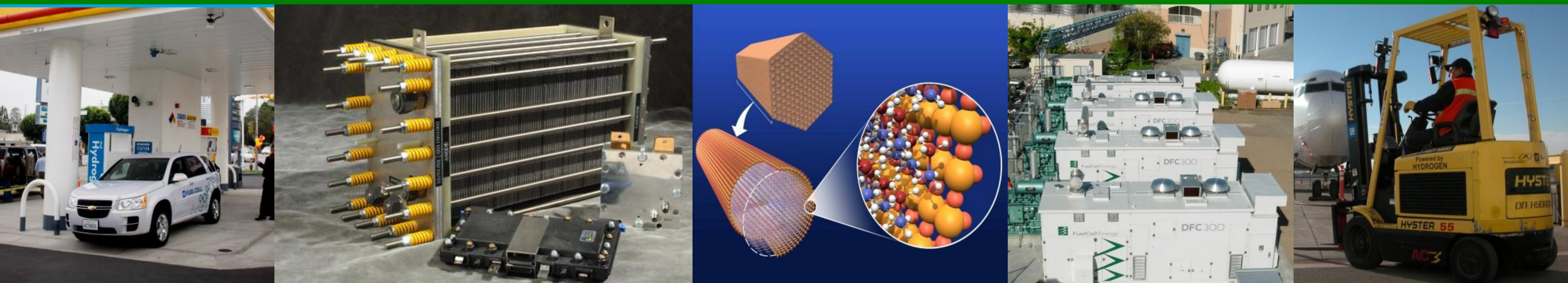
U.S. DEPARTMENT OF ENERGY



Biological 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

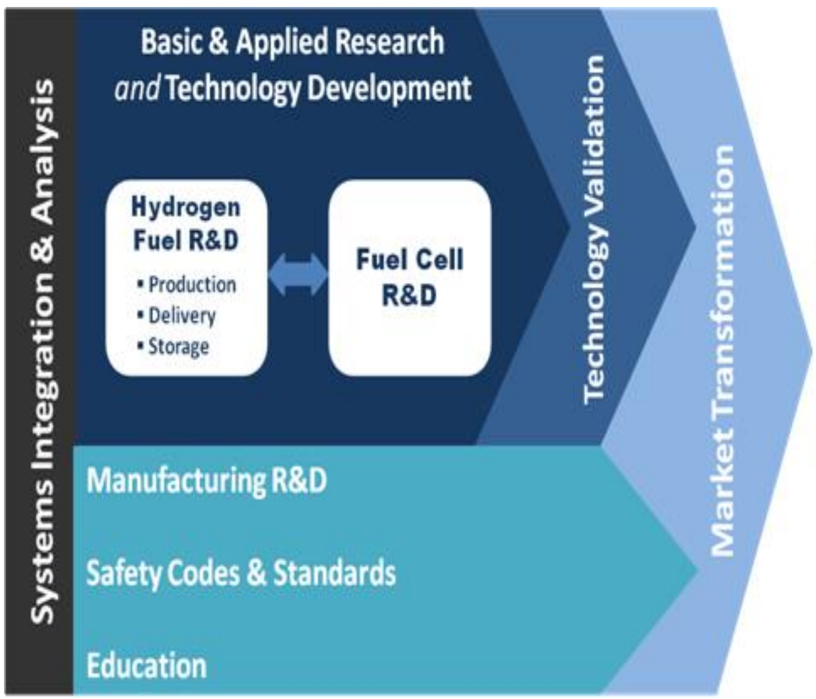
September 24, 2013

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).



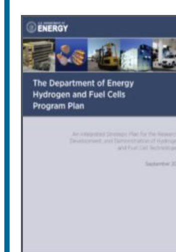
WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- 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: \$2 to \$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



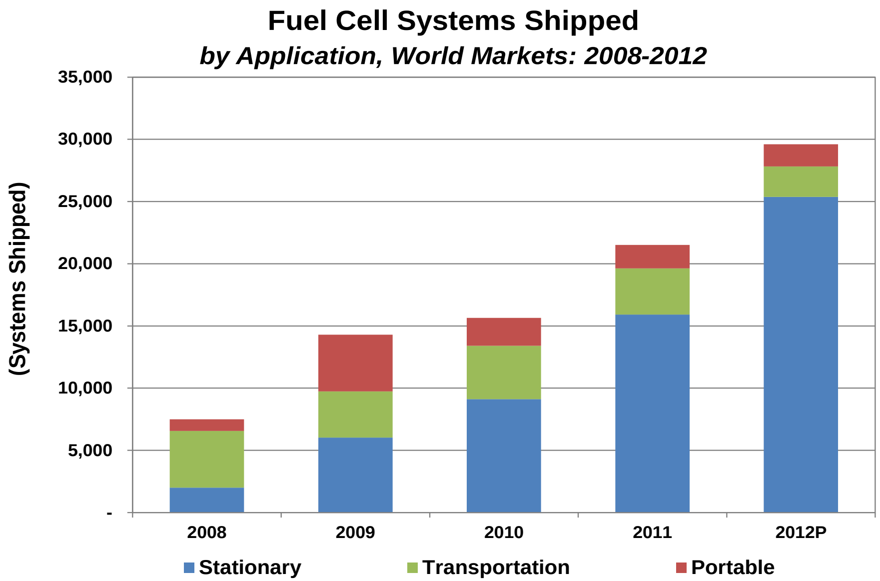
EERE Multi-year RD&D Plan updated

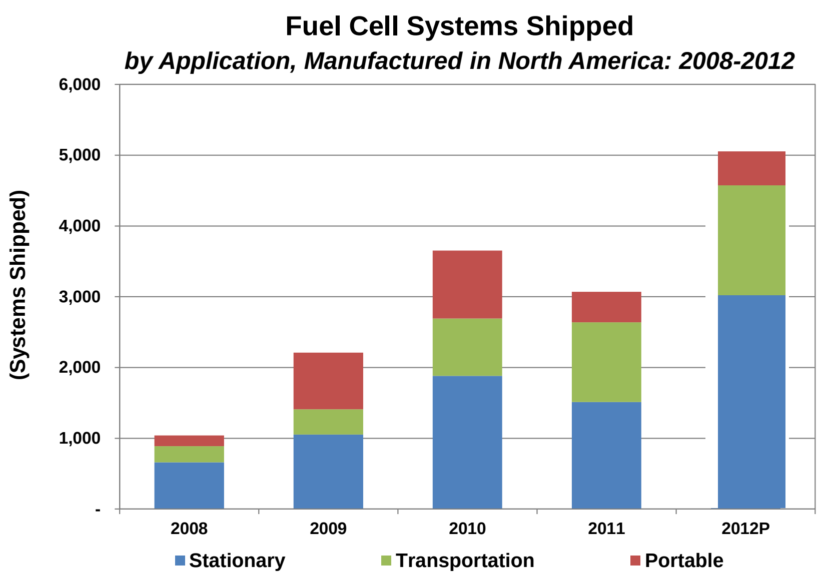
Nearly 300 projects currently funded at companies, national labs, and universities/institutes

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





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**

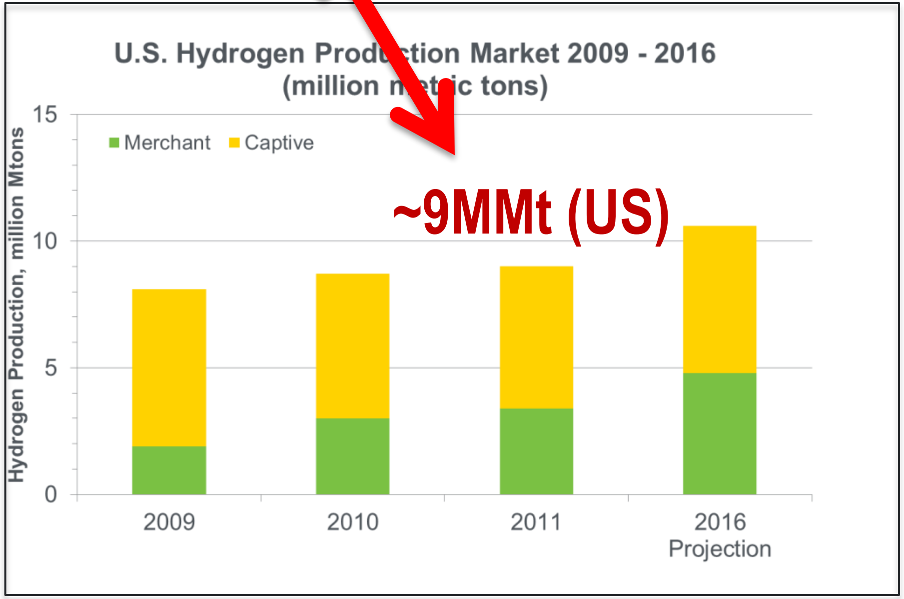
Several automakers have announced commercial FCEVs in the 2015-2017 timeframe.

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

H_2 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)	*early deployment*
250 million	175,000	~64 (>>9)	*~# cars on US roads*



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

Hydrogen Production & Applications

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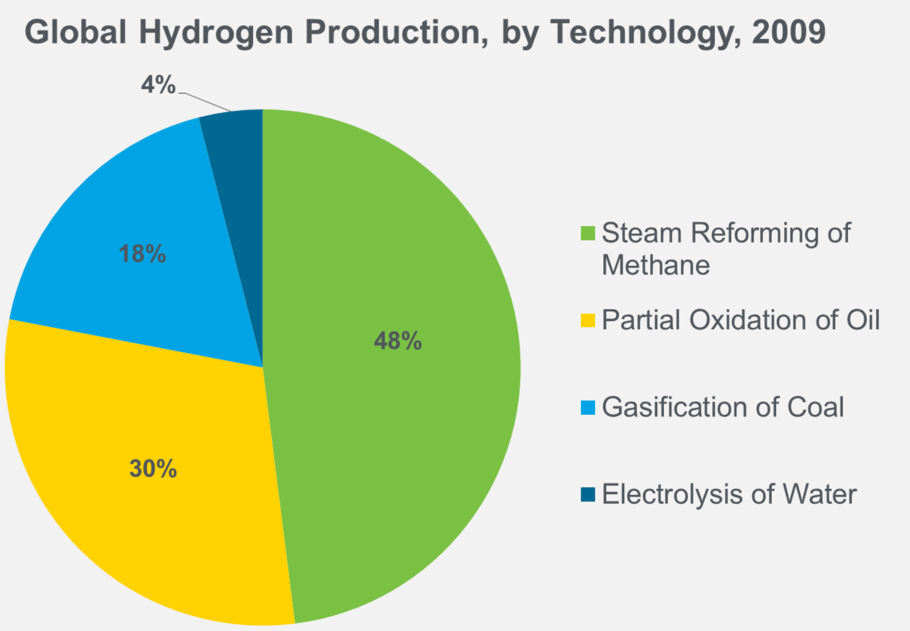
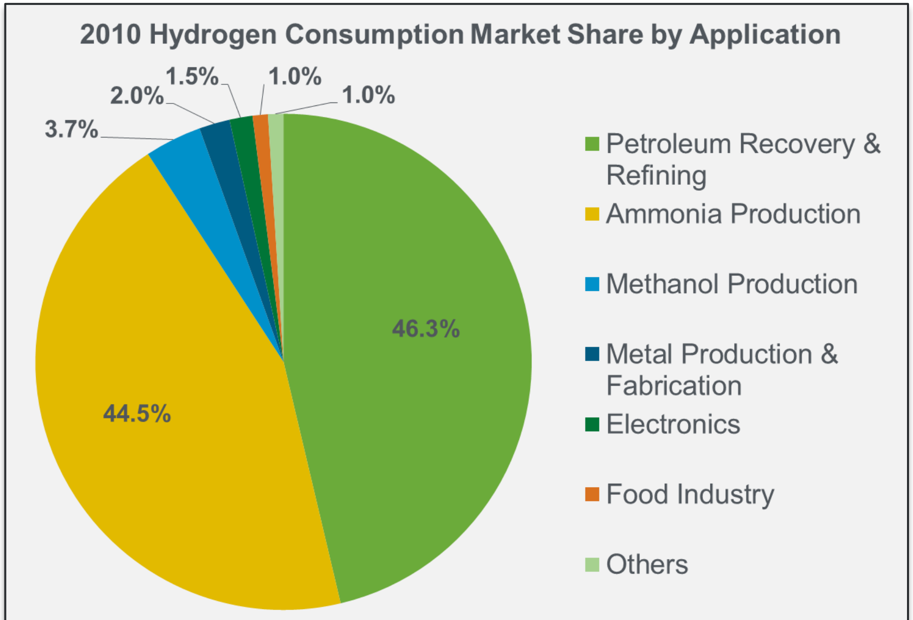


Hydrogen is produced through a variety of technologies, though ~95% of U.S. hydrogen production comes from SMR.

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.

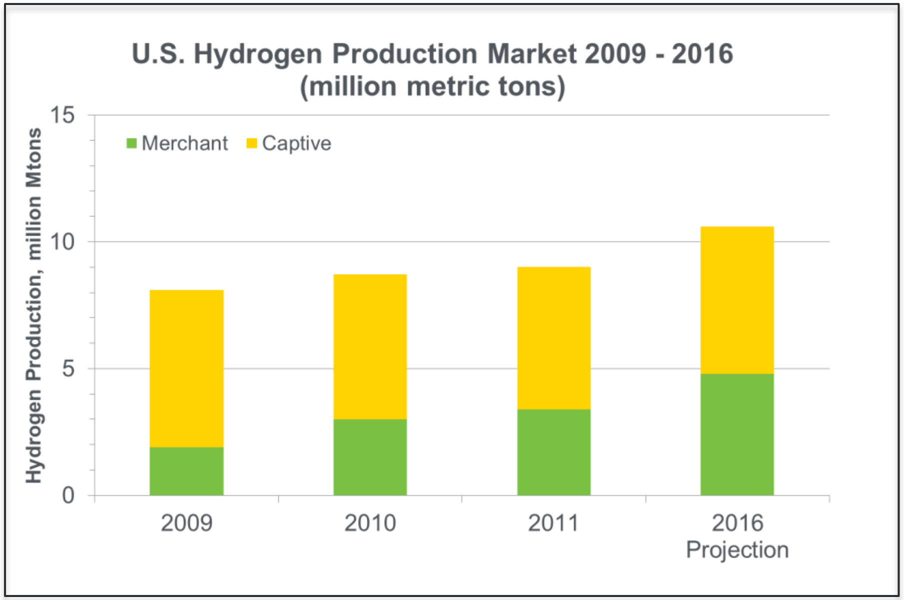
Major merchant suppliers

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



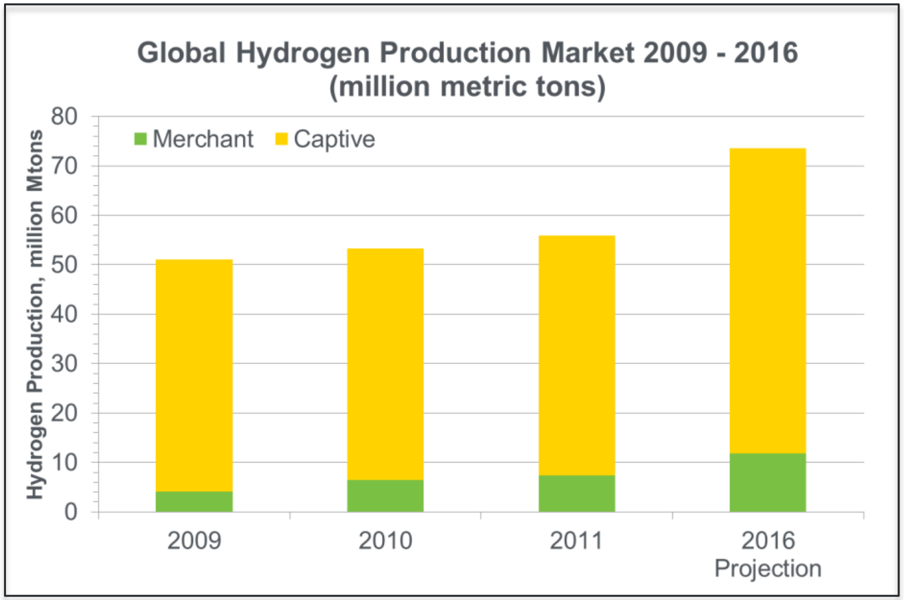
Hydrogen Production Markets

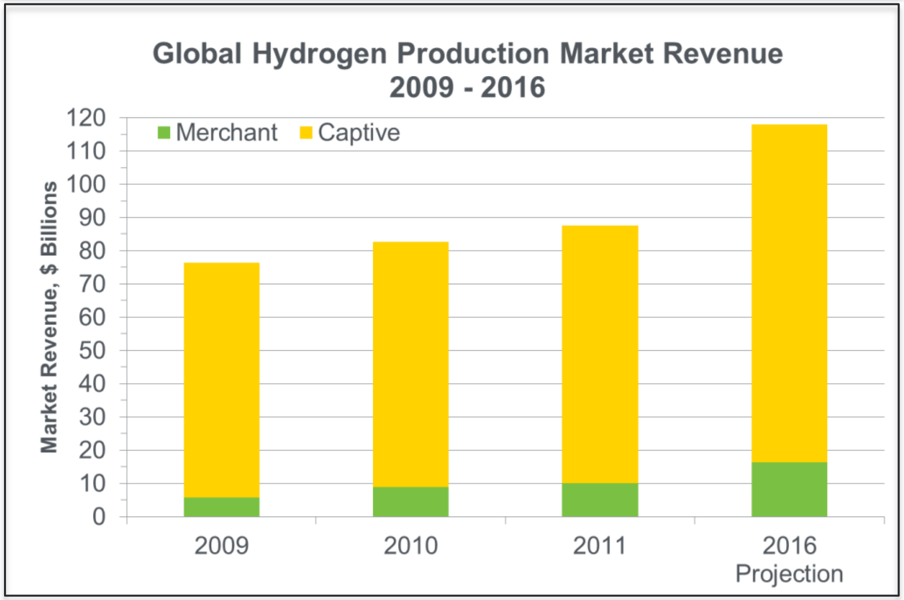
U.S. DEPARTMENT OF ENERGY



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.





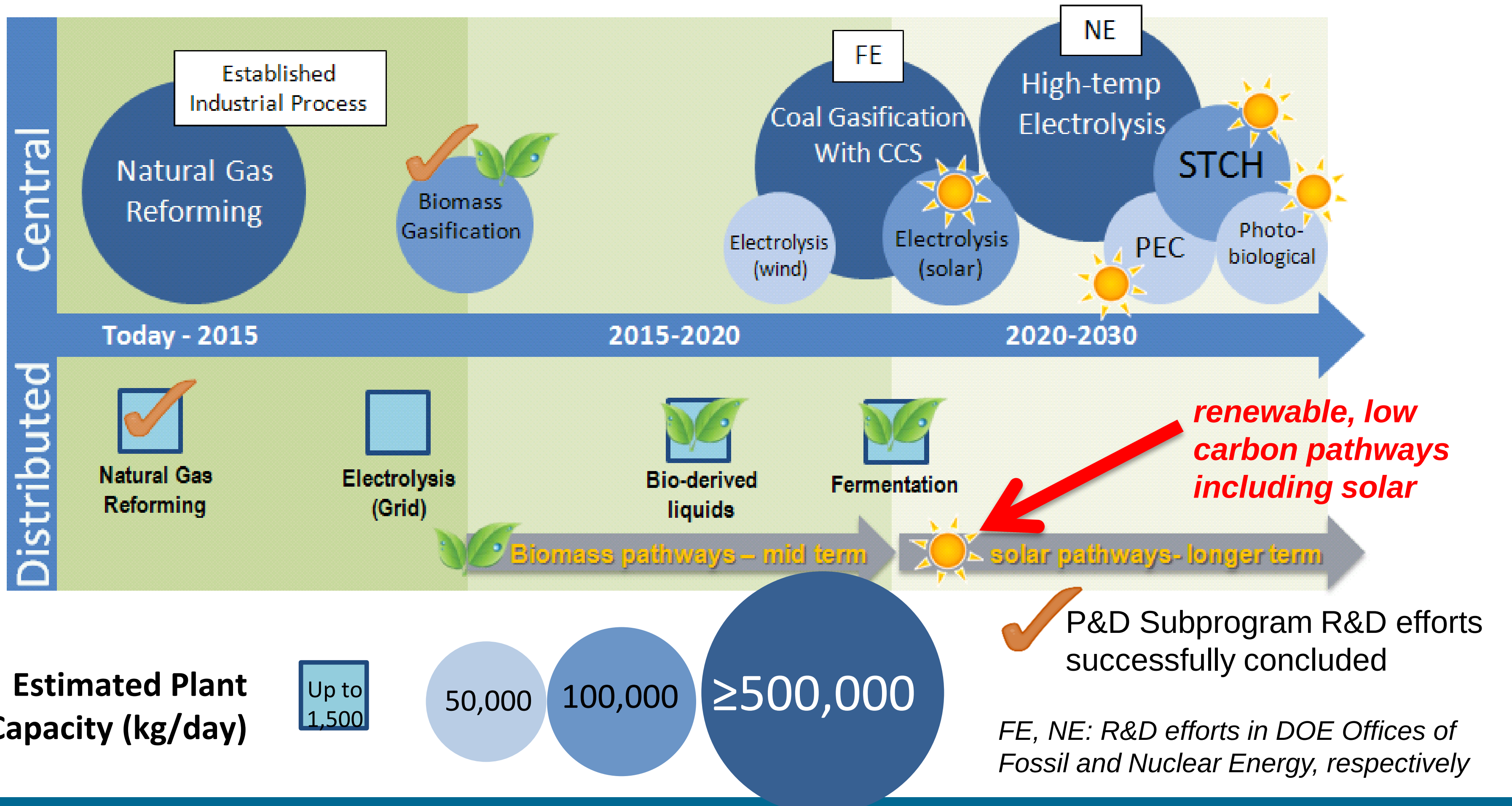
DOE Hydrogen Production Portfolio

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

Recent Program Accomplishments:

- *>550% return on investment (\$48M in direct revenues) from electroylzer products*
- *Reduced stack costs by >60% to less than \$400/kW since 2007 (Proton OnSite,Giner)*

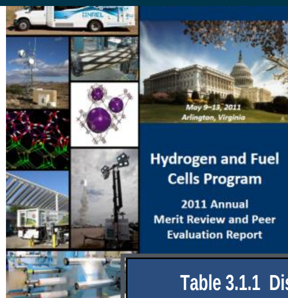


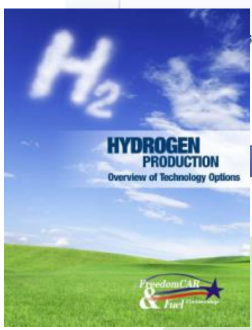
FE, NE: R&D efforts in DOE Offices of Fossil and Nuclear Energy, respectively

H_2 Production Program Strategy

U.S. DEPARTMENT OF ENERGY

Technoeconomic analyses inform programmatic decisions





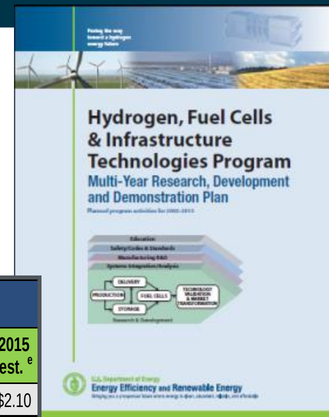


Table 3.1.1 Distributed Forecourt Natural Gas Reforming [a, b, c]

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

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

Informed Prioritization of Funding

2009

Identification of R&D pathways.

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

2010
2011

Cost Analysis

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

2012

Performance Target Analysis

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

Upgrade of Analysis Efforts

U.S. DEPARTMENT OF ENERGY

New project initiated to continue refinement of case studies

Team:

Strategic Analysis, Inc.

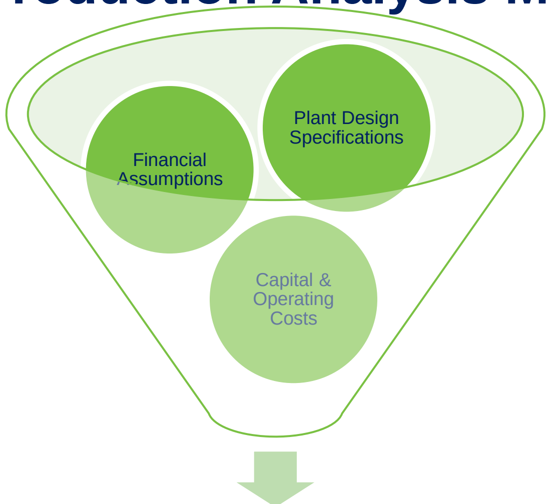
PI: Brian James

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	

Hydrogen Production Cost: Status vs. Goals

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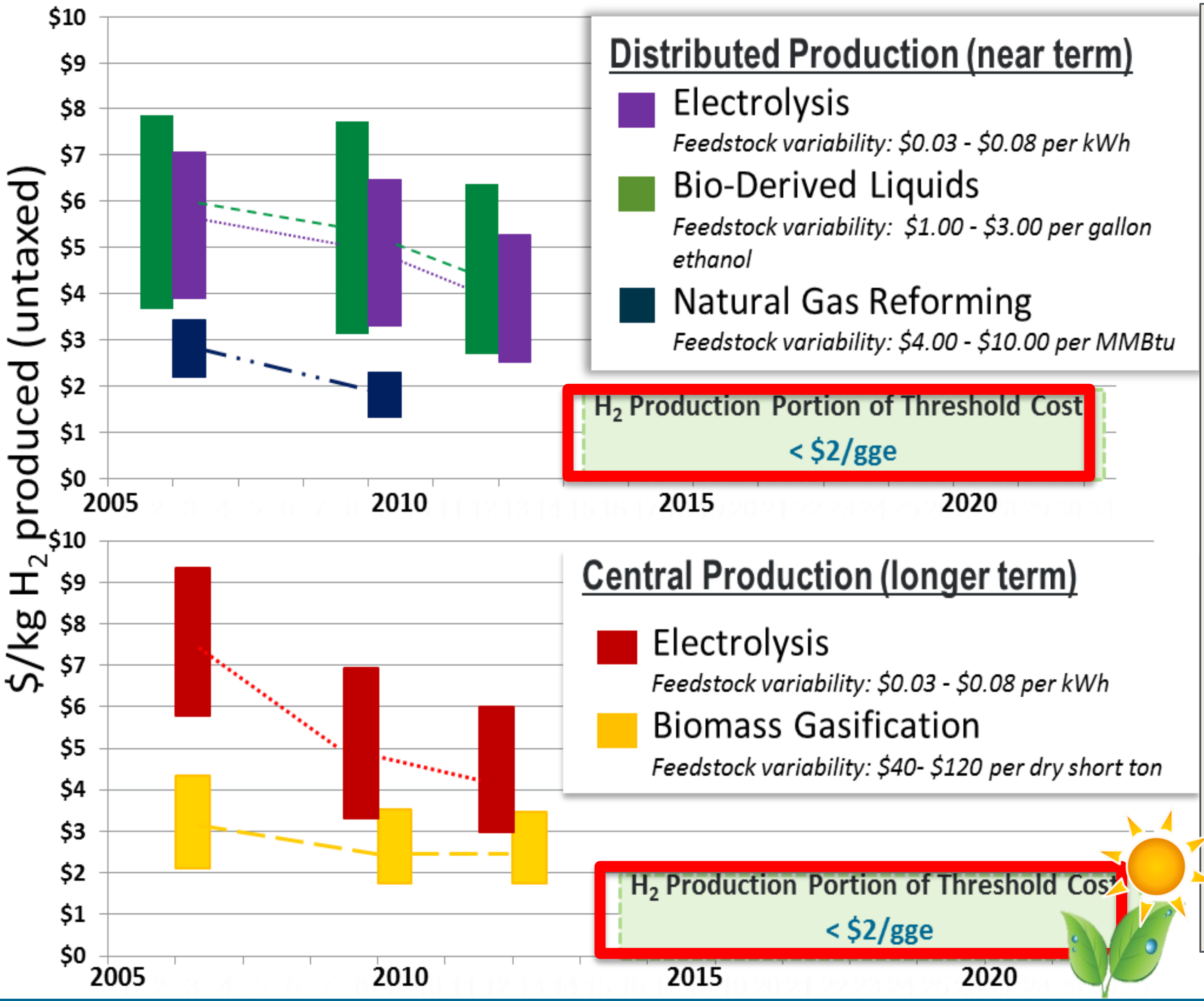
Projected High-Volume Cost of H_2 fuel for Near-Term Production Pathways



- **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).**
- **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.**

Biological Hydrogen R&D

U.S. DEPARTMENT OF ENERGY

Innovative reactor configurations and genetic engineering used to improve microbial hydrogen production

R&D Approach and Focus

- Development of strains with improved hydrogen production capacity
- Technoeconomic analysis to establish efficiency and production duration requirements for meeting DOE cost goal

Develop O_2-tolerant Photolytic Organisms

- Engineered cyanobacterial strains with non-native, oxygen-tolerant hydrogenases *(NREL, JCVI)*
- Algae with modified or replaced hydrogenases to reduce oxygen sensitivity *(NREL)*

Improved Photo-biological Activity

- Increase light utilization by reducing collection of excess photons *(UC-Berkeley)*
- Improved energy flow from photosynthesis to hydrogen production pathways *(NREL, JCVI)*

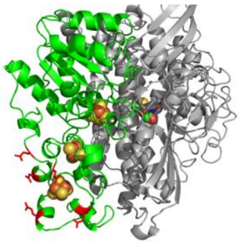
Feedstocks

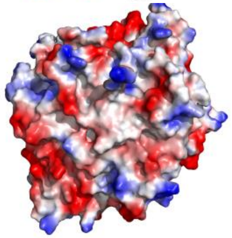
- Improved utilization of less refined biomass feedstocks (cellulose, corn stover) through genetic engineering, optimized mixtures of strains *(NREL)*
- Optimized Microbial Electrolysis Cells (MEC) to produce hydrogen from fermentation wastewater *(Penn State)*

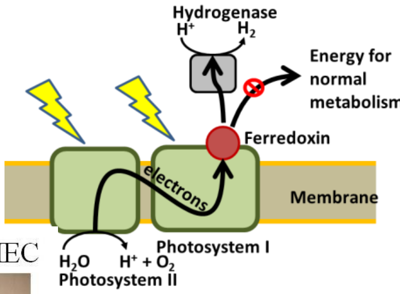
Reactor Designs

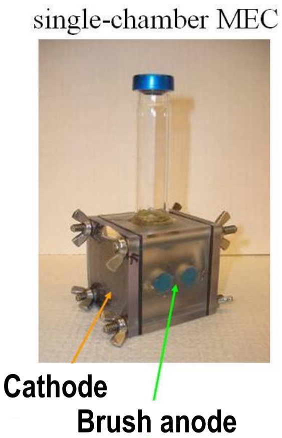
- Improved sequence-batch bioreactor systems *(NREL)*
- Innovative MEC designs to reduce or eliminate external power requirements *(Penn State)*

Genetic engineering to improve strain's hydrogen production capacity









Improved reactor designs for better feedstock utilization, hydrogen production rates

DOE Biological Hydrogen Pathway Targets

U.S. DEPARTMENT OF ENERGY

Technoeconomic analysis leads to aggressive targets

http://www.hydrogen.energy.gov/h2a_prod_studies.html

Photolytic

Table 3.1.10 Technical Targets: Photolytic Biological Hydrogen Production [a]

Characteristics	Units	2011 Status	2015 Target [c]	2020 Target [d]	Ultimate Target [e]
Hydrogen Cost [b]	$/kg	NA	NA	9.20	2.00
Reactor Cost [f]	$/m^2	NA	NA	14	11
Light utilization efficiency (% incident solar energy that is converted into photochemical energy) [g]	%	25 [h]	28	30	54
Duration of continuous H_2 production at full sunlight intensity [i]	Time Units	2 min [j]	30 min	4 h	8 h
Solar to H_2 (STH) Energy Conversion Ratio [k]	%	NA	2%	5%	17%
1-Sun Hydrogen Production Rate [l]	kg/s per m^2	NA	1.6E-7	4.1E-7	1.4E-6

Fermentation and MECs

Table 3.1.12 Technical Targets: Dark Fermentative Hydrogen Production and Microbial Electrolysis Cells (MECs) [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target [b]
Feedstock Cost [c]	cents/lb. sugar	13.5	10	8
Yield of H_2 production from glucose by fermentation [d]	mol H_2 /mol glucose	3.2 [e]	4	6
Yield of H_2 production from glucose by integrated MEC – fermentation [f]	mol H_2 /mol glucose	-	6 [e]	9 [e]
Duration of continuous production (fermentation)	Time	17 days [g]	3 months	6 months
MEC cost of electrodes	$/m^2	2,400 [h]	300	50
MEC production rate	L-H_2 / L-reactor-day	NA	1	4

Photofermentative

Table 3.1.11 Technical Targets: Photosynthetic Bacterial Hydrogen Production [a]

Characteristics	Units	2011 Status	2015 Target	2020 Target [b]
Efficiency of Incident Solar Light Energy to H_2 (E0*E1*E2) [c] from organic acids	%	NA	3	4.5
Molar Yield of Carbon Conversion to H_2 (depends on nature of organic substrate) E3 [d]	% of maximum	NA	50	65
Duration of continuous photoproduction [e]	Time	NA	30 days	3 mos

FCT Multi-Year Research, Development and Demonstration Plan: using H2A v3 analysis

http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/production.pdf

Short- term and Long-term Strategies Needed

U.S. DEPARTMENT OF ENERGY

How do we get from "NA" to ultimate goals?

Advances continue in all the biological hydrogen pathways, but to achieve aggressive targets the R&D communities must keep considering:

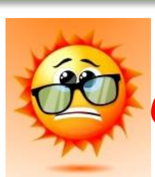
- What are the **THEORETICAL** limits?
- What are the **PRACTICAL** barriers?
- What **FUNDAMENTAL R&D** is needed?
- What **ENGINEERING R&D** in needed?
- What other barriers must be addressed?
- What R&D trajectories are possible in the near- and long-term?

Production at \$2/gge H_2, > 50,000 kg/day

- Unit sub-processes must be clearly defined with quantitative metrics and limits.
- Relationships of unit processes to system performance must be clearly mapped.
- **SYSTEM METRICS*** are critical.
- **SYNERGIES** across pathways should be exploited.

* *kinetics, efficiency, durability, etc.*

Cost, Production, Conversion Efficiency



Current Status: ???

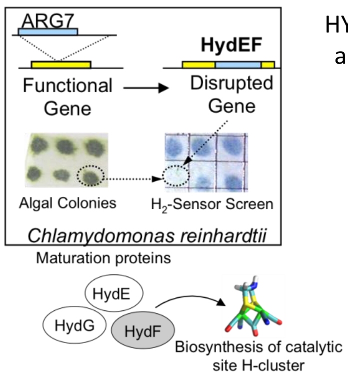
Collaborative Successes

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

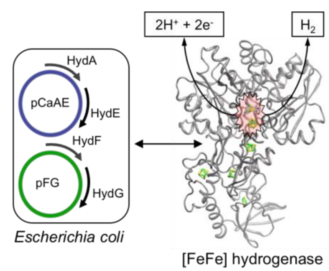
Biological: Tools developed to manipulate bacterial genome for O2 tolerant hydrogen production

Office of Science-funded research (Basic)

Goal: understand the growth factors and signal transduction pathways that regulate transcription of the H_2ase genes in green algae

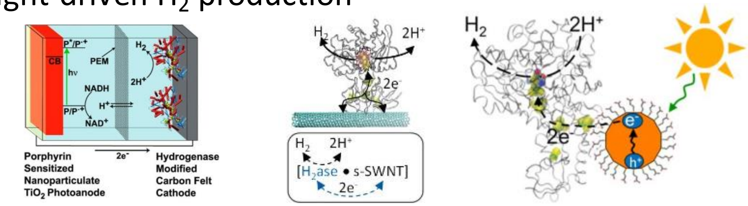


HYDEF mutant in *C. reinhardtii* cannot assemble [FeFe]-H_2ase catalytic site



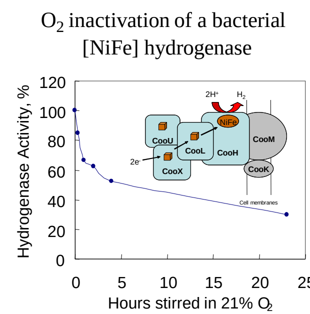
Over-expression of maturases HydE, F and G and structural protein HydA to produce active [FeFe]-H_2ases in the bacterium, *E. coli*

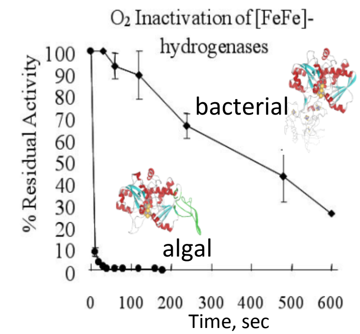
Goal: understand molecular assembly and function of H_2ases in artificial photosynthetic systems for light-driven H_2 production



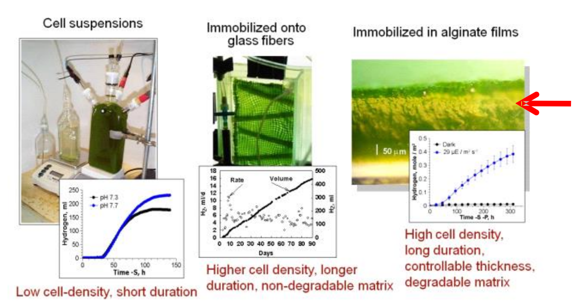
EERE-funded research (Applied R&D)

Goal: express a more O_2-tolerant bacterial H_2ase in oxygenic photosynthetic organisms (algae or cyanobacteria) to function under *aerobic* conditions





Goal: optimize sustained *anaerobic* H_2 production and use it to examine other limiting factors to guide development aerobic H_2 Production to meet targets



Yields H_2 with a conversion efficiency of ~1% under aerobic conditions and low fluorescent light intensity

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

International

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

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

National Laboratories

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

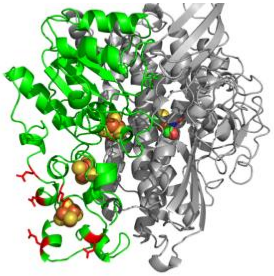
U.S. DEPARTMENT OF ENERGY

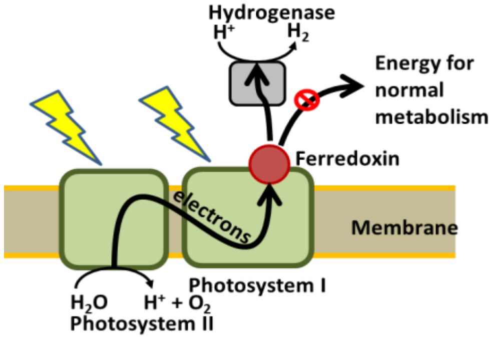
Objective:

To identify research and development (R&D) needs in the areas of photobiological and non-light driven bio-hydrogen production.

Outcome:

- Summary of key biological hydrogen production issues, barriers and opportunities
- Summary of key R&D areas with potential to meet DOE cost and performance goals
- Provide the resulting workshop report for public dissemination





Workshop Strategy

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Two Sessions: photobiological and non-light driven biological hydrogen production

- Expert panel discussions

- Breakout Sessions to Identify:
- Issues involved in developing low-cost biological hydrogen production methods

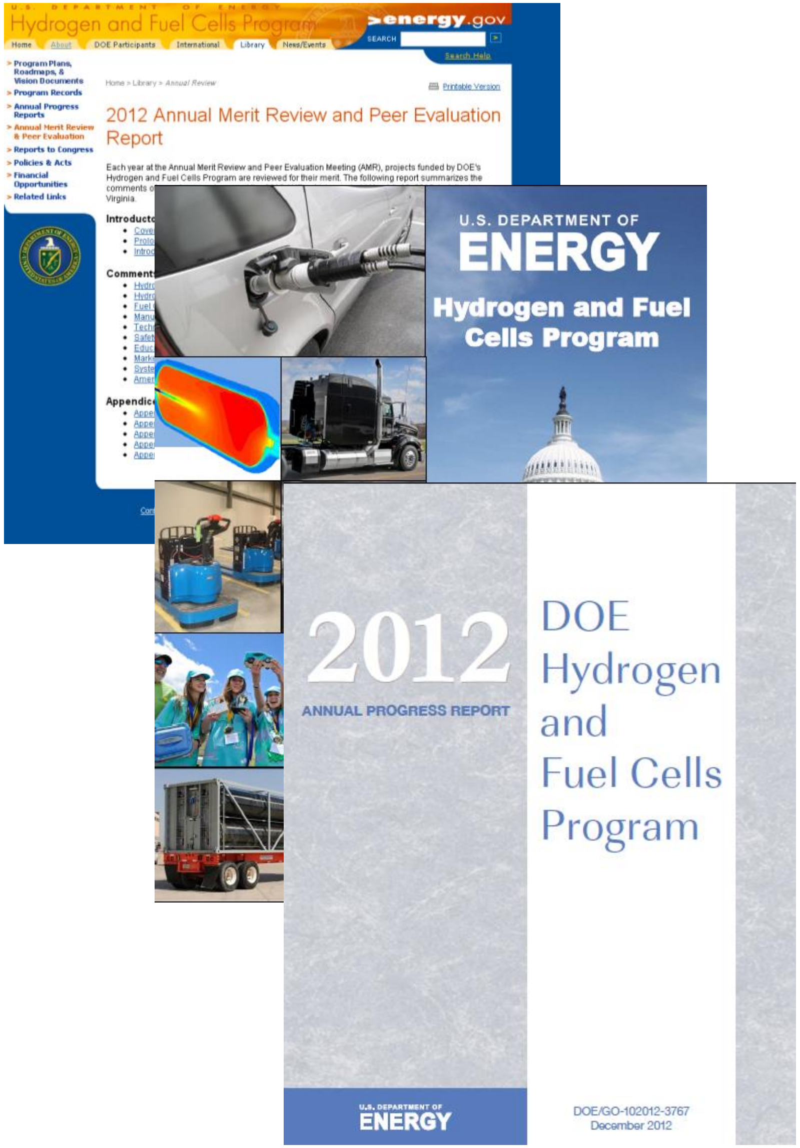
- Major barriers to developing low-cost biological hydrogen production

- R&D needed to achieve efficient, low-cost biological hydrogen production

- Key near-term activities for impact on production issues and barriers

Annual Merit Review

U.S. DEPARTMENT OF ENERGY



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 13– 17, 2014 Arlington, VA

http://annualmeritreview.energy.gov/

U.S. DEPARTMENT OF ENERGY

Thank You

For questions please contact:

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Or

Sarah.Studer@ee.doe.gov