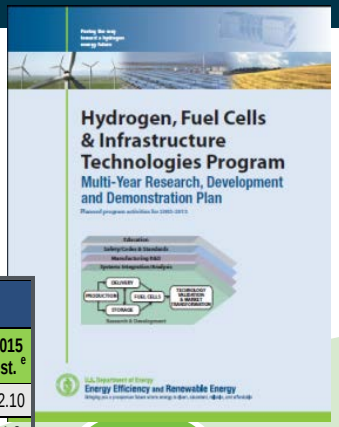
- Sustainable H2 production from microorganisms (O2 tolerance)
- Optimal microorganism functionality (maximize yields and rates)

H2 Production Program Strategy

U.S. DEPARTMENT OF ENERGY

Technoeconomic analyses inform programmatic decisions





H2A Analysis Tool Case Studies
(including feedstock, capital and O&M)
http://www.hydrogen.energy.gov/h2a_analysis.html

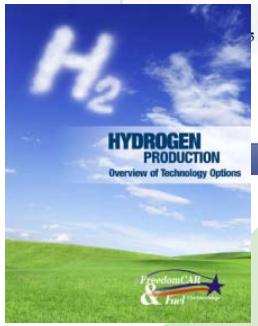


Table 3.1.1 Distributed Forecourt Natural Gas Reforming [a, b, c]

Characteristics	Units	2010 Status [d]	2015 est. [e]
Hydrogen Levelized Cost (Production Only) [f]	$/kg H_2	$2.03	$2.10
Production Equipment Total Capital Investment	$M	$1.5	$1.2
Production Energy Efficiency [g]	%	71.4	74
Production Equipment Availability [c]	%	97	97
Industrial Natural Gas Price [h]	average $/mmBtu	$7.78	$8.81

2009

2010
2011

2012

Identification of R&D pathways.

- **Develop near-zero emission H_2 production and delivery technologies**
- ***Hydrogen Production Roadmap***
- ***Hydrogen Delivery Roadmap***

Cost Analysis

- **Update of H2A v.3 and HDSAM analysis models**
- **Apportionment of cost threshold**

Performance Target Analysis

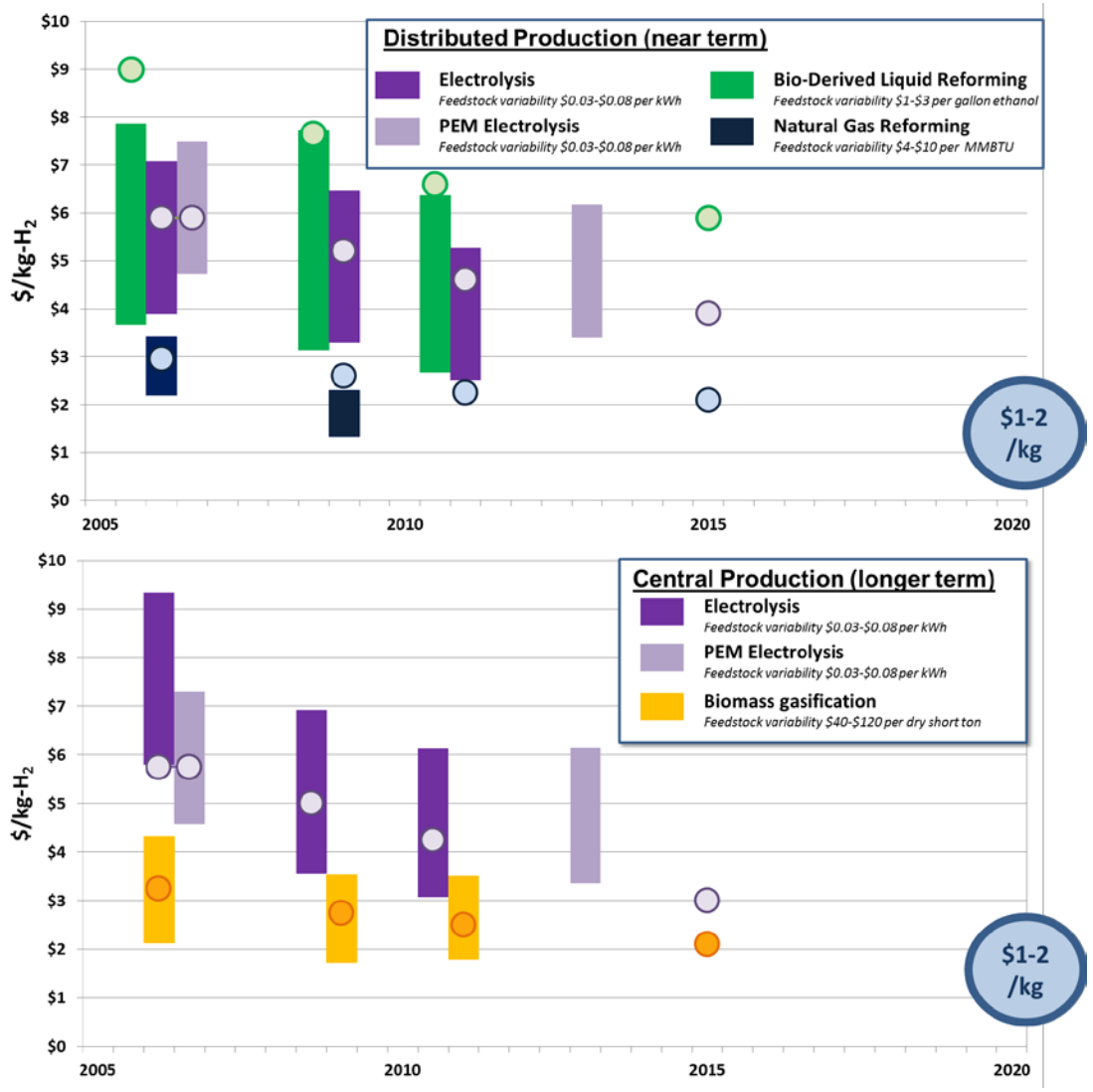
- ***Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan (MYRD&D)***

Informed Prioritization of Funding

Production Cost Status for Near/Mid-Term Pathways

U.S. DEPARTMENT OF ENERGY

Projected high-volume cost of hydrogen for near-term production pathways



- **Status of hydrogen cost (production only, does not include delivery or dispensing costs) is shown in vertical bars, reflecting values based on a range of assumptions (feedstock/capital costs).**
- **Targets for hydrogen cost are shown in circles.**
- **Targets shown are normalized for consistency in feedstock assumptions and year-cost basis (2007 dollars)**
- ***Targets prior to 2015 are extrapolated based on 2015 and 2020 targets in the FCT Office's Multi-year RD&D Plan.***
- **Cost ranges are shown in 2007 dollars, based on projections from H2A analyses, and reflect variability in major feedstock pricing and a bounded range for capital cost estimates.**
- **Projections of costs assume Nth-plant construction, distributed station capacities of 1,500 kg/day, and centralized station capacities of ≥50,000 kg/day.**

Upgrade of Analysis Efforts

U.S. DEPARTMENT OF ENERGY

New project in 2013 initiated to continue refinement of case studies

Team:

Strategic Analysis, Inc.

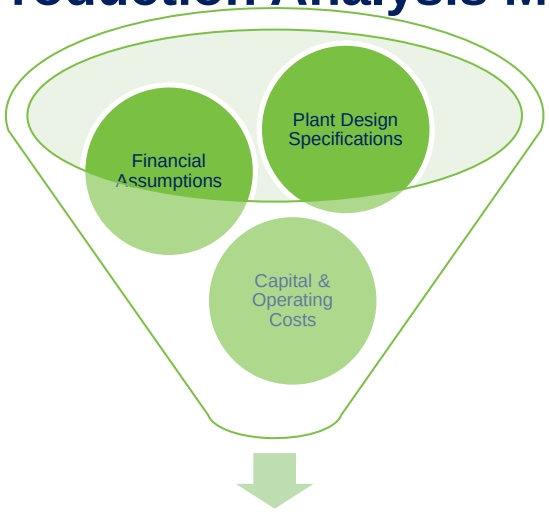
PI: Brian James

Partners: NREL, ANL

Scope:

- **Establish cost and performance baselines and track progress for R&D projects (with R&D project teams)**
- **Update pathway cases and develop new pathway case studies as needed**
- **Standardize assumptions & metrics for longer term pathways (with DOE and project teams)**

H2A Production Analysis Model



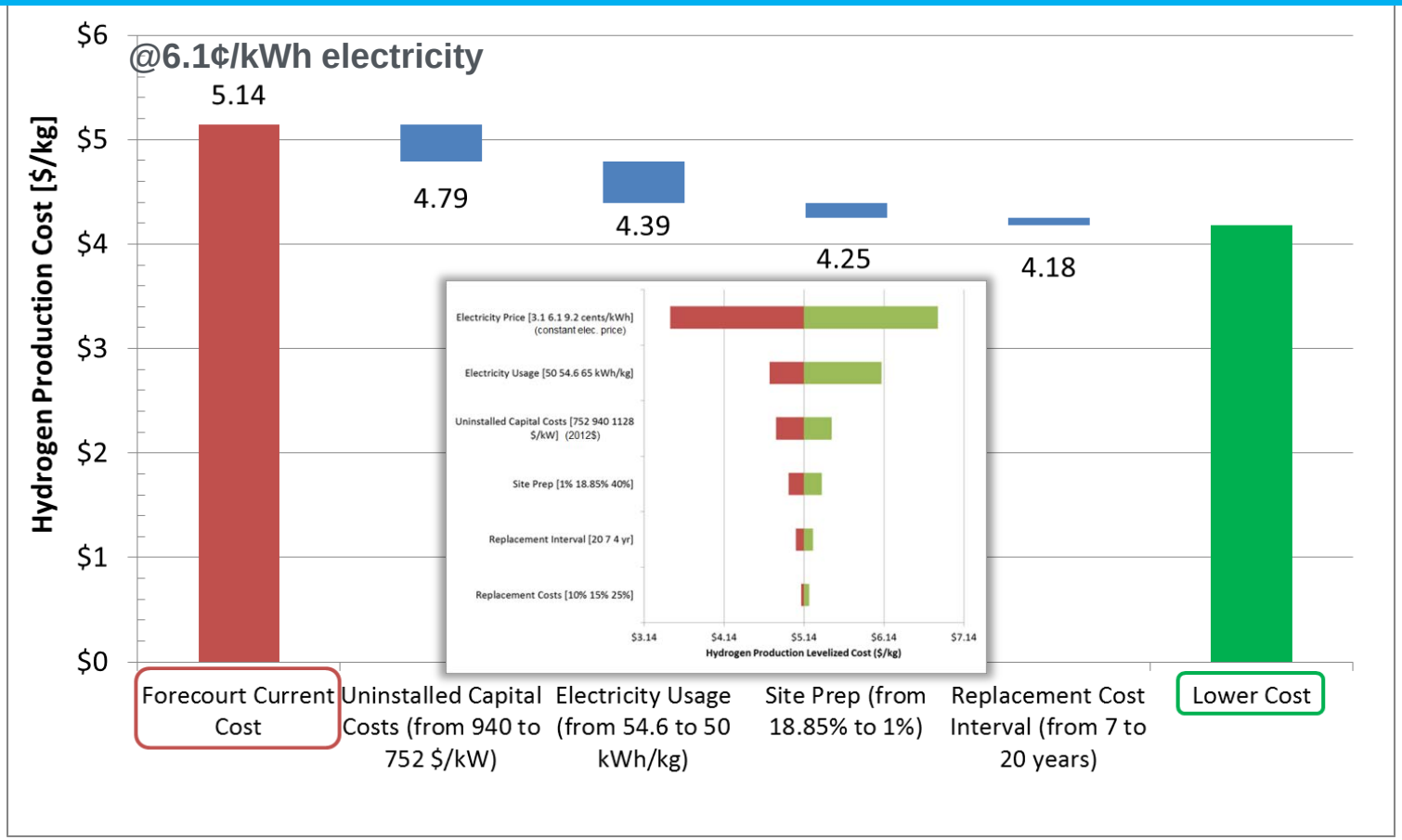
Required Selling Price of H2 ($/kg)

	$/kg (production costs only)	2011 Status	2015 Target	2020 Target	Ultimate Production Target
Distributed	Electrolysis from grid electricity	$4.20	$3.90	$2.30	$1-$2
	Bio-derived Liquids (based on ethanol reforming case)	$6.60	$5.90	$2.30	
Central	Electrolysis From renewable electricity	$4.10	$3.00	$2.00	
	Biomass Gasification	$2.20	$2.10	$2.00	
	Solar Thermochemical	NA	$14.80	$3.70	
	Photoelectrochemical	NA	$17.30	$5.70	
	Biological	NA	NA	$9.20	

Near Term Technology Case:
Gaps in PEM Electrolysis (Distributed)

U.S. DEPARTMENT OF ENERGY

Incremental improvement can be made in efficiency, durability & capital cost. Largest cost driver is still the cost of the electricity feedstock.



Forecourt analysis with H2a V3.

Source: James, B., et. al., *Techno-Economic Analysis of Hydrogen Production Pathways,* Strategic Analysis, Inc. briefing to DOE 2013.

FCTO Hydrogen Production Program: Recent Activities

U.S. DEPARTMENT OF ENERGY

- An MOU with the National Science Foundation (NSF) allowing joint RD&D funding with FCTO.
- The DOE Photoelectrochemical Hydrogen Production Working Group published the Springer Brief in Energy: “Photoelectrochemical Water Splitting: Standards, Experimental Methods, and Protocols”.
- A Biological Hydrogen Production Workshop (Sept, 2013) was held to identify key R&D needs. Workshop report posted on website.
- HTAC Hydrogen Production Expert Panel Report published with DOE response.
- Developed a comprehensive PEM Electrolysis H2Av3 Case Study based on input from four electrolyzer companies with PEM electrolysis expertise. (SAINC/NREL)
- Funding Opportunity Announcements released for Hydrogen Production Analysis and Hydrogen Production RD&D

Broader Collaborations

U.S. DEPARTMENT OF ENERGY

New in 2013: H_2USA- Public-private partnership to enable the widespread commercialization of FCEVs and address the challenge of hydrogen infrastructure

Federal Agencies

- DOC
- DOD
- DOE
- DOT
- EPA
- GSA
- DOI
- DHS
- NASA
- NSF
- USDA
- USPS

- *Interagency coordination through staff-level Interagency Working Group (meets monthly)*
- *Assistant Secretary-level Interagency Task Force mandated by EPACT 2005.*

External Input

- Annual Merit Review & Peer Evaluation
- H2 & Fuel Cell Technical Advisory Committee
- National Academies, GAO, etc.

Industry Partnerships & Stakeholder Assn's.

- Tech Teams (U.S.DRIVE)
- Fuel Cell and Hydrogen Energy Association (FCHEA)
- Hydrogen Utility Group
- ~ 65 projects with 50 companies

Universities

~ 50 projects with 40 universities

DOE Hydrogen & Fuel Cells Program

State & Regional Partnerships

- California Fuel Cell Partnership
- California Stationary Fuel Cell Collaborative
- SC H_2 & Fuel Cell Alliance
- Upper Midwest Hydrogen Initiative
- Ohio Fuel Coalition
- Connecticut Center for Advanced Technology

International

- IEA Implementing agreements – 25 countries
- International Partnership for Hydrogen & Fuel Cells in the Economy – 17 countries & EC

National Laboratories

National Renewable Energy Laboratory P&D, S, FC, A, SC&S, TV, MN	Sandia P&D, S, SC&S	Lawrence Livermore P&D, S, SC&S
Argonne A, FC, P&D, SC&S	Pacific Northwest P&D, S, FC, SC&S, A	Savannah River S, P&D
Los Alamos S, FC, SC&S	Oak Ridge P&D, S, FC, A, SC&S	Brookhaven S, FC
	Lawrence Berkeley FC, A	Idaho National Lab P&D

Other Federal Labs: Jet Propulsion Lab, National Institute of Standards & Technology, National Energy Technology Lab (NETL)

P&D = Production & Delivery; S = Storage; FC = Fuel Cells; A = Analysis; SC&S = Safety, Codes & Standards; TV = Technology Validation, MN = Manufacturing

Meeting Objective and Outcome

U.S. DEPARTMENT OF ENERGY

Objective:

To identify research, development and demonstration(RD&D) needs to enable DOE cost goals for hydrogen production to be met by the electrolysis of water

Outcomes:

- Summary of key electrolysis production issues, barriers and opportunities
- Summary of key RD&D areas with potential to meet DOE cost and performance goals
- Workshop report for public dissemination

Source: Giner, Inc.

Workshop Strategy

U.S. DEPARTMENT OF ENERGY

Two Sessions each day

Thursday: Near-Term and Long term Technical Challenges and RD&D Needs

Friday: Markets and Manufacturing

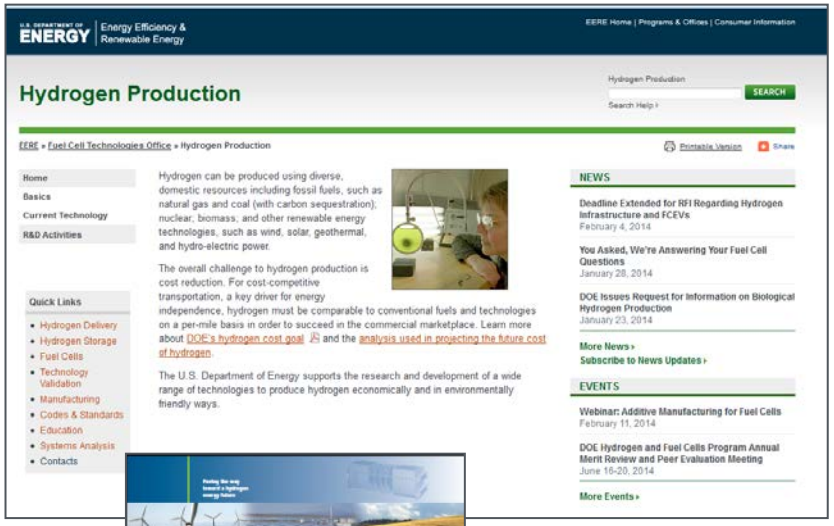
Expert panel discussions and Breakout Sessions to

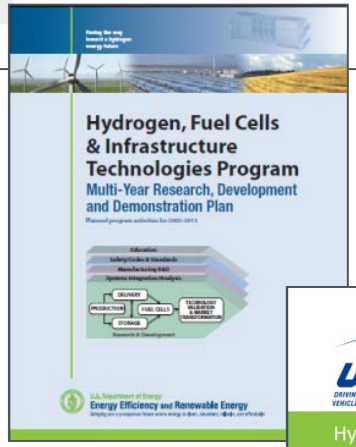
- Challenges (internal and external) to achieving DOE's cost goals for hydrogen production
- RD&D activities needed to overcome these barriers, including timeframe. When should these start and end?

Key Issues:

- *Development of standard metrics for "apples to apples" comparison of Electrolysis with other production pathways*
  - *Consistent protocols and assumptions for efficiency (e.g., report as a function of current density; consensus on practical limits)*
  - *Identification of game-changing technologies and strategies*
  - *Synergies with respect to energy storage; power to gas*
  - *Market opportunities at various scales*

For More Information on the Hydrogen Production Portfolio





Fuel Cell Technologies Office Hydrogen Production website

http://www1.eere.energy.gov/hydrogenandfuelcells/production/photobiological.html

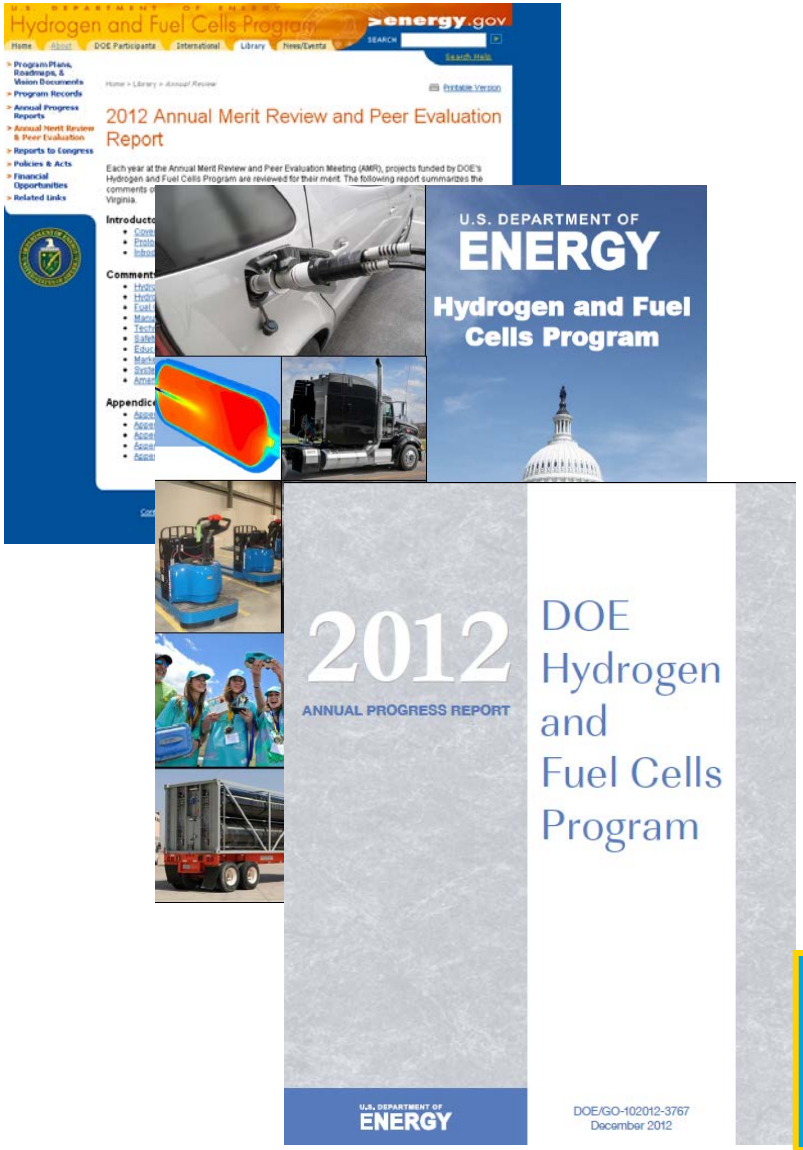
Multi-Year Research, Development and Demonstration Plan

http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

U.S. Drive Hydrogen Production Technical Team Roadmap

http://www1.eere.energy.gov/vehiclesandfuels/about/partnerships/roadmaps-other_docs.html

Annual Merit Review



Annual Merit Review & Peer Evaluation Proceedings

Includes downloadable versions of all presentations at the Annual Merit Review

http://www.hydrogen.energy.gov/annual_review13_proceedings.html

Annual Merit Review & Peer Evaluation Report

Summarizes the comments of the Peer Review Panel at the Annual Merit Review and Peer Evaluation Meeting

http://www.hydrogen.energy.gov/annual_review12_report.html

Annual Progress Report

Summarizes activities and accomplishments within the Program over the preceding year, with reports on individual projects

http://www.hydrogen.energy.gov/annual_progress12.html

Save the Date

Next Annual Review: June 16–20, 2014 Washington, DC

http://annualmeritreview.energy.gov/

Thank You

For questions please contact:

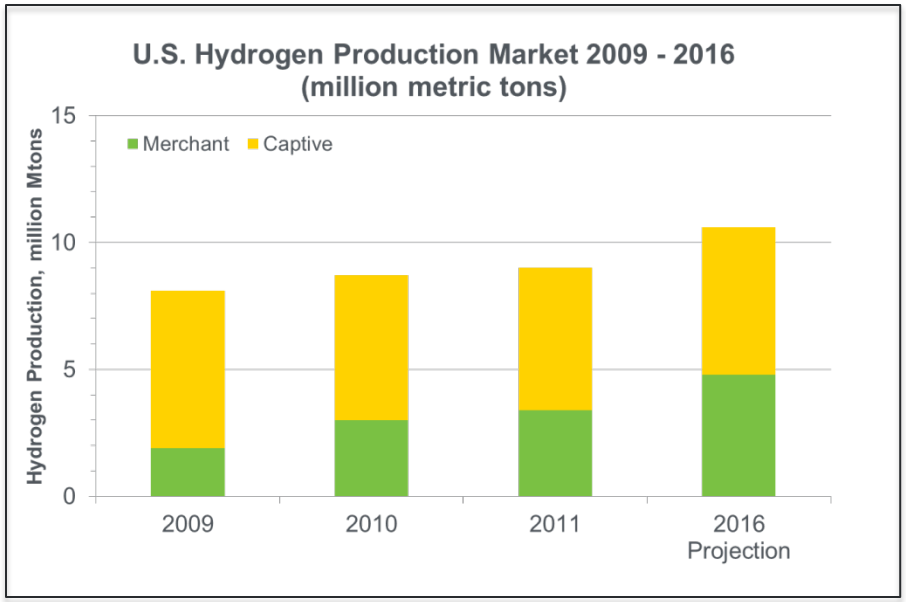
David.Peterson@go.doe.gov

Or

Chris.Ainscough@go.doe.gov

hydrogenandfuelcells.energy.gov

Hydrogen Production Markets



Hydrogen production markets both in the U.S. and worldwide are expected to increase in the next 5 years, with a ~30% growth estimated for global production.

The expected global hydrogen production market revenue in 2016 is $118 billion.