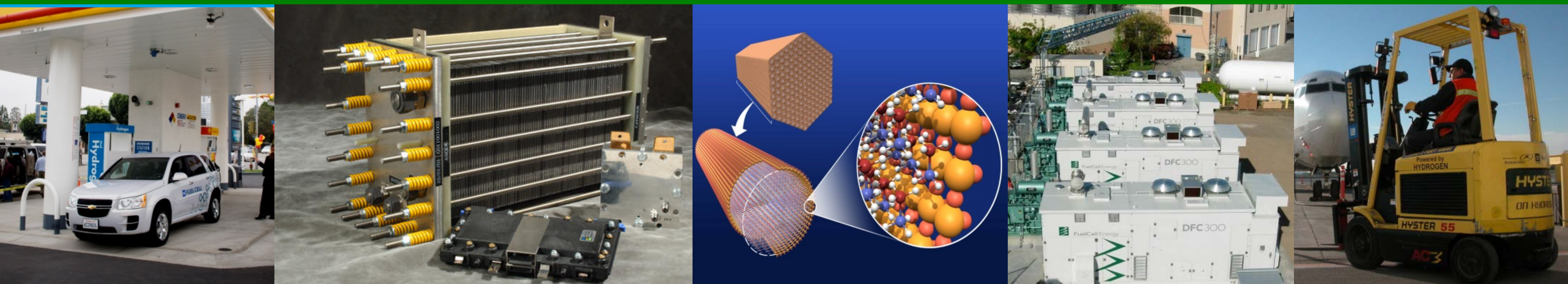
U.S. DEPARTMENT OF
ENERGY



Hydrogen Production & Delivery Program
- Plenary Presentation-

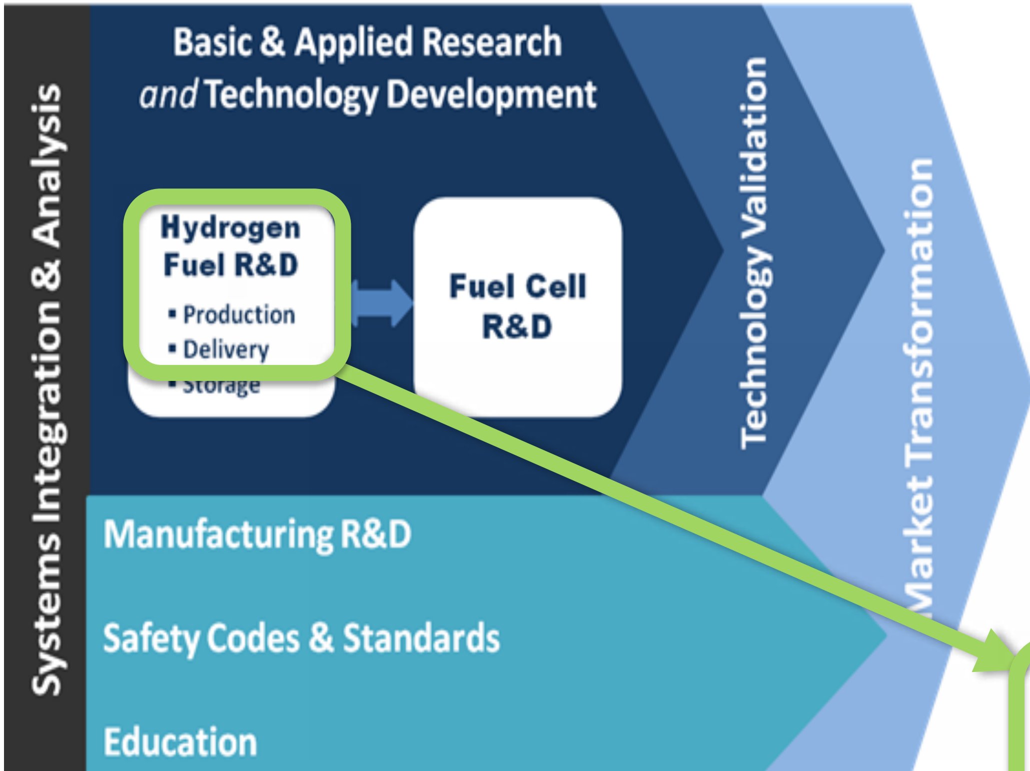
Eric L. Miller

2015 Annual Merit Review and Peer Evaluation Meeting

June 8 - 12, 2014

H_2 Production & Delivery Program Goal

Integrated Work Areas



2020 Targets by Application

Fuel Cell Cost	$40/kW	$1,000/kW* $1,500/kW**
Durability	5,000 hrs	80,000 hrs

*For Natural Gas
**For Biogas

H_2 Storage Cost (On-Board) $10/kWh
1.8 kWh/L, 1.3 kWh/kg

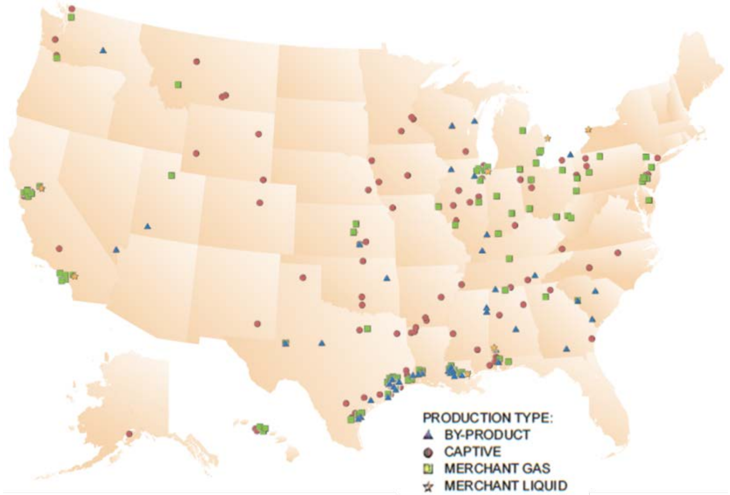
H_2 Cost at Pump <$4/gge
<$2 Production and <$2 Delivery & Dispensing

Program MYRD&D includes pathway-dependent technical metrics and targets tied to the cost goal

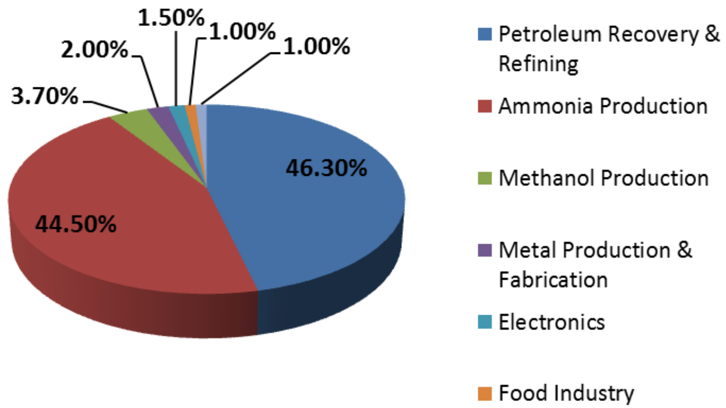
Develop technologies to produce H_2 from clean, renewable domestic resources for <$4/gge (delivered & dispensed, but untaxed) by 2020

H_2 Production & Delivery: Current Status

- **~10 million tonnes H_2 in US from NG reforming for petroleum refining, ammonia production, etc. today**
- **NG can provide near-term cost-competitive H_2 at scale:**
  - <$2/gge produced ($4.50/gge delivered)
- **>1,500 miles of H_2 pipeline**
- **~50 current H_2 stations (10 public)**
- **Plans for H_2 stations:**
  - 100 in CA; 100 each in Germany & Japan (1,000 each in Germany & Japan by 2025)
- **Growing demand for renewable H_2**
  - renewable electrolysis, bio-conversion, etc.



Existing centralized H_2 production facilities



H_2 consumption market share by application

Early adoption of H_2 and fuel cell technologies can leverage production and delivery infrastructure associated with low cost NG reforming

Growing Transportation Market for Hydrogen

- **Fuel cell cars are here today: the Toyota Mirai is the first commercially available fuel cell electric vehicle (FCEV) for sale in the USA**
- **Fueling infrastructure for FCEV is needed in the immediate near-term**
- **Traditional resources (natural gas in particular) can meet the near term hydrogen demand**
- **Large-scale production from renewable resources will be needed in the long-term to meet the needs of emerging FCEV markets and other end uses**

FCEV Announcements: 2013-2015

Number of Fuel Cell Cars Served	Hydrogen Demand (metric tons)	
	Daily	Yearly
1 million	~685	~0.25 M <<10 *(USA usage)*
250 million	~171 k	~63 M >>10

See Fuel Cell Technologies Office Program Record # 12014

Market penetration of FCEVs can have significant energy-security and environmental benefits, if clean/renewable H_2 can be supplied at scale

Hydrogen P&D Needs and Priorities

Immediate Needs

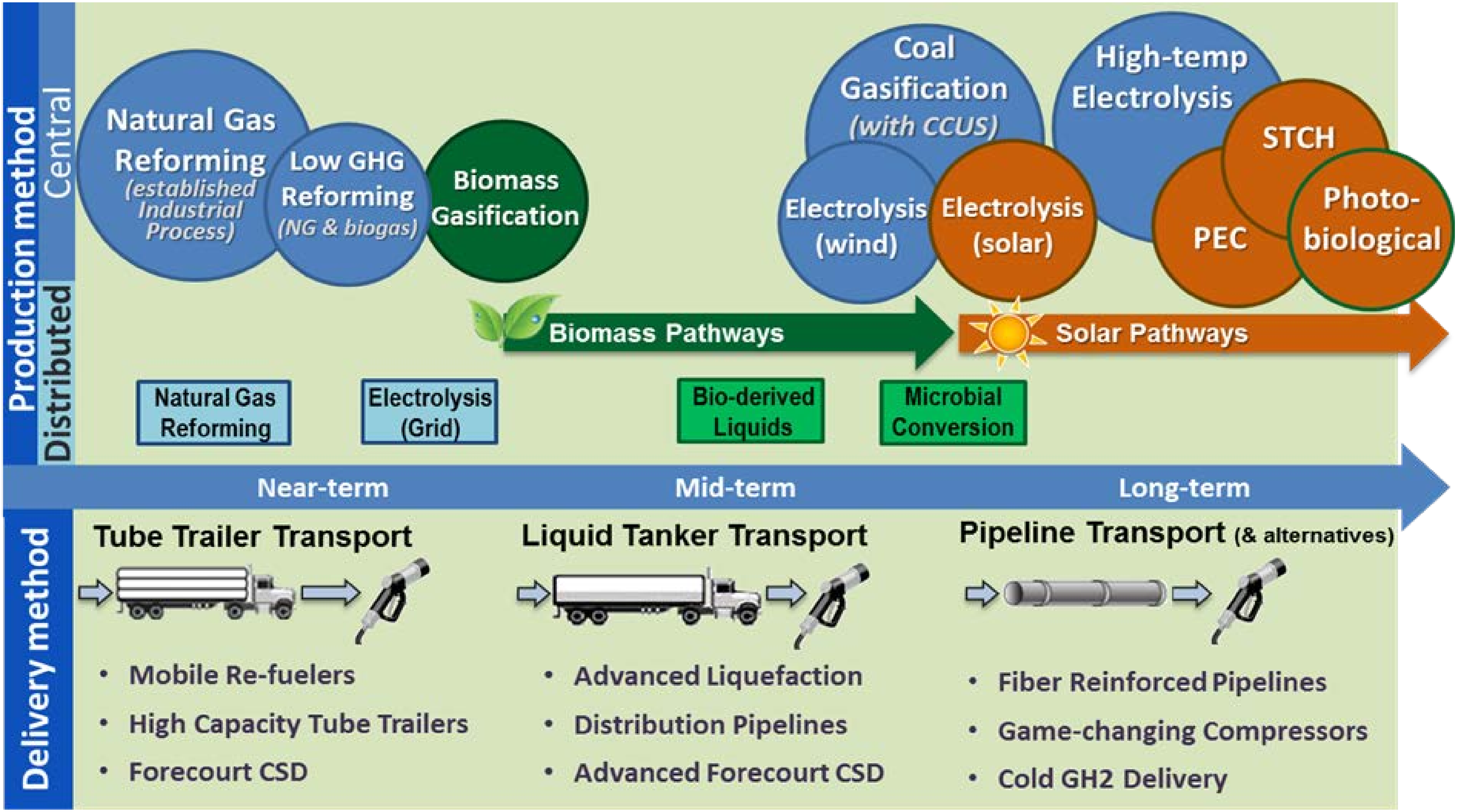
- Utilize existing infrastructure (e.g. NG) to support H_2 production and delivery for growing markets in FCEVs and other end uses
- Improve cost, reliability & efficiency of forecourt components, including compressors, hoses, seals and station storage
- Improve reliability and cost of near-term renewable H_2 options, such as renewable electrolysis and bio-derived feedstock conversion

Ongoing Priorities

- Applied RD&D in materials & devices (leveraging basic research) to address efficiencies, performance, durability, cost, and safety in the portfolio of renewable H_2 production and delivery options
- System-level innovations including renewable integration schemes, tri-generation, energy storage, balance-of-plant improvements, etc.
- Continued resource assessments to identify near-term regional solutions and a long-term sustainable portfolio of cost-competitive H_2 production and delivery options

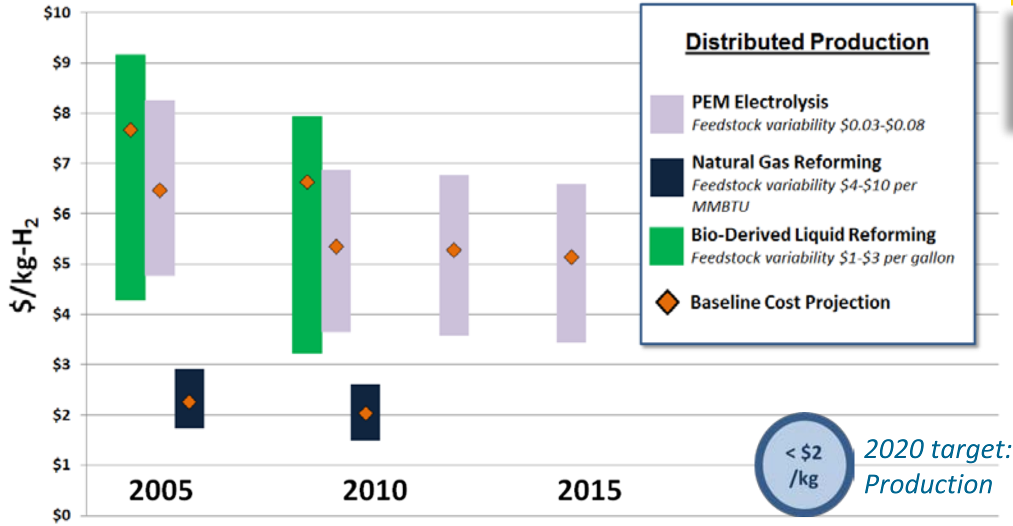
Large-scale market acceptance of H_2 and fuel cell technologies requires continued cost reductions in hydrogen production and delivery options

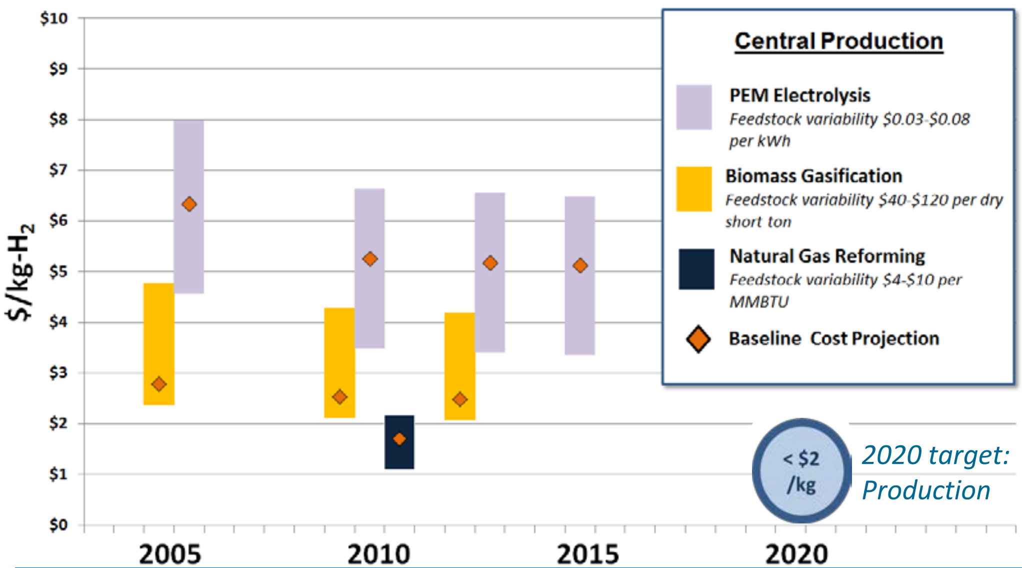
H_2 Production & Delivery RD&D Portfolio



Addressing the near-term infrastructure rollout needs as well as the longer-term transition to large-scale renewable hydrogen

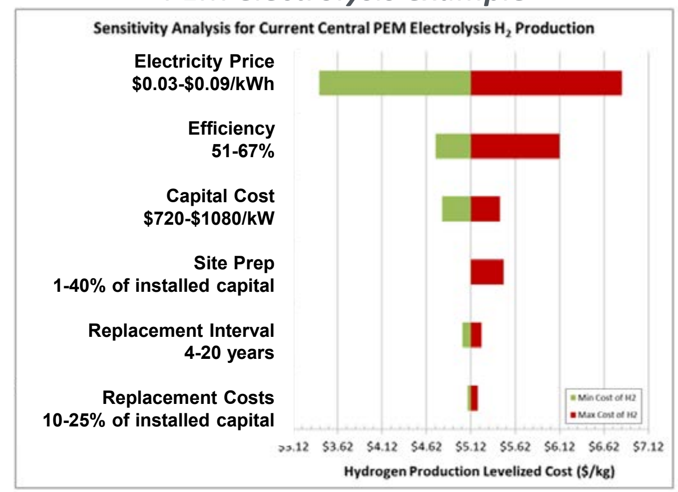
Near-Term H_2 Production Pathways Cost Status

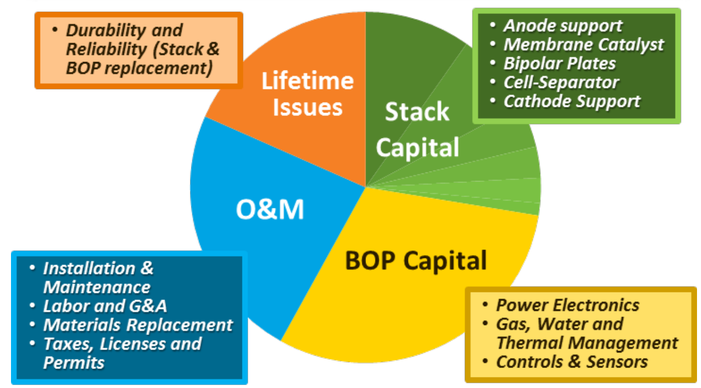




Program uses techno-economic analysis to quantify RD&D cost-reduction opportunities

PEM electrolysis example

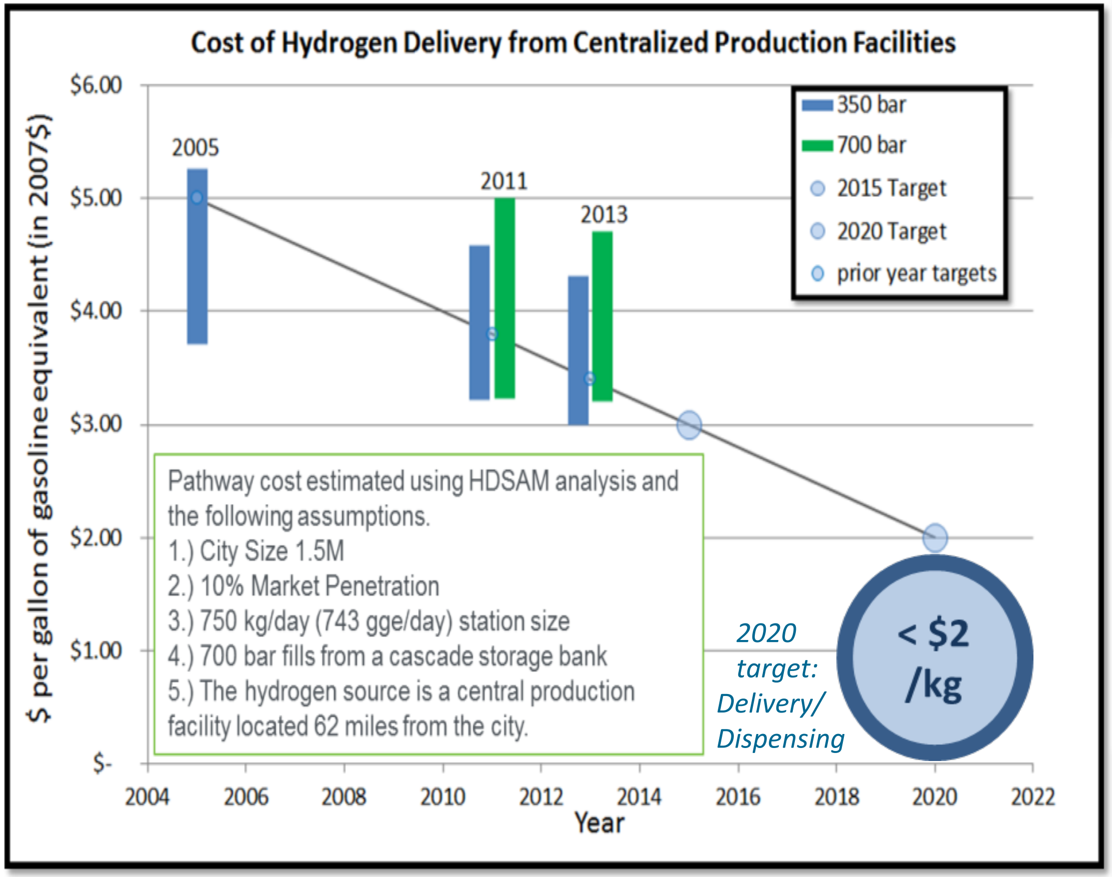




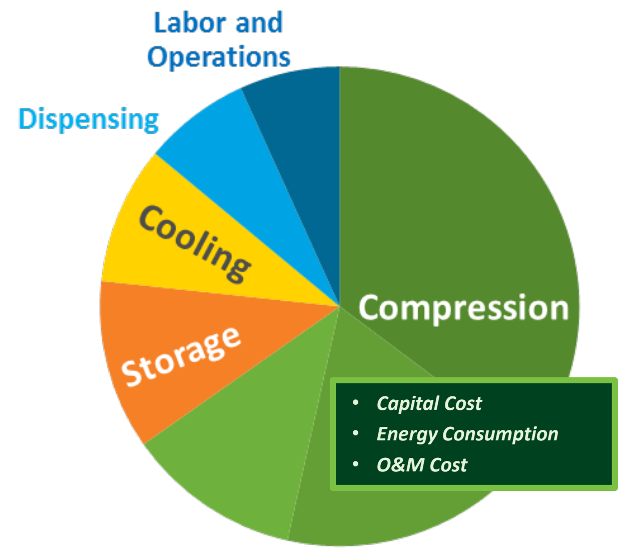
breakdown: non-electricity costs

Feedstock & capital cost sensitivities show that NG reforming meets the DOE H_2 cost target - further RD&D is needed to reduce cost of renewable pathways

H_2 Delivery and Dispensing Cost Status



Techno-economic analysis quantifies RD&D cost-reduction opportunities in H_2 delivery & dispensing



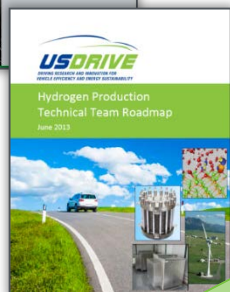
In the pipeline delivery scenario Station CSD costs adds between $1.00 - $3.00 to the cost of dispensed hydrogen, ~70% attributed to compression and storage

H_2 delivery and station compression, storage and dispensing costs remain high; reducing cost of 700 bar refueling stations for FCEV roll-out is a critical priority

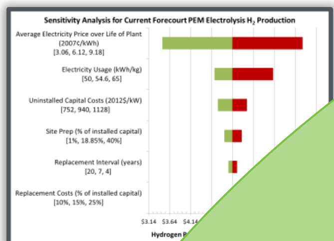
RD&D Portfolio Development Approach

Workshops

U.S. DRIVE Tech Team Roadmaps

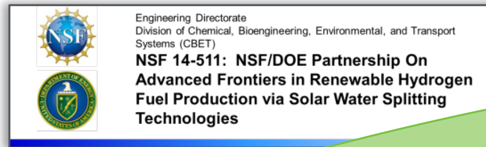


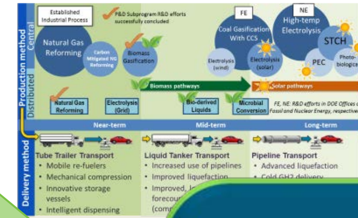
H2A



HDSAM

SBIR / STTR
Small Business Innovation Research
Small Business Technology TRansfer





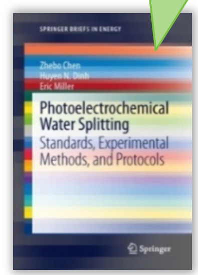
Analysis & Studies

Stakeholder Input

Collaboration & Coordination

H2FIRST
Hydrogen Fueling Infrastructure Research and Station Technology

H2USA



Pathway Working Groups

RD&D Portfolio

priorities, metrics, targets

Table 3.1.7 Technical Targets: Solar-Driven High-Temperature Thermochemical Hydrogen Production

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Solar-Driven High-Temperature Thermochemical Cycle Hydrogen Cost	$/kg	NA	14.80	3.70	2.00
Chemical Tower Capital Cost (installed cost)	$/TPD H_2	NA	4.1MM	2.3MM	1.1MM
Annual Reaction Material Cost per TPD H_2	$/yr-TPD H_2	NA	1.47M	89K	11K
Solar to Hydrogen (STH) Energy Conversion Ratio	%	NA	10	20	26
1-Sun Hydrogen Production Rate	kg/s per m²	NA	8.1E-7	1.6E-6	2.1E-6

FCTO MYRD&D Plan for Meeting Cost Goals

Techno-economic analyses & stakeholder input inform programmatic decisions & priorities for P&D portfolio of pre-competitive RD&D

Stakeholder Engagements are Critical

Ongoing Collaborative Activities

- H2USA Station Working Group and H2First Projects (*NREL / SNL)*
- U.S.DRIVE Tech Teams – *Production, Delivery, Analysis*
- Cross-Office/Agency Collaborations– *BES, ARPA-E, NSF*
- DOE Cross-Cutting Efforts – *AMM/MGI, WBS, CEMI, Grid Integration*
- FCTO H_2 Working Groups – *Electrolysis, PEC, Biological and STCH*
- IEA-HIA – *Tasks in Renewable Hydrogen & Hydrogen and Infrastructure*

Welcome BES, ARPA-E and NSF!

H_2 P&D PIs are early adopters of accelerated materials development approaches

Recent Workshops and Meetings

- **Workshops –*H_2 and Bio-products from Wastewaters (FCTO/BETO); International Workshop on H_2 Infrastructure; Advanced Materials Manufacturing …..***
- **Meetings & Symposia– *Spring ECS Meeting on Cross-cutting Technology Metrics; Spring MRS Meeting Session on Photochemical H_2 Production, & others***

Collaborative activities, workshops and meetings help focus portfolio RD&D priorities

Strategies and Key Areas in H_2 P&D Portfolio

Challenge	Strategies	RD&D Focus	Key Areas
Reduce the cost of sustainable low-carbon hydrogen production & delivery while meeting safety and performance requirements • Feedstock costs • Capital costs • O&M costs	***Near-term*** Minimize cost of 700 bar hydrogen at refueling stations ***Long-term*** Improve performance and durability of materials and systems for production from renewable sources	• Techno-economic analysis • Reliability and cost of compression, storage and dispensing • Renewable integration • Advanced materials and systems for H_2 delivery • Innovations in materials, devices and reactors for renewable H_2 production • Improved balance of plant for P&D systems	***Delivery*** • Polymers & composites for delivery technologies • Liquefaction technologies • Compressor reliability • Low cost onsite storage ***Production*** • Advanced electrolysis • Biomass/biogas conversion • Hybrid fossil/renewable approaches • Solar water splitting: PEC, STCH, biological

RD&D Support Framework:

- FCTO FOA & Lab Calls
- SBIR/ STTR
- NSF/DOE MOU
- Incubator Projects
- Prizes and Other

A balanced portfolio of pre-competitive RD&D addresses the near and longer term needs for widespread acceptance of H_2 & fuel cells

H_2 Production & Delivery Analysis Projects

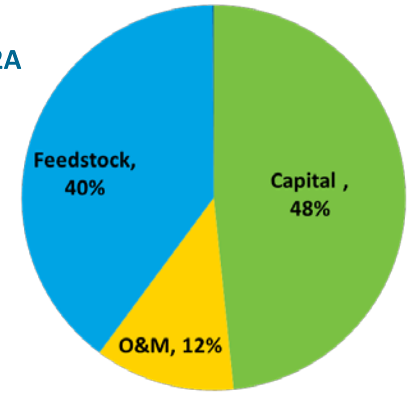
Advanced H_2 Production Pathways Analysis

***Strategic Analysis Inc.**, NREL, ANL*

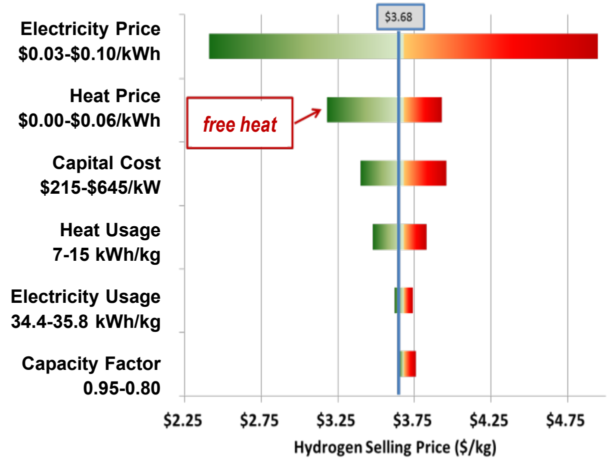
FOA/Lab PD102

- **Focus:** Analyze H_2 P&D pathways to determine economical, environmentally-benign, and societally-feasible paths for the P&D of H_2 fuel for fuel cell vehicles
- **Highlight:** Completed case studies for high-temperature electrolysis and fermentation using H2A V3.1

Fermentation H2A case cost breakdown



Hi-Temp electrolysis H2A case cost sensitivity



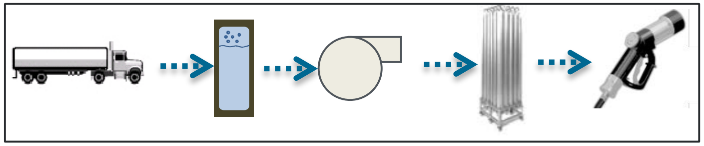
Hydrogen Delivery Infrastructure Analysis

***ANL**, NREL, PNNL, LLNL*

FOA/Lab PD014

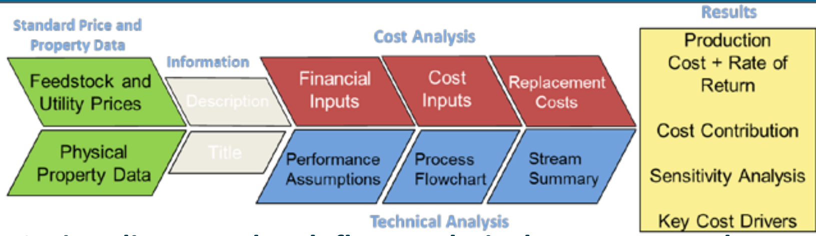
- **Focus:** Analyze delivery pathways to assess the impacts of key design and economic parameters, and identify cost drivers of current technologies
- **Highlight:** Developed the Hydrogen Refueling Station Analysis Model (HRSAM), which determines the current low-volume levelized cost of hydrogen fueling stations given user inputs on station design and utilization

Hydrogen delivery infrastructure components



Continued improvements in techno-economic analysis tools and case studies

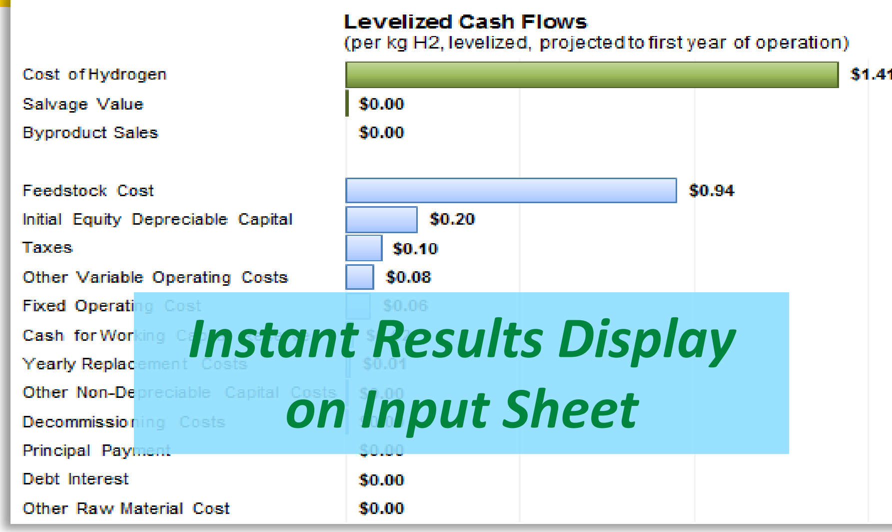
Analysis Accomplishment: H2A Tool Upgrade



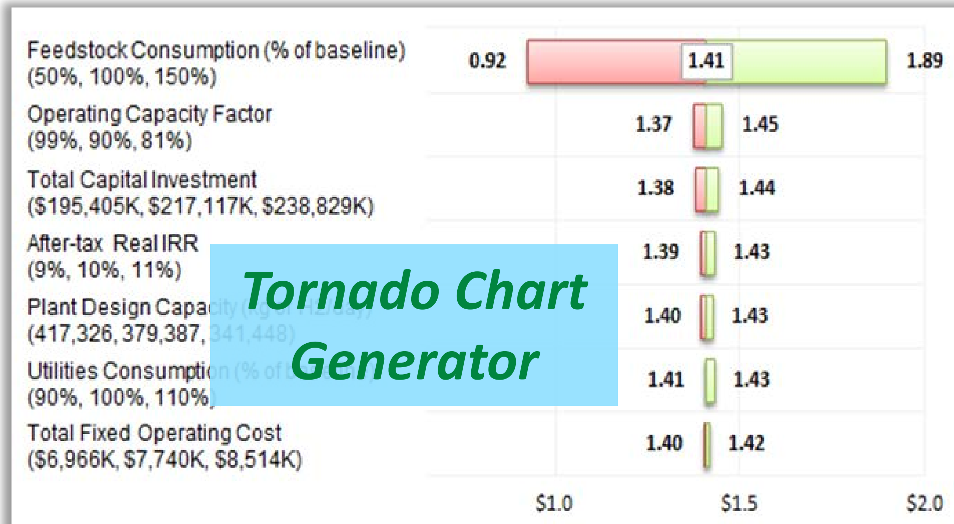
- H2A is a discounted cash flow analysis that computes the required price of H_2 for a desired after-tax internal rate of return
- Developed by NREL and DOE EERE-FCTO
- H2A Production Objectives
  - Establish a standard format for reporting the production cost of H_2, to compare technologies in case studies
  - Provide transparent analysis
  - Provide consistent approach
  - Prioritize research and development efforts

Updated Economic Basis

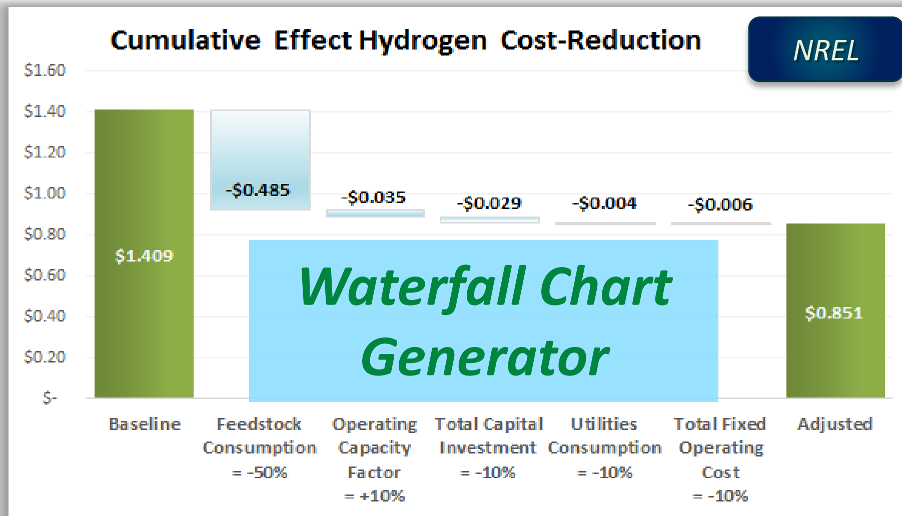
PD/SA



Instant Results Display on Input Sheet



Tornado Chart Generator

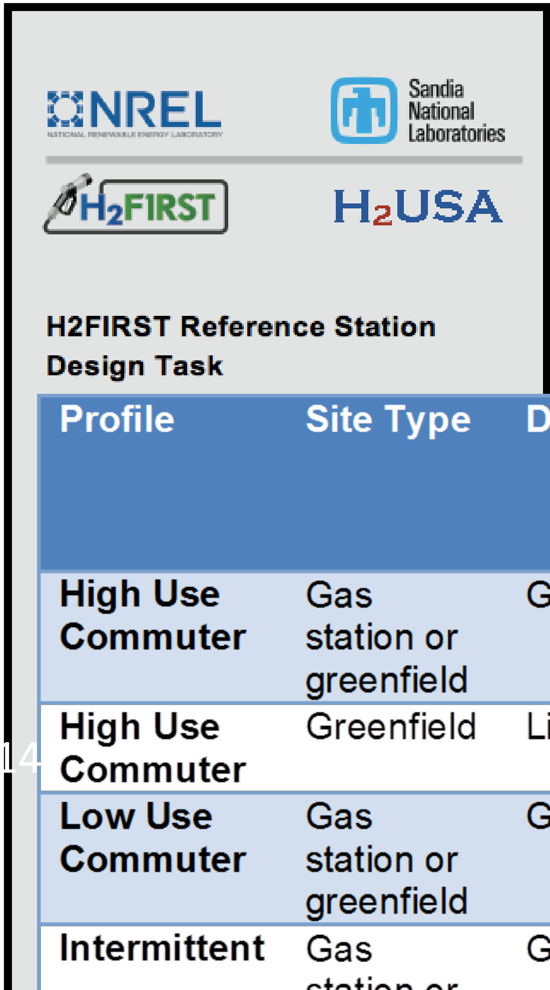


NREL

Waterfall Chart Generator

New and powerful automated features improve the H2A tool and facilitate the development of advanced case studies

H2FIRST Project Accomplishment


NREL NATIONAL RENEWABLE ENERGY LABORATORY
Sandia National Laboratories
H2FIRST
H2USA
H2FIRST Reference Station Design Task

Reference Station Design Report

PD/SCS/TV

- ✓ **Analyzed 160 station permutations and selected four high-priority, near-term station concepts based on economics, technical feasibility, and market need**
- ✓ **Produced spatial layouts, bills of materials, and piping & instrumentation diagrams and detailed cost estimates**

Profile	Site Type	Delivery	Capacity (kg/day)	Consecutive Fills	Hoses	Station Contribution to Hydrogen Cost ($/kg)	Capital Cost (2009$)
High Use Commuter	Gas station or greenfield	Gaseous	300	6	1	$6.03	$1,251,270
High Use Commuter	Greenfield	Liquid	300	5	2	$7.46	$1,486,557
Low Use Commuter	Gas station or greenfield	Gaseous	200	3	1	$5.83	$1,207,663
Intermittent	Gas station or greenfield	Gaseous	100	2	1	$13.28	$954,799

Determination of top-performing station types that best-match market needs, and initiation of detailed conceptual designs

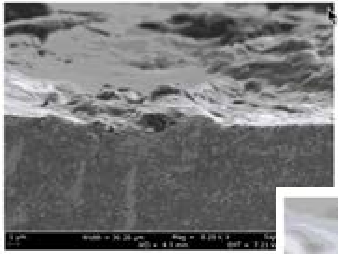
Advanced Barrier Coatings for Seals

***GVD**, Greene Tweed, ORNL, Hydropac, Praxair*

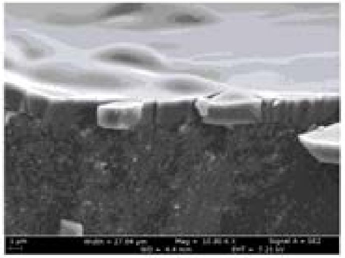
SBIR/BES

- **Focus:** Develop a novel vapor deposition process for flexible barrier coatings to prevent hydrogen ingress into seals, e.g., in H_2 compressors
- **Highlight:** Successfully optimized the coating process to reduce seal roughness and defects in the barrier layer, reducing hydrogen permeation

GVD barrier layer coating process



Prior to coating



Post coating

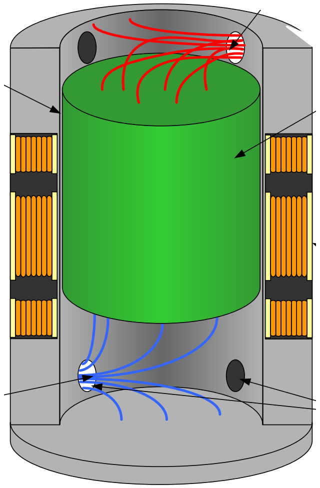
Linear Motor Reciprocating Compressor

***Southwest Research Institute**, ACI Services*

FOA/Lab | PD108

- **Focus:** Develop a novel and patented concept of driving a permanent magnet piston inside a hermetically-sealed compressor cylinder through electromagnetic windings to minimize mechanical part count and reduce leakage paths
- **Highlight:** Completed initial design, FEA and thermodynamic analysis of the LMRC

LMRC Concept



Addressing critical need to improve compressor reliability and cost

CSD Highlights: Stationary Storage

Steel/Concrete Composite Vessels

ORNL*, Temple U., Wiretough, Hanson Pressure Pipe, Bki*

FOA/Lab PD109

- **Focus:** Develop and demonstrate novel SCCV designs and fabrication technologies that meet DOE technical and cost targets
- **Highlight:** Identified opportunities for significant cost reductions in the hydrogen permeation barrier, the steel vessel design, the concrete reinforcement design, and in novel sensor technologies

ORNL steel/concrete composite vessel

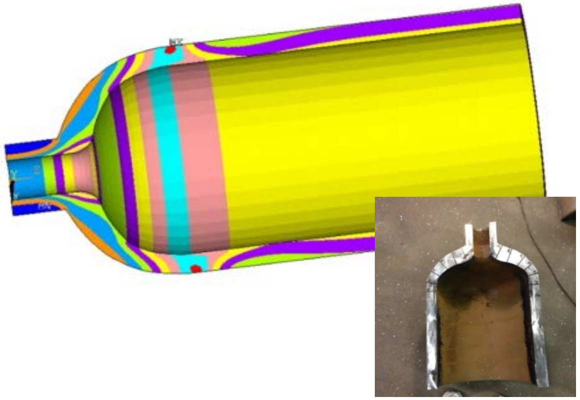
Steel Liner & Steel Wire Wrap Vessels

Wiretough*, ORNL, N&R Associates, CP Industries*

FOA/Lab PD110

- **Focus:** Develop a pressure vessel with a capacity of 765 liters to safely store hydrogen at 875 bar that also meets the DOE storage tank cost target of <$1000/kg H_2
- **Highlight:** Completed successful burst test on short wrapped cylinder, including pressures up to 38,100 psi, exceeding the target pressure based on a safety factor of 3

Wiretough steel liner & steel wire wrap vessel



Addressing near-term need for cost reduction in 875 bar stationary storage

CSD Highlights: Dispenser Hoses

700 Bar Refueling Hose RD&D

***Nanosonic**, CSA, NREL, Swagelok, Lillbacka*

SBIR | PD101

- **Focus:** Develop a flexible, reliable, and cost effective hydrogen dispensing hose for 700 bar service which can survive 25,550 fills/year cycled to pressures of 875 bar and temperatures as low as -50°C.
- **Highlight:** The polymer, fiber reinforced hose successfully passed the cold triple flex test with a predicted burst pressure of >1,700 bar

700 Bar H_2 Dispenser Hose Reliability RD&D

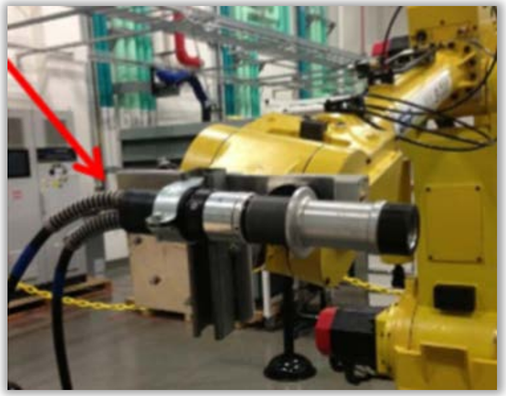
***NREL, SNL,** Spir Star, Colorado School of Mines*

FOA/Lab | PD100

- **Focus:** Assess the performance of state-of-the-art dispensing hoses during simulations of 1 year of service (25,000 cycles).
- **Highlight:** Determined that hose maintains structural integrity under torsional stress from -50°C up to 60°C

Polymer fiber reinforced H_2 dispensing hose

Hydrogen dispenser testing apparatus



Hose segment for torsional stress tests

Addressing near-term need for reliable & cost-effective dispensing hoses

Delivery Highlights: Pipelines

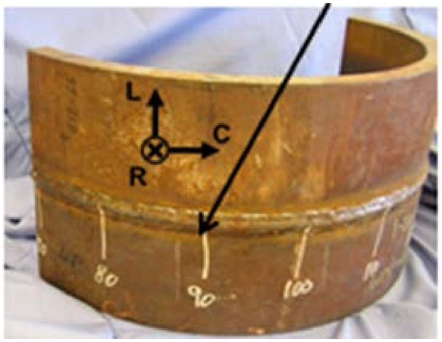
Hydrogen Embrittlement of Pipeline Steels

SNL, *ORNL, NIST, ExxonMobil*

FOA/Lab PD025

- **Focus:** Develop a quantitative, predictive model of hydrogen-assisted fatigue crack growth as a function of steel microstructure, and integrate with models of weld microstructures
- **Highlight:** Determined that pipeline wall thickness required for service in hydrogen does not have to exceed that of service in natural gas

Testing pipeline steel for H_2 service



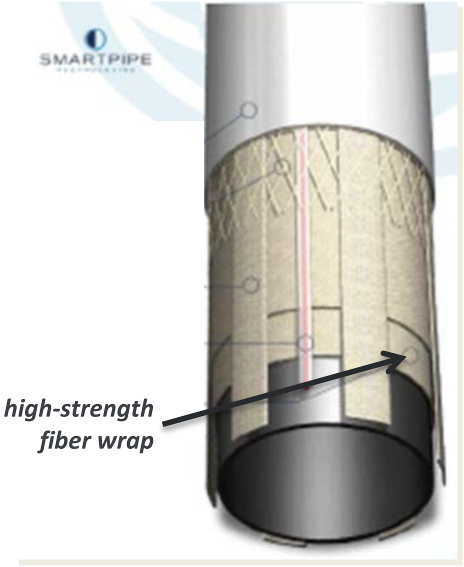
Fiber Reinforced Composite Pipelines

SRNL, *FRP Manufacturers, ASME, U. of Hawaii*

FOA/Lab PD022

- **Focus:** Provide data to support a technical basis for fiber reinforced piping in hydrogen service, and support integration of FRP into ASME B31.12
- **Highlight:** Successful codification of fiber reinforced pipelines into the ASME B31.12

Fiber reinforced composite pipeline design



Addressing critical longer term need for cost-effective pipeline delivery options

Production Highlights: Advanced Electrolysis

Renewable Electrolysis Integrated Systems

NREL, *Xcel Energy, Proton OnSite, Giner, Inc.* PD/TV PD031

- **Focus:** Provides independent performance testing of advanced electrolyzer stacks, BOP components, and systems for developing and optimizing stack and sub-system performance using grid and renewable power systems
- **Highlight:** Completed installation of large active area stack electrolyzer test bed (sub-MW scale) and dryer skid, and initiated testing of variable flow drying techniques

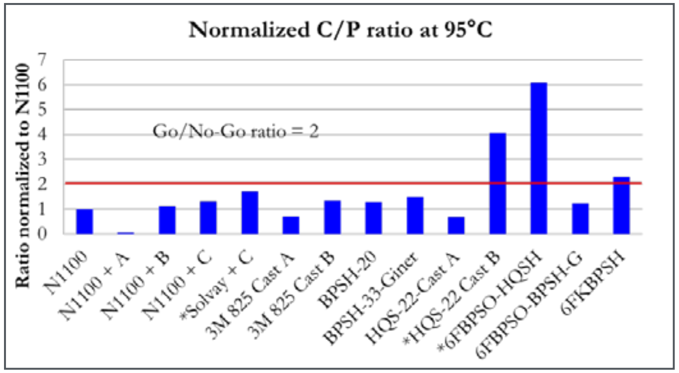
NREL electrolysis grid-integration test bed

High Temperature, High Pressure Electrolysis

Giner, Inc., *Virginia Tech* SBIR PD117

- **Focus:** Develop a PEM water electrolysis process that can provide high-pressure hydrogen at efficiency and durability higher than today's benchmark
- **Highlight:** Demonstrated operation for 1000 h at 95°C and for 500 h at 95°C and 1000 psi in advanced PEM electrolysis membranes

Giner advanced electrolyzer membrane screening



Exploring new modes of operation and system integration for cost-effectiveness

Production Highlights: Advanced PEM Electrolysis

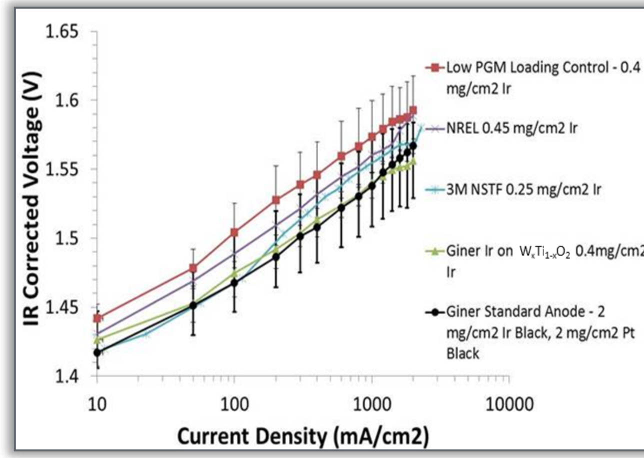
High Performance, Long Lifetime Catalysts

***Giner, Inc.**, 3M, NREL, ORNL, U. Mass Lowell*

SBIR PD103

- **Focus:** Develop advanced, low PGM-loading catalysts for high-efficiency and long lifetime PEM water electrolysis with improved mass and specific activity
- **Highlight:** Three different types of low loaded (< 0.5 mg PGM/cm^2) anode catalysts demonstrated performance similar to Giner's standard anode (4 mg PGM/cm^2)

Giner testing of 3 types of low PGM catalysts



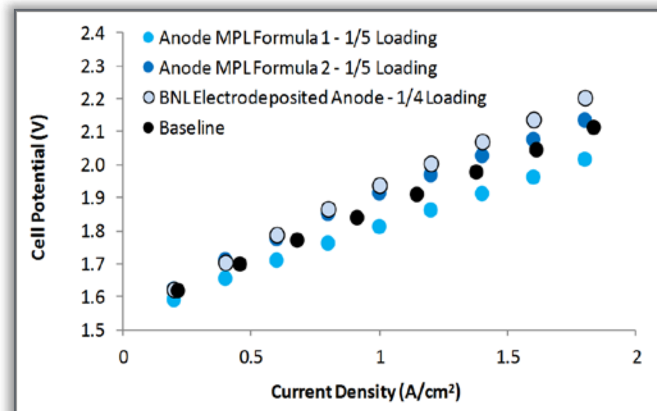
Low-Noble-Metal-Content Catalysts/Electrodes

***Proton OnSite**, BNL, U. Connecticut*

SBIR PD098

- **Focus:** Leverage BNL's low PGM-loading core shell catalyst technology originally developed for PEM fuel cells and transfer to electrolysis
- **Highlight:** Developed a manufacturable ultra-low loaded cathode with > 500 hrs durability, and demonstrated anode core shell catalysts with activity advantages for enabling lower loadings at equivalent performance

Performance testing of Proton low-PGM anode



Reducing cost through advanced low-PGM catalysts, levering fuel cell RD&D

Production Highlights: Bio-Feedstock Conversion

Reformer-Electrolyzer-Purifier

FuelCell Energy Inc., UC Irvine

FOA/Lab PD112

- **Focus:** Develop a commercial scale REP unit capable of reforming NG or biogas to high purity H_2 with higher efficiency, lower cost and lower CO_2 emissions compared to NG SMR
- **Highlight:** Demonstrated single cell performance with >30% increase in H_2 production and >20% increase in H_2 purity achieved through implementation of electrolysis step

FuelCell Energy industrial platform for demonstration of the REP unit

Rapid Swing Piston Reforming Reactor

PNNL, Cormetech, Washington State U., Dason Technology

FOA/Lab PD111

- **Focus:** Develop a compact reactor unit that can be readily transported and installed for cost-effective distributed H_2 production from biomass-derived liquids
- **Highlight:** Identified two promising CO_2 sorbents for respective low-T and high-T sorption, and two promising low-T reforming catalysts through modeling and bio-oil reforming tests

PNNL bio-derived liquid reforming reactor test platform

Providing near-term options for low-cost renewable bio-derived feedstocks

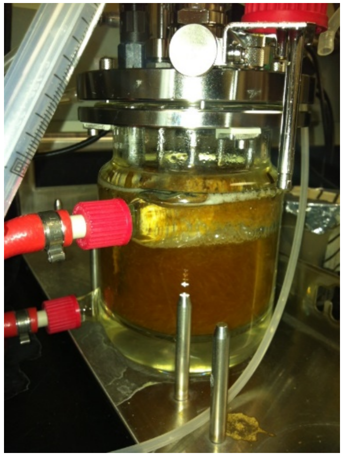
Production Highlights: Biological Hydrogen

Fermentative and Electro-hydrogenic H_2

NREL, ***Penn State*** FOA/Lab PD038

- **Focus:** Develop fermentation and bio-electrochemical technologies to convert renewable biomass to H_2
- **Highlight:** Demonstrated hydrogen production at an average rate of 757 mL H_2/L/d from de-acetylated and mechanically refined (DMR) feedstock, which has potential for lower costs

NREL fermentation test reactor

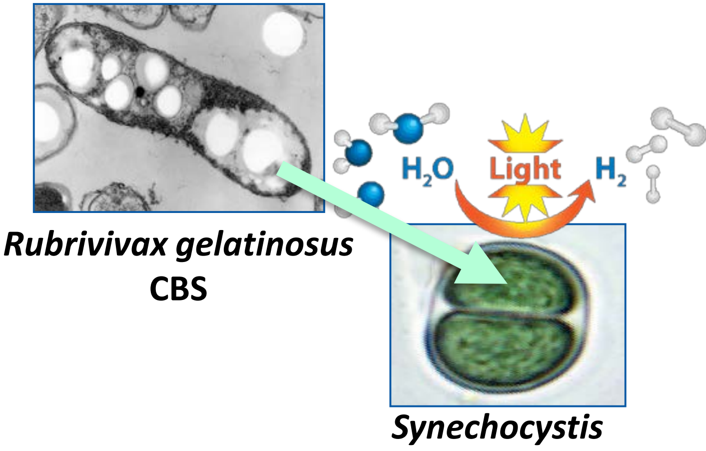


Cyanobacteria with O_2-Tolerant Hydrogenase

NREL FOA/Lab PD095

- **Focus:** Develop an O_2-tolerant cyanobacterial system for sustained light-driven H_2-production by transferring hydrogenases from *Rubrivivax gelatinosus* Casa Bonita Strain (CBS) to the cyanobacteria *Synechocystis*
- **Highlight:** Confirmed roles of the two different sets of hydrogenase maturation genes, and developed *Synechocystis* strain that expresses the CBS hydrogenase and maturation proteins

Transferring O_2-tolerant hydrogenase



Developing new options for sustainable biological hydrogen production

Production Highlights: Photoelectrochemical

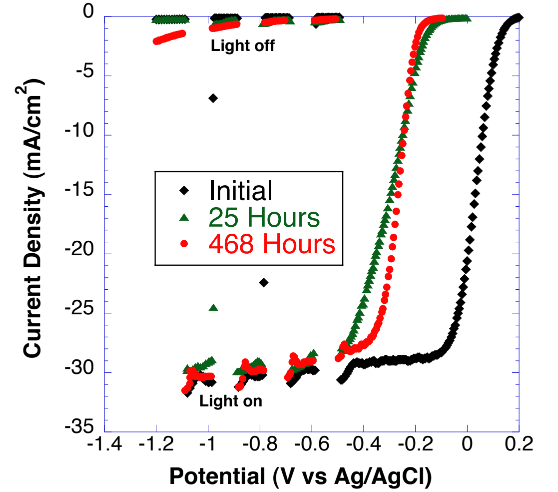
High Efficiency Tandem Absorbers

***NREL**, Stanford, LLNL, UNLV, U. Hawaii, LANL*

FOA/Lab | PD115

- **Focus:** Develop III-V semiconductor-based tandem devices capable of >20% solar-to-hydrogen efficiency with >1000 hr durability to meet DOE solar-H_2 cost targets
- **Highlight:** Demonstrated >460 hr of stabilized device operations using NREL-developed ion bombardment surface passivation process (patent pending)

Stabilized operations in NREL III-V electrode



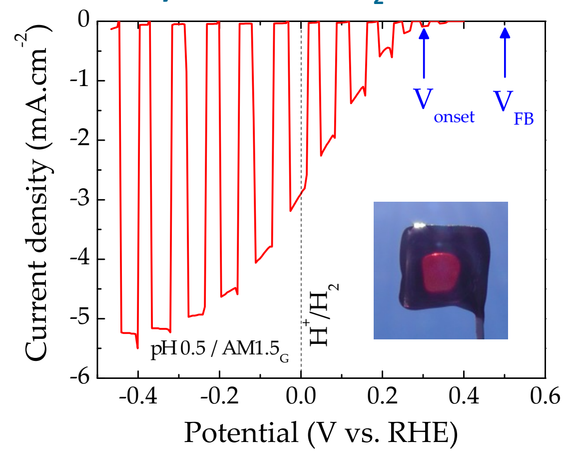
Wide Bandgap Chalcopyrite Photoelectrodes

***U. Hawaii**, UNLV, Stanford, LLNL, NREL*

FOA/Lab | PD116

- **Focus:** Develop efficient, bandgap-tunable thin-film chalcopyrites using an innovative low-cost synthesis process with 1.8-2.4 eV bandgaps optimized for solar H_2 production
- **Highlight:** Successful fabrication of photoactive $CuInGaS_2$ with controlled composition and tunable bandgap in the 1.5 – 2.4eV range; and initial demonstration of chalcopyrite surface protection with MoS_2

Photactivity in UH $CuInGaS_2$ PEC electrode



Developing advanced materials & interfaces for efficient solar hydrogen

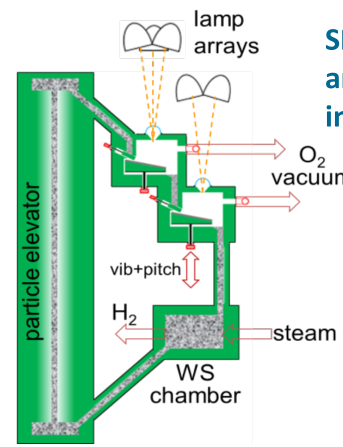
Production Highlights: Solar Thermochemical

High Efficiency Redox STCH Reactor

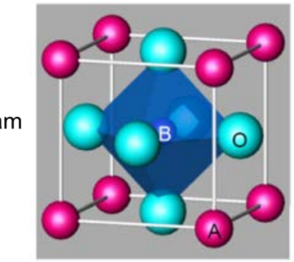
***SNL**, ASU, Bucknell, CS Mines, Northwestern, Stanford, DLR*

FOA/Lab | PD115

- **Focus:** Develop novel cascading pressure particle receiver-reactor and new materials for two-step, non-volatile metal oxide thermochemical water-splitting cycles
- **Highlight:** Designed a prototype 3kW cascading pressure reactor/receiver, and extended approach to material discovery and engineering of thermochemical properties



SNL STCH reactor and redox material innovations



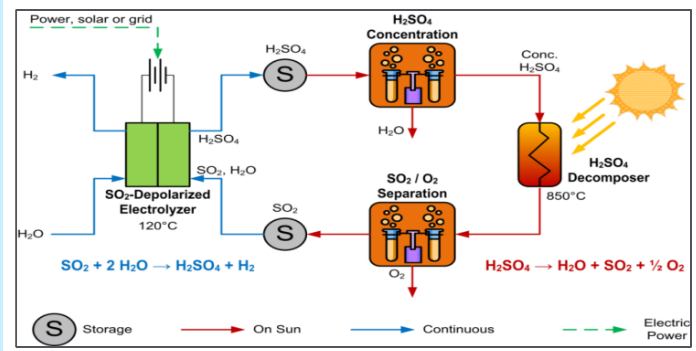
Solar Hybrid Sulfur Cycle System

SRNL

FOA/Lab | PD096

- **Focus:** Develop efficient process for coupling the hybrid sulfur (HyS) STCH cycle with concentrated solar energy using an advanced high-temperature electrolysis step
- **Highlight:** Designed a Solar HyS process that uses a bayonet acid decomposer and thermal energy storage, including an Aspen Plus™ flowsheet and performance evaluation

Flow diagram of SRNL solar HyS STCH process



Developing new materials and reactors for high-T solar hydrogen

Production Highlights: Solar Thermochemical

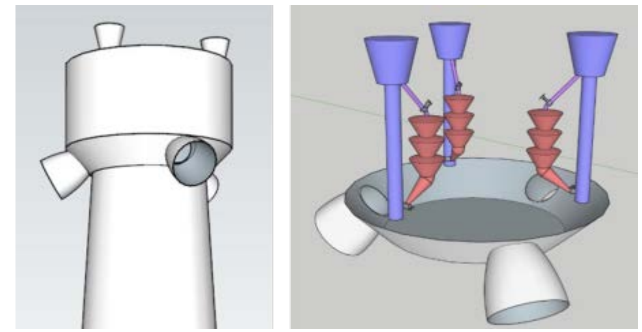
Flowing Particle Bed STCH Redox Reactor

CU Boulder, *NREL*

FOA/Lab PD114

- **Focus:** Design and test individual components of a novel flowing particle STCH water splitting system capable of producing 50,000 kg H_2/day at a cost < \$2/kg H_2
- **Highlight:** Completed flowing particle reactor design, including AspenPlus process modelling; and synthesized >2g Hercynite active material by spray drying, and characterized for composition, particle size, & surface area

CU Boulder STCH receiver/particle reactor design

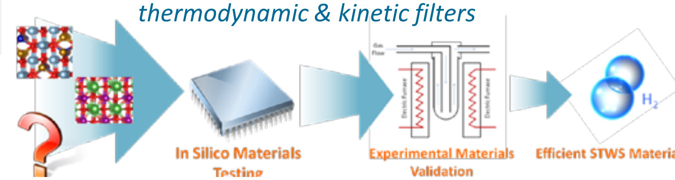


Accelerated Discovery of Redox Materials

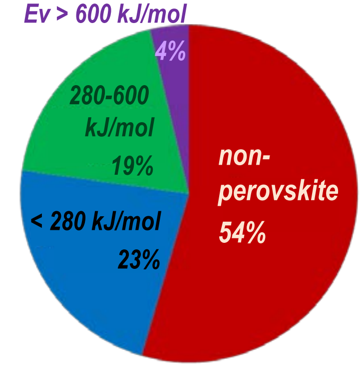
CU Boulder

NSF/DOE PD120

- **Focus:** Use state-of-the-art electronic structure theory to develop design rules for new materials and develop digital data base for material screening to down-select candidate redox materials with the best performance
- **Highlight:** Screened 1,045 possible binary perovskites, of which 199 materials show potential for use in STCH



1045 materials screened since 4/10/2015



Collaboratively discovering & developing new STCH materials & reactors

NSF-DOE Joint Projects on Solar Hydrogen

NSF/DOE MOU

Engineering Directorate
Division of Chemical, Bioengineering, Environmental, and Transport Systems (CBET)

NSF 14-511: NSF/DOE Partnership On Advanced Frontiers in Renewable Hydrogen Fuel Production via Solar Water Splitting Technologies

PD118 — New Metal Oxides for Efficient Hydrogen Production Via Solar Water Splitting

– *The University of Toledo, Yanfa Yan*

PD119 — Engineering Surfaces, Interfaces, and Bulk Materials for Unassisted Solar Photoelectrochemical Water Splitting

– *Stanford University: Thomas Jaramillo*

PD120 — Accelerated Discovery of Advanced Redox Materials for Solar Thermal Water Splitting to Produce Renewable Hydrogen

– *The University of Colorado at Boulder: Charles Musgrave*

PD121 — Tunable Semiconductor/Catalyst Interfaces for Efficient Solar Water Splitting

– *Rutgers University New Brunswick: Charles Dismukes*

Investigating the fundamental mechanisms of solar water splitting materials and devices in support of FCTO's applied H_2 production RD&D

Hydrogen P&D Incubator Selections

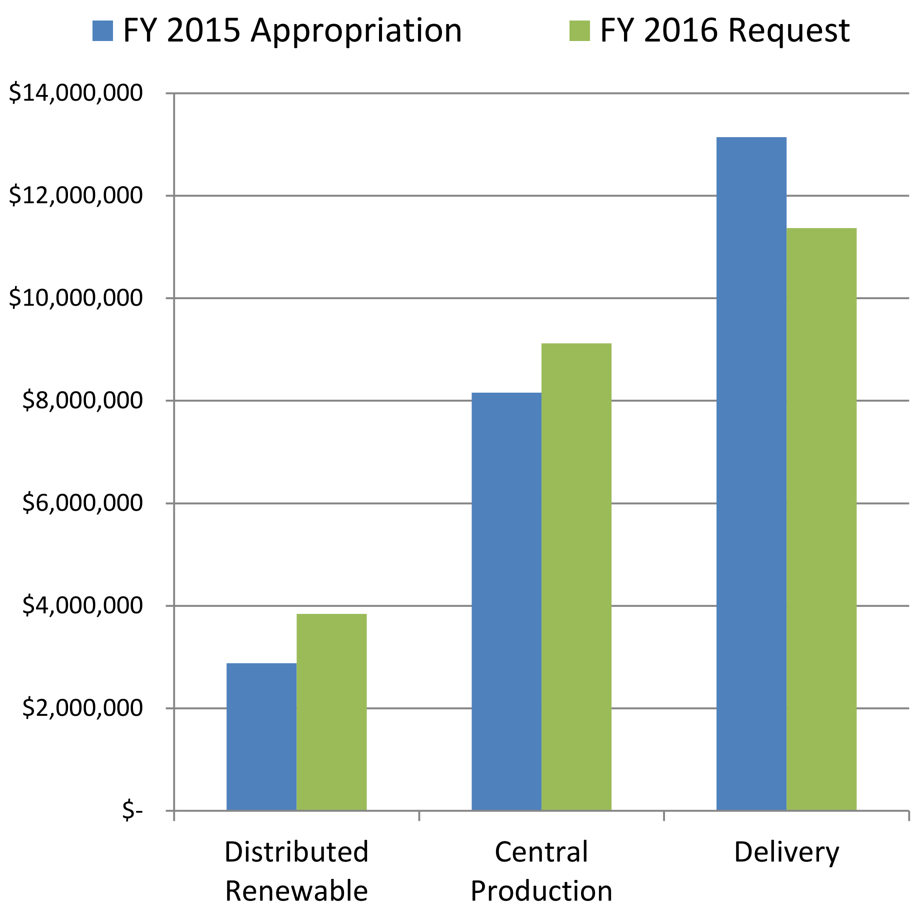
- **Gas Technology Institute,** *Des Plaines, Illinois, will assess the technical and economic feasibility of thermal compression for cost-effective pressurization of hydrogen to 700 bar for hydrogen fueling stations, as well as demonstrate the concept in a small-scale test system*
- **Proton OnSite,** *Wallingford, Connecticut, will advance alkaline exchange membrane-based electrolysis technology by developing durable and efficient PGM-free electrolysis cells*
- **Versa Power Systems,** *Littleton, Colorado, will develop hydrogen production technologies using high temperature solid oxide electrolysis capable of operating at high current densities (i.e., high hydrogen production rates) and high efficiencies*
- **University of California, Irvine**, *will develop a novel photocatalyst particle-based slurry reactor with the potential for low-cost renewable hydrogen production via solar water splitting*
- **Virginia Tech,** *Blacksburg, Virginia, will develop a cell-free biological hydrogen production technology based on an in vitro synthetic biosystem composed of numerous thermoenzymes and biomimetic coenzymes*

High-risk / high-reward projects complementing FCTO RD&D in: compression, advanced electrolysis, PEC and biological H_2

Hydrogen Production & Delivery Budget

FY 2016 Request = $23.6M

FY 2015 Appropriation = $19.6M



EMPHASIS

- **Continued Analysis of Production & Delivery Pathways**
  - *Fermentative H_2 Production*
  - *High Temperature Electrolysis*
  - *Integrated Analysis of Project Pathways*
- **Develop Balanced Portfolio of Near-, Mid- and Long-term P&D technologies**
  - *P&D Infrastructure RD&D*
  - *RD&D of Cost-effective Forecourt Components for 700 bar Refueling*
  - *RD&D of Renewable Production from Diverse Pathways*
- **Continued Cross-Office Coordination and Collaboration**
- **Continued International Collaborations and Communications**

Stabilized budgets are critical to sustaining balanced RD&D portfolio in H_2 P&D; Continued leveraging of broader research resources remains important

Hydrogen Production & Delivery Collaborations

INTERNATIONAL ACTIVITIES

Examples:

- IEA HIA Tasks
- Infrastructure Workshops
- IPHE

DOE/EERE FCTO

H_2 Production and Delivery Applied RD&D

- ~ 20 projects
- SBIR projects
- Joint NSF projects
- Incubator projects

INDUSTRY

- U.S. DRIVE Tech teams:
  - *H_2 Production*
  - *H_2 Delivery*
  - *Analysis*
- H_2USA – H_2First
- Codes & Standards Organizations

DOE CROSS-CUTS

- AMM/MGI
- WBS Institute
- Grid Integration

TECHNOLOGY VALIDATION

Grid Integration/ Electrolysis

INTER- AND INTRA-AGENCY COLLABORATIONS

- DOE Basic Energy Sciences *Including JCAP*
- DOE Bioenergy Technologies
- DOE Fossil Energy
- DOE Nuclear Energy
- ARPA-E
- National Science Foundation
- NIST

Recent Activities and Upcoming Milestones

- Workshops, including FCTO/BETO Joint Workshop, International Infrastructure Workshop
- Awarded 9 P&D projects from FY14 Production and Delivery RD&D FOAs, and 5 Incubator selections
- Awarded 4 projects under joint FOA with NSF addressing Solar Water Splitting
- Two topics in FY15 FCTO FOA and 2 areas of interest in FCTO FY15 Lab call to balance portfolio
- Initiated 2 new projects under H2First in support of the H2USA mission
- Cross-office collaborations with AMM/MGI, CEMI, WBS Institute, Grid Integration
- Webinars on topics including infrastructure, AMM/MGI projects, WBS opportunities & H-Prize

FY 2015 | FY 2016 | FY 2017

4Q 2014 Successfully negotiated and awarded nine P&D projects

4Q 2014 Selected and awarded four projects from NSF/DOE Joint Solicitation

1Q 2015 Launched H2 Refuel H-Prize competition

3Q 2015 Publish Program Records on SOEC and Fermentation

3Q 2015 Demonstrate potential for PEC systems with > 15% STH efficiency.

4Q 2015 Validate low cost forecourt storage to meet the 2015 cost target.

4Q 2015 Evaluate P&D technologies against 2015 metrics

1Q 2016 Negotiate and award FY15 Office Wide FOA Selections

2Q 2016 Release of Office-wide FOA with new P&D topics, subject to appropriations

3Q 2016 FCTO/WBS workshop on power electronics for electrolysis

4Q 2016 H2 RENEW collaborations subject to appropriations

2Q 2017 Joint NSF funding opportunity subject to appropriations

4Q 2017 Design a reactor/receiver system for solar-based central production of > 50,000 kgH_2 /day.

4Q 2017 Complete development of advanced H_2 metering technology.

H2 Refuel H-Prize Announced in 2014

H2 refuel
U.S. Department of Energy

$1 million competition for on-site home and community-scale H_2 fueling systems

1st Year
Teams form and submit designs

2nd Year
Selection of finalists and testing

Late 2016
Technical & cost analysis to select winner

Award
$1M

Key Dates
October 22: Contestant registration deadline
October 29: Design submission deadline

To learn more, check out poster PD128 or visit http://hydrogenprize.org/

Promoting H_2 fueling system development in the community

Hydrogen P&D Topics in FY 2015 FOA

FOA Title	Release Date	Topics Included	Due Date
Hydrogen and Fuel Cell Technologies Research, Development, and Demonstrations	3/2/2015	• Subtopic 1a: Microbial Biomass Conversion • Subtopic 1c: Integrated Intelligent Hydrogen Dispensers for 700 bar Gaseous Refueling of Fuel Cell Electric Vehicles	6/4/2015

Hydrogen Production by Microbial Biomass Conversion

- *Fermentation, microbially-aided electrolysis, or hybrid processes that integrate multiple systems*
- *Demonstration of hydrogen production of at least 5 LH2/L-reactor/day on average in a system operating for at least 24 hours continuously, at a reactor scale of at least 1 liter*

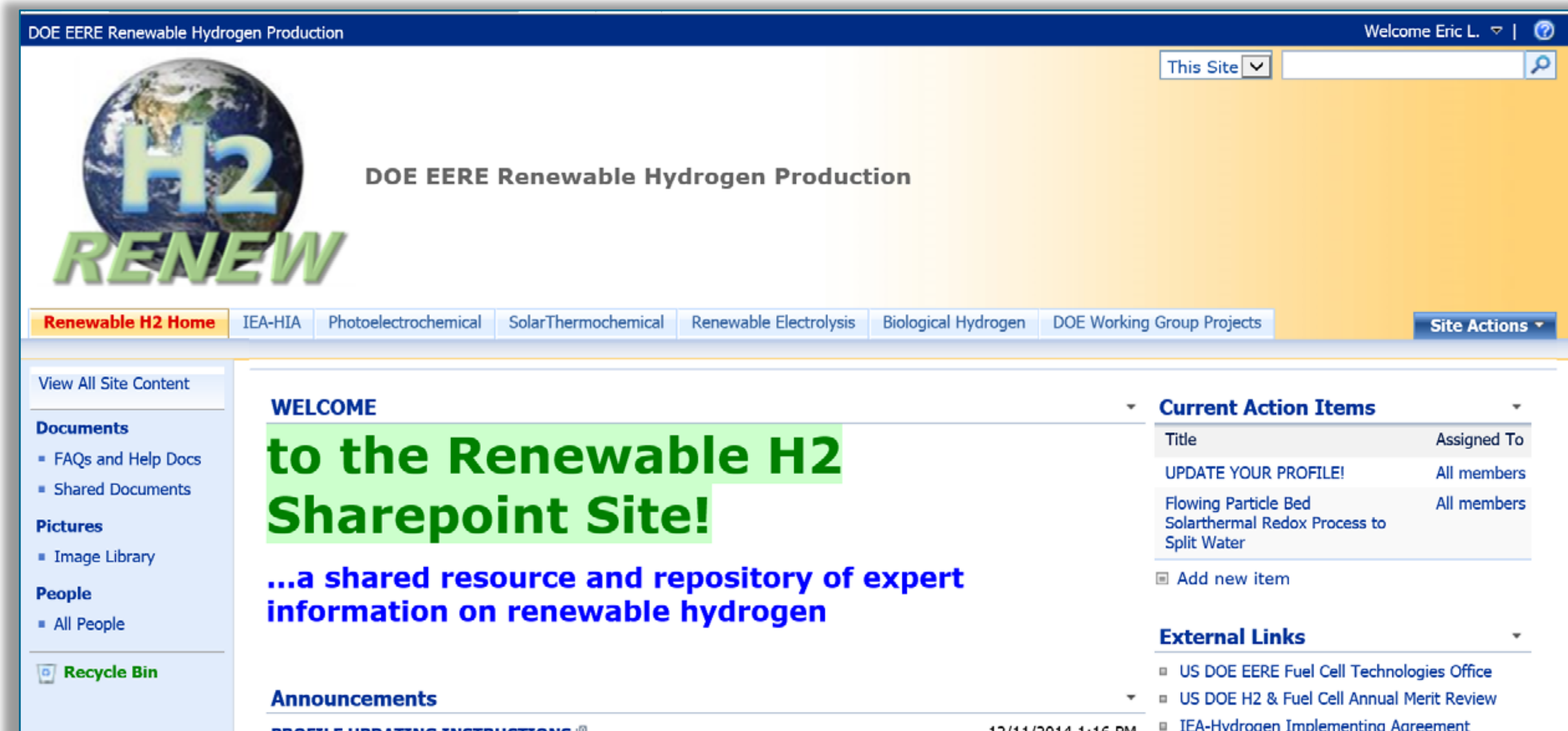
Integrated Intelligent Hydrogen Dispensers for 700 bar Gaseous Refueling of FCEVs

- *Improved reliability of state-of-the-art communication equipment to ensure complete fills*
- *Targets dispensing accuracy of at least 4%, and cost reduction in dispensing components*
- *Enabling complete SAE J2601 fills, and adaption of alternative filling methods*

Continuing to fill gaps in the RD&D portfolio, guided by stakeholder engagements and techno-economic analysis

H2 RENEW Collaborative Resource Network

With the growing importance of renewable hydrogen to energy security and the environment, experts in all fields of renewable hydrogen have an opportunity to work collaboratively to address key cross-cutting technical challenges in catalysis, separations, material compatibility, systems & grid integration, etc.



Cross-cutting session of H_2 Production Working groups being held Wednesday at 5:15 PM

Bringing together leading experts in electrolysis, STCH, PEC and bio-conversion

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http://energy.gov/eere/fuelcells/fuel-cell-technologies-office