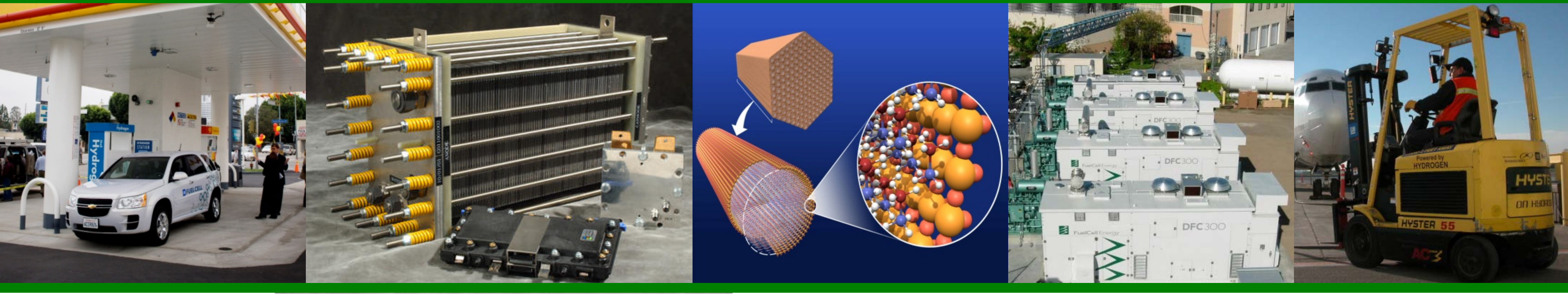
U.S. DEPARTMENT OF ENERGY



Hydrogen Production & Delivery

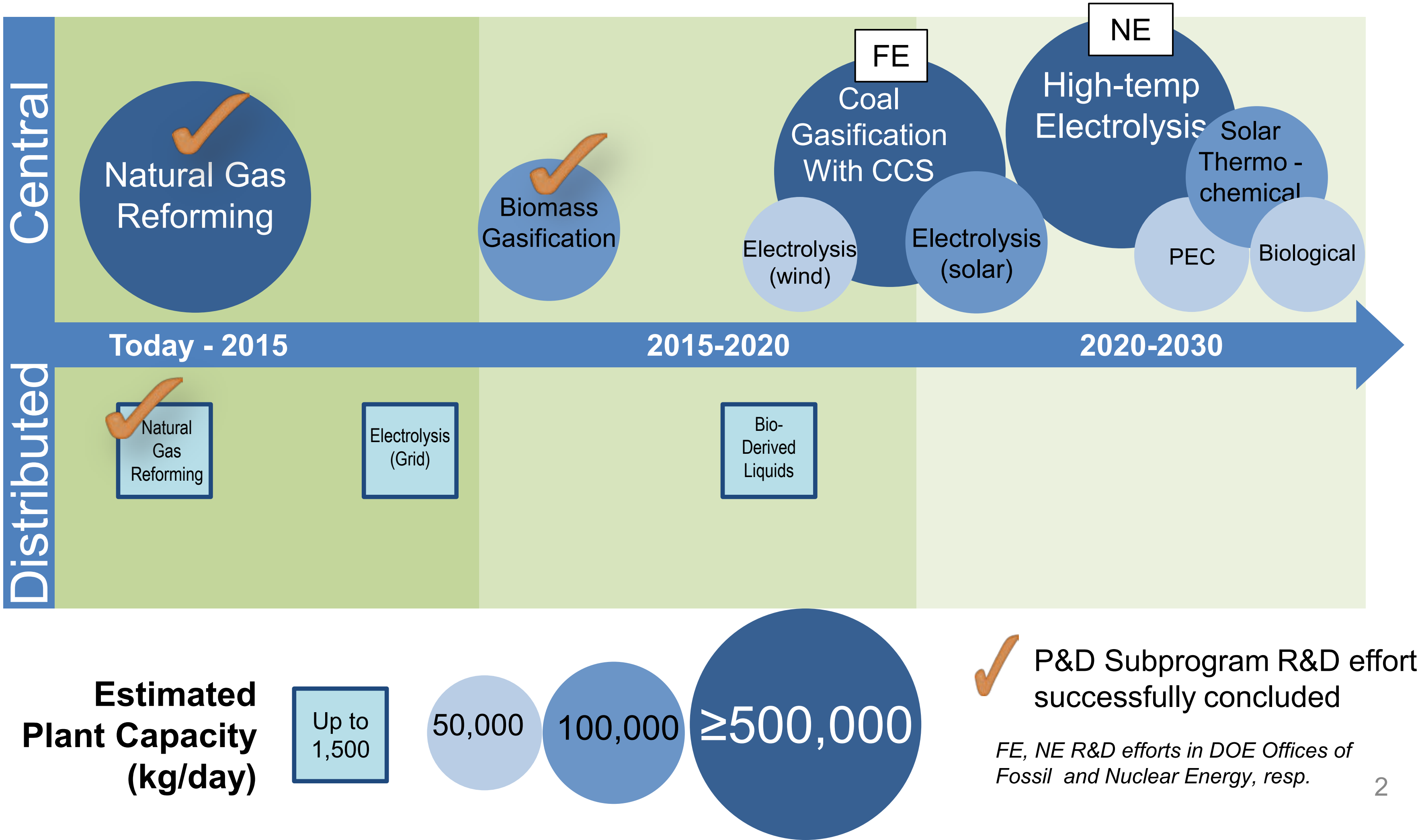
Sara Dillich

2012 Annual Merit Review and Peer Evaluation Meeting

May 14, 2012

Goals and Objectives

Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of \$2–\$4/gge H_2 by 2020



✓ P&D Subprogram R&D efforts successfully concluded

FE, NE R&D efforts in DOE Offices of Fossil and Nuclear Energy, resp.

Challenges & Barriers

Distributed Production

Bioderived Liquid Reforming
- Capital costs
- Operation and Maintenance costs
- Design for manufacturing
- Feedstock quantity and quality

Electrolysis
- System efficiency and capital costs
- Integration with renewable energy sources
- Design for manufacturing

Central Production

Solar Thermochemical
- Cost-effective reactor
- Effective and durable construction materials

Photoelectrochemical
- Effective photocatalyst material

Biological
- Sustainable H_2 production from microorganisms
- Optimal microorganism functionality
- Cost effective reactor materials

Biomass Gasification
- Capital costs
- Feedstock costs & purity
- System efficiency

Delivery

Forecourt
- Compressor reliability
- Station infrastructure (compression, storage, and dispensing) costs

Tube Trailer Delivery
- Vessel capacity

Liquid Delivery
- Liquefaction efficiency & associated GHG emissions

Pipelines
- Embrittlement/cyclic fatigue effects on pipeline steel
- Infrastructure installation and lifetime costs

Analysis & Standards
- Impact of code requirements
- Trade study: production pressure vs. station compression.

Materials durability, efficiency improvements, and capital cost reductions are key challenges for all pathways

Challenges: Production

The hydrogen threshold cost ($2-$4/gge dispensed) is a key driver of Hydrogen Production R&D.

Projected High-Volume Cost of Hydrogen Production[1]—Status

(production costs only, not including delivery or dispensing)

Distributed Production (near term)

🟪 Electrolysis

Feedstock variability: $0.03 - $0.08 per kWh

🟩 Bio-Derived Liquids

Feedstock variability: $1.00 - $3.00 per gallon ethanol

⬛

Natural Gas Reforming[3]

Feedstock variability: $4.00 - $10.00 per MMBtu

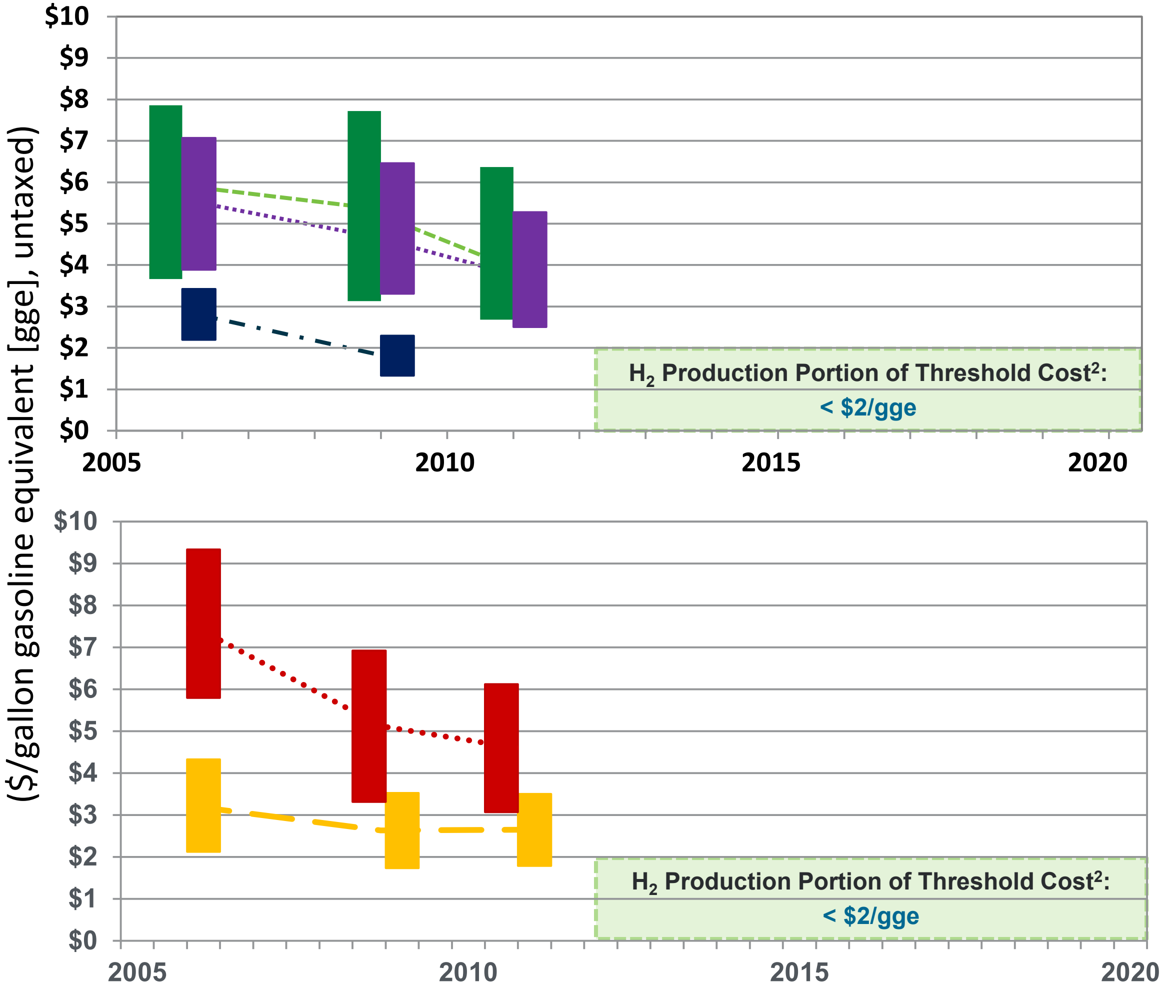
Central Production (longer term)

🟥 Electrolysis

Feedstock variability: $0.03 - $0.08 per kWh

🟨 Biomass Gasification

Feedstock variability: $40- $120 per dry short ton



H$_2$ Production Portion of Threshold Cost[2]:
< $2/gge

H$_2$ Production Portion of Threshold Cost[2]:
< $2/gge

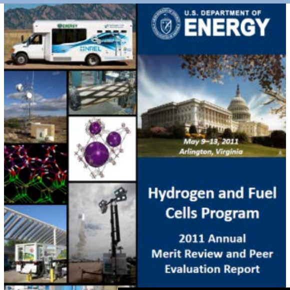
Notes:

[1] *Cost ranges for each pathway are shown in 2007$, based on H2A analyses, reflecting variability in major feedstock pricing and a bounded range for capital cost estimates. Costs shown do not include delivery and dispensing costs.*

[2] *The Hydrogen Production Threshold Cost of <$2/gge reflects the Production apportionment (Record 12001, in preparation) of the 2010-revised Hydrogen Production and Delivery Cost Threshold of $2-4/gge (Record 11002,* Hydrogen Threshold Cost Calculation, 2011).

Production & Delivery Strategy

Technical and economic analyses inform programmatic decisions.



U.S. DEPARTMENT OF ENERGY

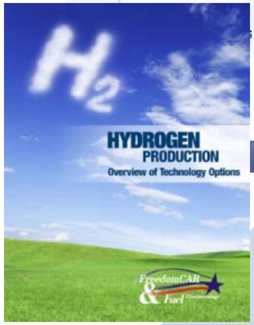
May 9–13, 2011
Arlington, Virginia

Hydrogen and Fuel Cells Program

2011 Annual Merit Review and Peer Evaluation Report

FreedomCAR & Fuel Partnership

Hydrogen Delivery Technology Roadmap



HYDROGEN PRODUCTION
Overview of Technology Options

FreedomCAR & Fuel Partnership

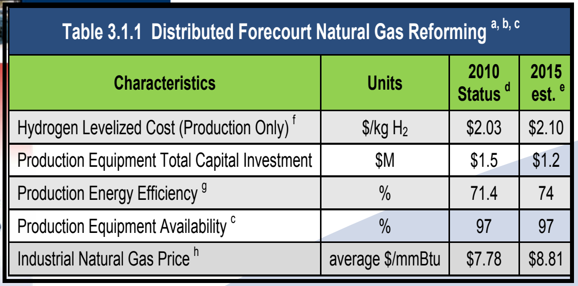
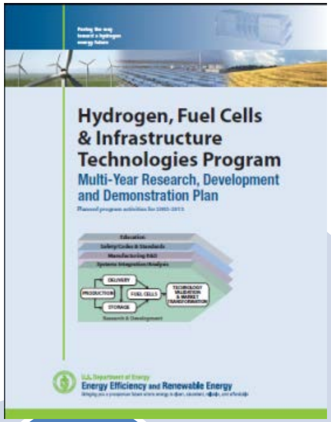


Table 3.1.1 Distributed Forecourt Natural Gas Reforming [a, b, c]

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



Hydrogen, Fuel Cells & Infrastructure Technologies Program

Multi-Year Research, Development and Demonstration Plan

U.S. Department of Energy
Energy Efficiency and Renewable Energy

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)*

Informed Prioritization of Funding

Hydrogen Production Strategies

*Cost status and targets for hydrogen production**

	$/gge (production costs only)	2011 Status	2015 Target	2020 Target	Ultimate Production Target
Distributed	Electrolysis from grid electricity	$4.10	$3.90	$2.30	$1-$2
	Bio-derived Liquids (based on ethanol reforming case)	$6.65	$5.10	$2.25	
Central	Electrolysis From renewable electricity	$4.10	$3.00	$2.00	
	Biomass Gasification	$2.20	$2.10	$2.00	
	Solar Thermochemical	NA	$8.00	$3.00	
	Photoelectrochemical	NA	$17.00	$6.00	
	Biological	NA	NA	$10.00	

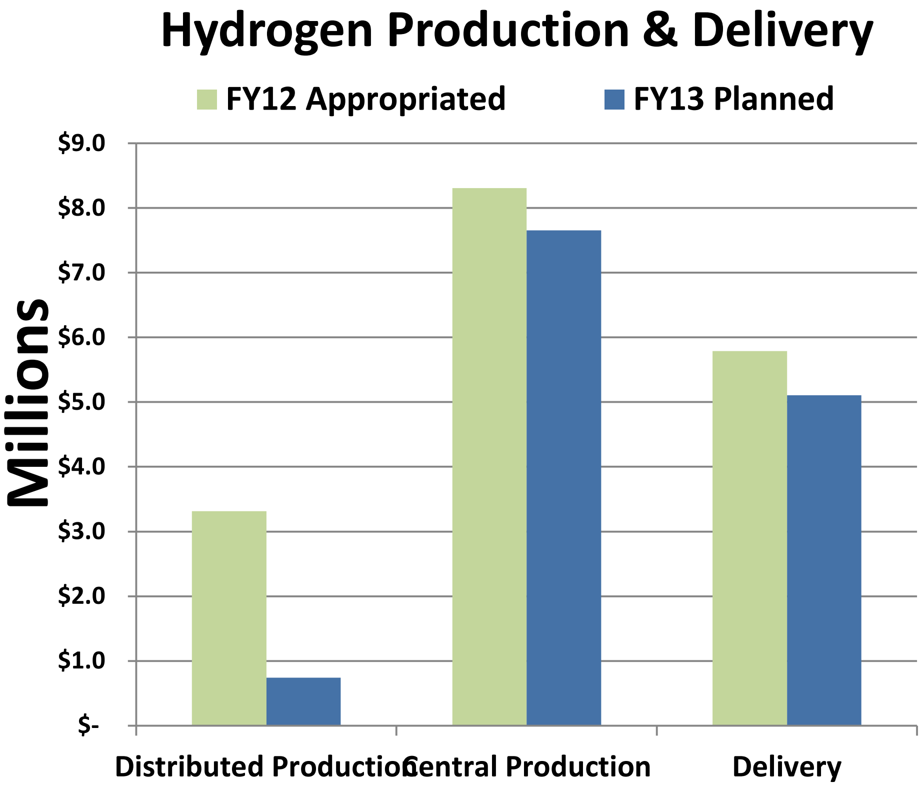
Apportionment of Threshold Cost: $1-$2/gge for production, $1-$2/gge for delivery.

New H2A v3 Case Studies are Published @ http://www.hydrogen.energy.gov/h2a_production.html

*Based on the new DOE-FCTP MYRD&D cost status and targets for Hydrogen Production – in final review.

Budget – P&D Sub-program

FY12 Appropriation $17.4M ***FY 13 Planned Funds $13.5M***



2012/13 Emphasis

- Update cost projections and 2015 and 2020 targets using H2A v3.

Distributed Production

- Develop production and forecourt technologies for early markets
- Analyze production - to -dispensing pathways to identify optimal capital investments.

Central

- Address key materials needs for renewable hydrogen production: Membranes, Catalysts, PEC Devices, Reactors, and Tanks
- Use recommendations from the HTAC Hydrogen Production Expert Panel in portfolio planning for future new starts.

The Nuclear Hydrogen Initiative was discontinued at end of FY2009 as a separate program. Funding of high temperature electrolysis continued under the NGNP project through FY2011. After INL demonstration of pressurized stack operation in FY 2012, technology readiness will be sufficiently advanced (TRL5) to allow for further development by industry. Congressional direction to DOE for FY2012 was to focus on conversion of coal and biomass to liquid fuel. No funding for H_2 production from coal was provided.

2012 Progress: Technical and Economic Evaluation of R&D

The "New & Improved" H2A Model: Updated Capital Cost (2007 dollars)

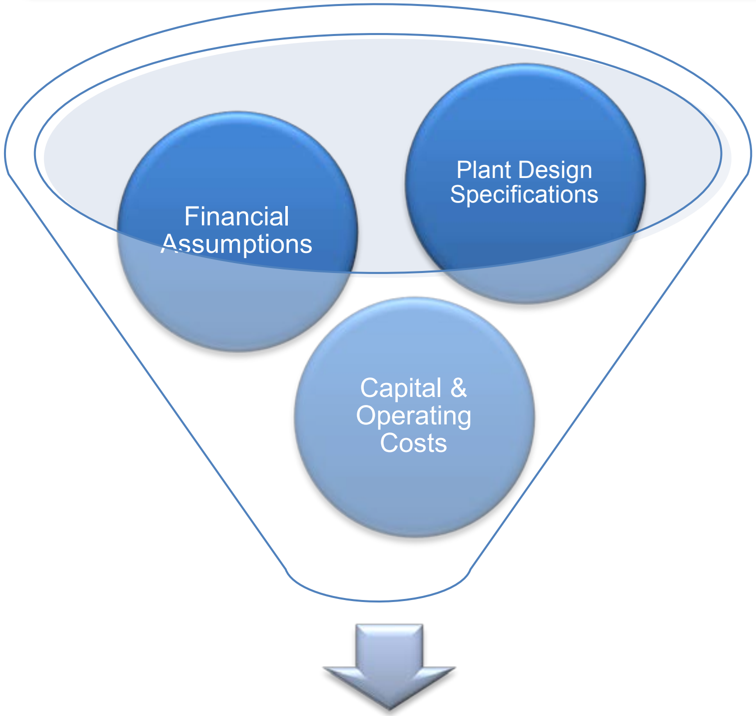
General Features

User Input
Process modeling
Vendor quotes
Literature sources

H2A Values
AEO fuel prices
Fuel properties
GREET emissions factors
Industry cost indexes

H2A Calculations
- Cost escalation
- Plant Scaling
- Financial Calculations
- Cash flow calculations and leveled cost of hydrogen

Hydrogen Analysis Model



Required Selling Price of H2 ($/kg)

Improvements

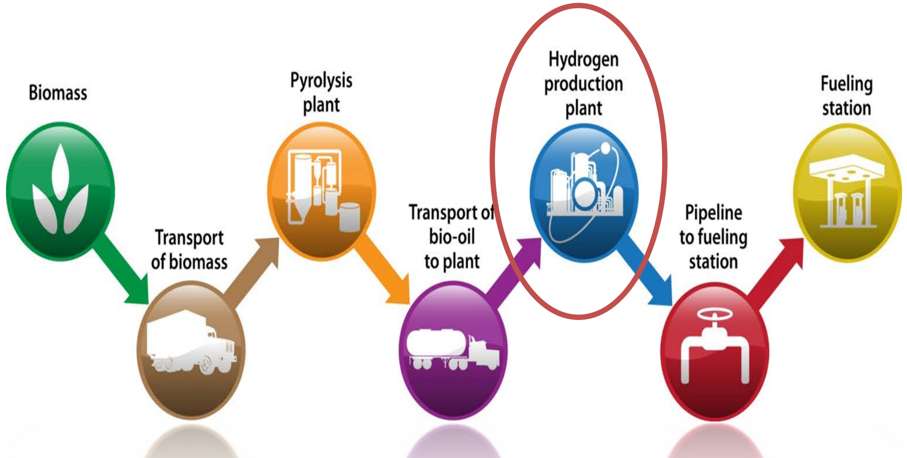
- Streamlined and clarified user input
- Updated H2A "Built-In" database
- New plant scaling and CSD calculations

2012 Progress: Bio-Derived Liquids – Pyrolysis Oil

Pyrolysis oil: feedstock costs dominate cost of H2 production

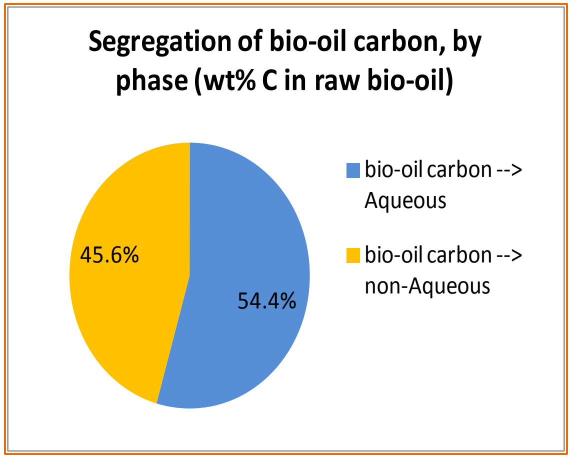
Catalytic Autothermal Reforming (NREL)

✓ An integrated bench-scale system for the production of 100 L/h hydrogen from pyrolysis bio-oil has been constructed. This system includes all the basic unit operations as the design for a 1500 kg/day hydrogen plant. Demonstration of 100 hrs of commercial catalyst performance is on-going.



Aqueous Phase Reforming (PNNL)

✓ Pt-Co/ZrO_2 catalysts identified as having potential to improve H_2 yields from water soluble components of bio-oil up to 2-3X the yields with other Pt-based catalysts.



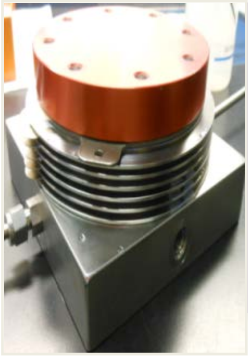
Economic and technical analyses indicate bio-oil best suited for semi-central production or co-production of H_2 at bio-fuel plants.

2012 Progress: Electrolysis

Higher pressure H_2 production through stack & system design innovations

Higher Pressure Stacks 2k to 5k psig

Giner Inc.



- 2,000 psig performance testing completed
- 6,500 psig proof pressure testing completed
- 5,000 psig testing to begin shortly.

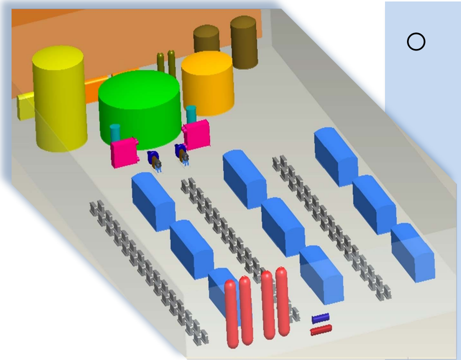
Proton OnSite

- Performance testing at 2,400 psig completed.
- 5,000 psig, 2.2 kg/day home refueling system has been fabricated.
- Proof pressure testing to 7,500 psig complete
- Performance tests at 5,000 psig to begin soon.

Higher pressure production through stack and system design innovations has the potential to reduce compression at the point of use

System Scale-up at 200-300 psig

- Fabrication of system level prototype to be delivered to NREL in May for system verification testing against DOE performance and cost targets at their new diagnostics laboratory.



- Component identification for a 50,000 kg H_2/day plant design (optimized for cost reduction) allows for improved H2A cost projection.

The scale up of system designs and prototypes improves the accuracy of H2A projections against DOE targets

2012 Progress: Biomass Gasification

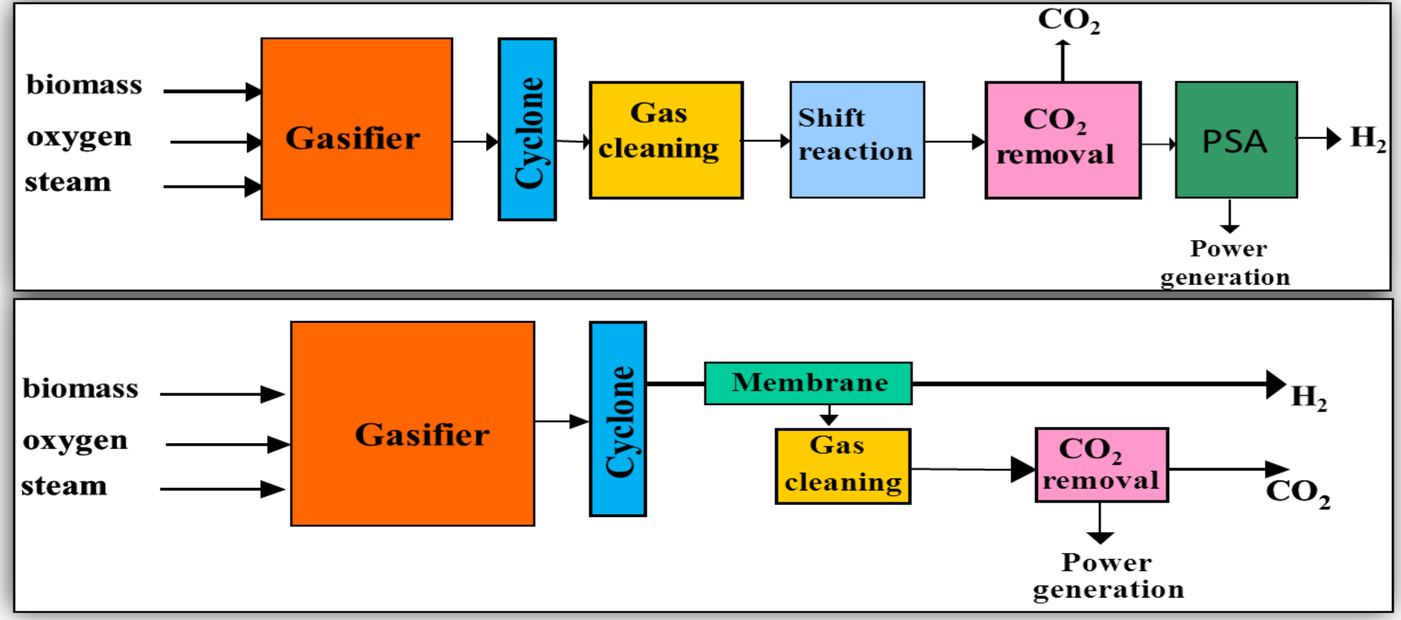
Economic Analysis of One Step Biomass Gas Reforming-Shift Separation Membrane Reactor Predicts \$1.82/kg H_2 as compared to \$2/kg H_2 from conventional PSA method

✓ By combining the reactor and membrane into a 1-step process, a **~35% increase in H_2 recovery** is possible as compared to conventional PSA method because H_2 removal via membrane drives the equilibrium limited WGS reaction to products (GTI)

H2A v.3 Results (2007\$)

	PSA	Membrane Reactor
H_2, \$/kg	2.00	1.82

Process Diagrams



gti

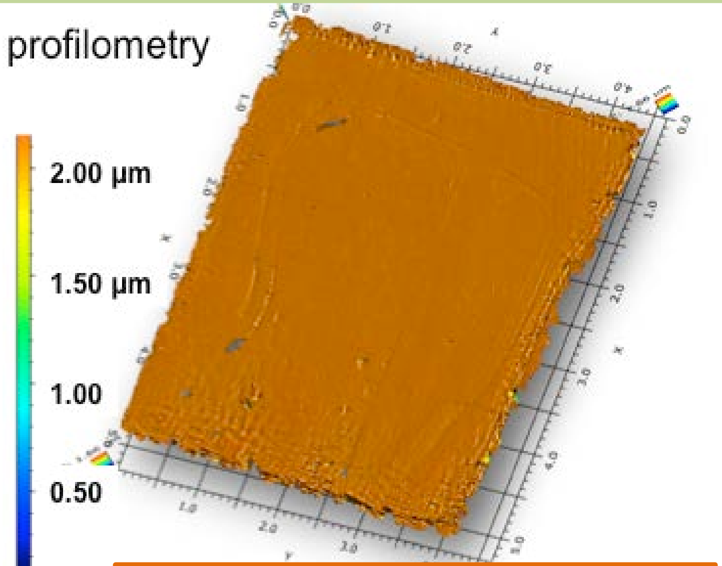
2012 Progress: Photoelectrochemical (PEC)

U.S. DEPARTMENT OF ENERGY

Materials fabrication innovations lead to new benchmarks for durability.

✓ Durability in high-efficiency III-V crystalline systems extended to >100 hours

A low-energy N_2^+ ion treatment of $GaInP_2$ surfaces forms a capping surface nitride and passivates the interface against corrosion. (NREL)



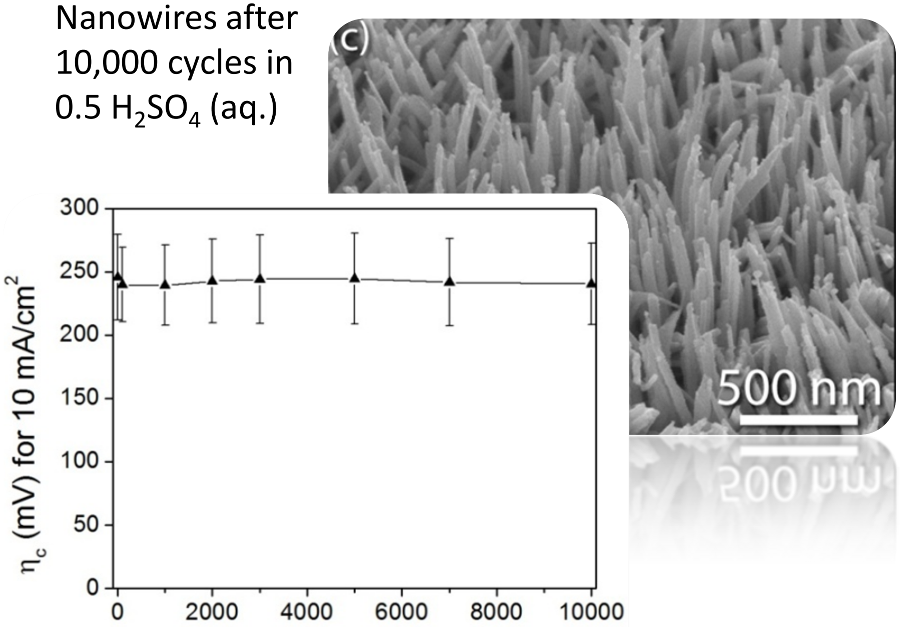
Nitrogen Ion Bombardment
Pristine surface after 115 hours at current density equivalent to 12% STH

Next step**:** Determine the durability benchmarked against the 100-hour operational lifetime at 10% efficiency target.

✓ Stability in acidic electrolyte demonstrated through 10,000 cycles

Highly Stable H_2 Evolution by Core-shell MoO_3-MoS_2 Nanowires (Stanford)

Nanowires after 10,000 cycles in 0.5 H_2SO_4 (aq.)



The core-shell nanowires are **100% stable** even after 10,000 cycles in sulfuric acid, and the conformal MoS_2 completely protects the otherwise unstable MoO_3 core.

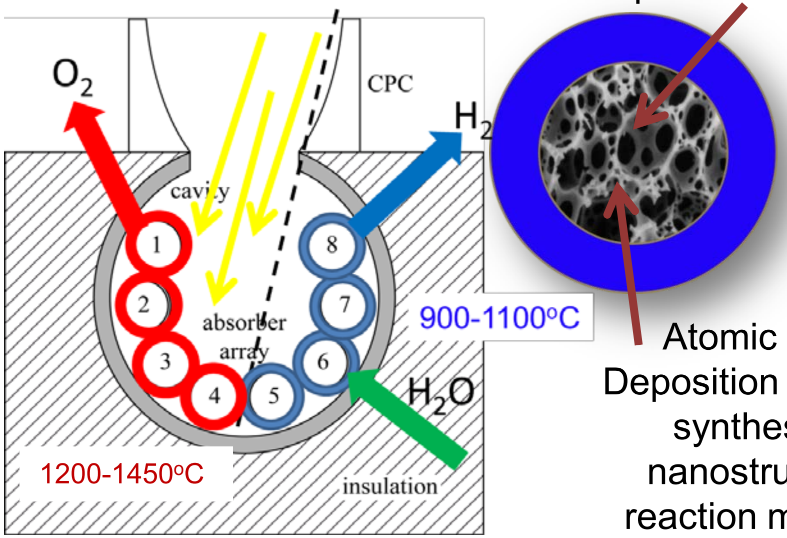
2012 Progress: Solar-Thermochemical (STCH)

System improvements through material and design innovations

✓ Developed nanostructured materials design for optimal performance of hercynite cycle (U of CO-Boulder)

✓ Optimized performance of the electrolysis stage of the CuCl cycle (ANL)

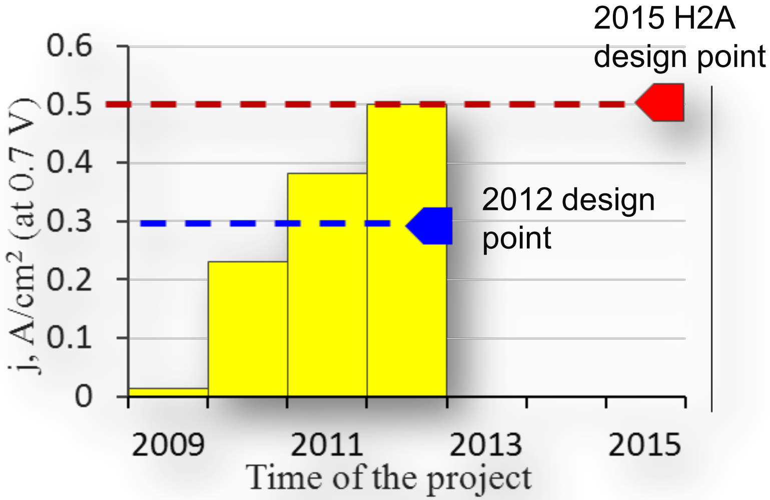
reactor/receiver



Sacrificial Polymer Template for porosity and pore diameter

Atomic Layer Deposition (ALD) for synthesis of nanostructured reaction materials

- ✓ Fast radiative heat transport
- ✓ Fast mass flow (large pores & porosity)
- ✓ Ultrathin walls to limit sensible heat loss
- ✓ Ultrathin active films to eliminate diffusional resistances (i.e. fast kinetics)

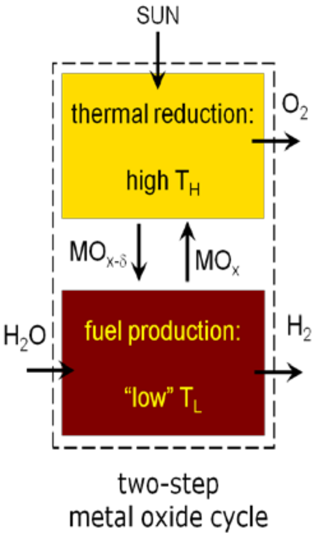


- ✓ 2012 electrolyzer performance target (0.3 A/cm^2 @0.7 V) achieved with two best membranes
- ✓ 60% reduction in Pt loading
- ✓ Copper deposition eliminated and crossover mitigated
- ✓ Full size (300 cm^2) electrolyzer fabricated & tested

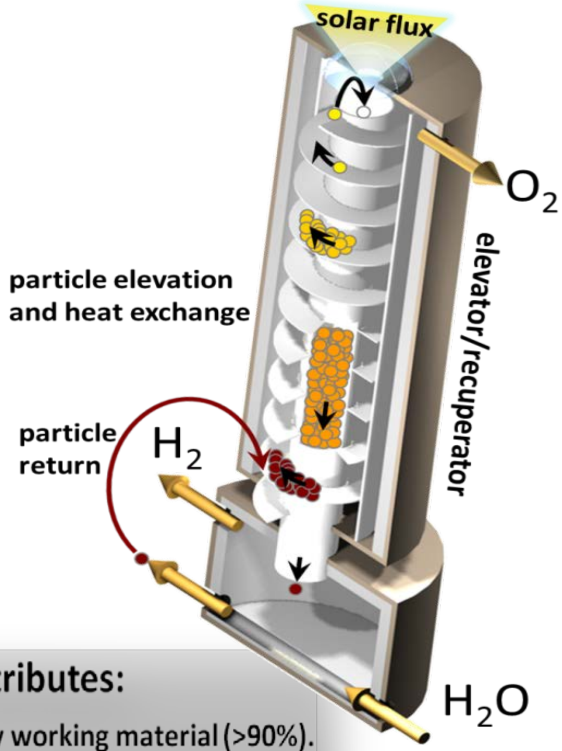
2012 Progress: Solar-Thermochemical (STCH)

Innovative reactor designs allow successful solar interface for reaction cycles.

✓ ***Designed Particle Bed Reactor for particle cycling, high solar utilization, and solar efficiency > 30% (theoretical). (SNL)***



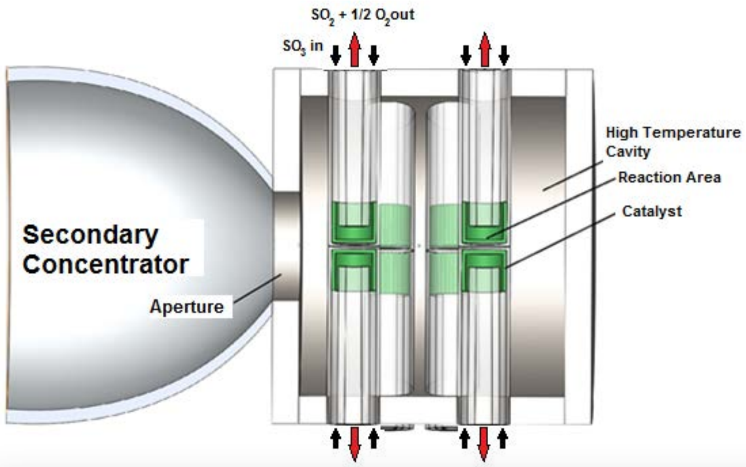
two-step metal oxide cycle



Key Design Attributes:

- DIRECT solar absorption by working material (>90%).
- EFFICIENT heat recovery between T_H & T_L (>75%).
- CONTINUOUS on-sun operation.
- INTRINSIC gas and pressure separation (H_2 from O_2).

✓ ***Developed Conceptual High-Temperature Receiver based on Sandia bayonet reactor for ~ 100kW peak thermal input for up to ~0.8 kg/hr H2 (SAIC)***

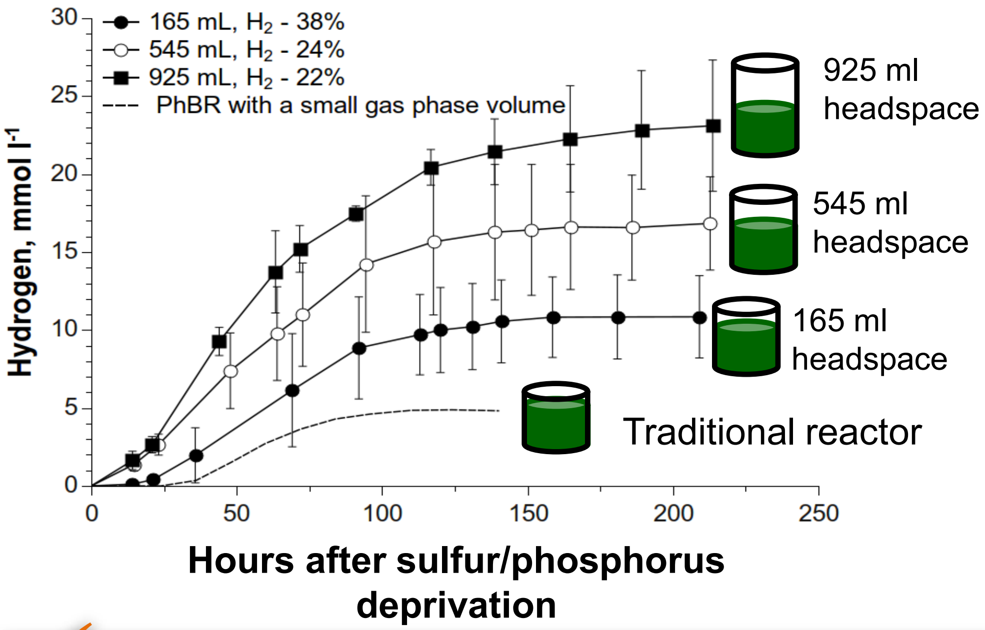


Key Design Attributes:

- Design focused on High Temp SO_3 decomposition
- Heat recuperation through heat transfer between inlet and outlet flows
- Back reaction minimized; products cooled without contact from catalyst

2012 Progress: Biological

Significant advancements in system design improve hydrogen yield.

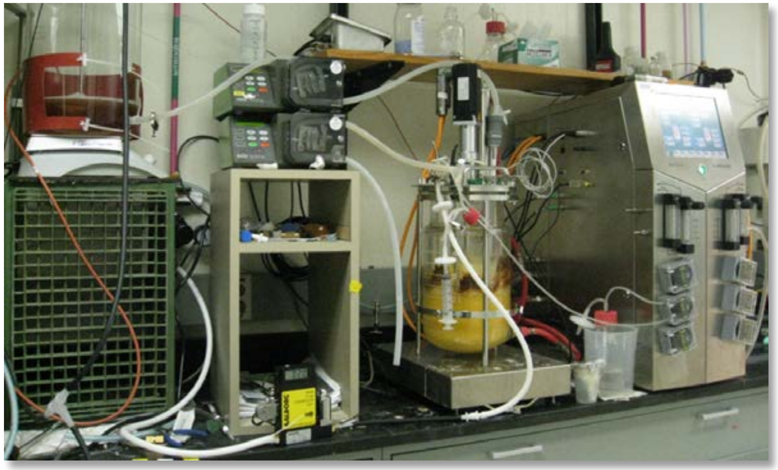


✓ Achieved the **highest reported yield** for a wild-type algae culture in less than 180 hours: 565 mL per liter of suspended culture, by increasing the space above the culture in a closed reactor. (NREL)

Publication: Kosourov, S.N., et al. (2012). "Maximizing the hydrogen photoproduction yields in *Chlamydomonas reinhardtii* cultures: The effect of the H_2 partial pressure." *International Journal of Hydrogen Energy*.

✓ Increased hydrogen production rate **over 2 fold** through increased cellulose feedstock feeding using new automated bioreactor design for fermentative H_2 production, demonstrating scalability of the system. (NREL)

Cellulose feed rate (g/L/day)	**Amount of H_2 produced** (mmoles)	**Max H_2 production rate** (mmol L^{-1} h^{-1})
2.5	18.5	1.2
5	35.3	2.6
10	51.9	3.5

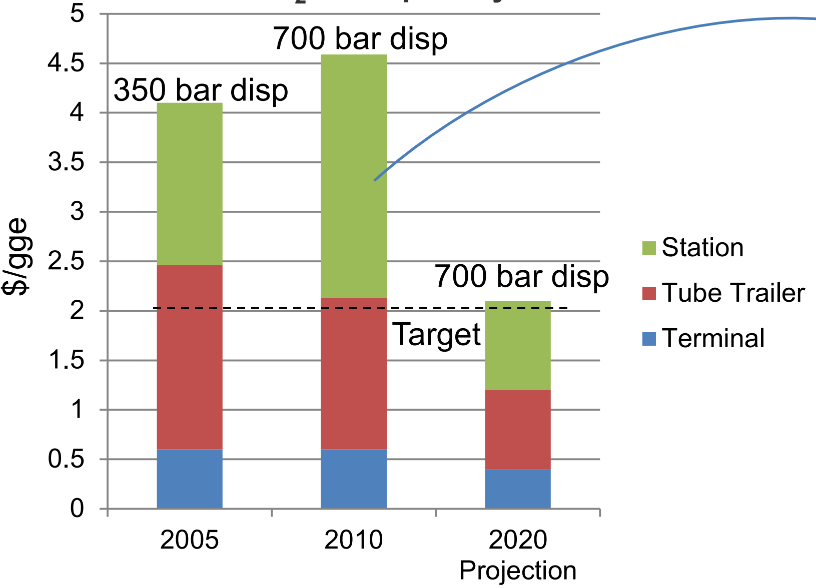


Challenges: Delivery

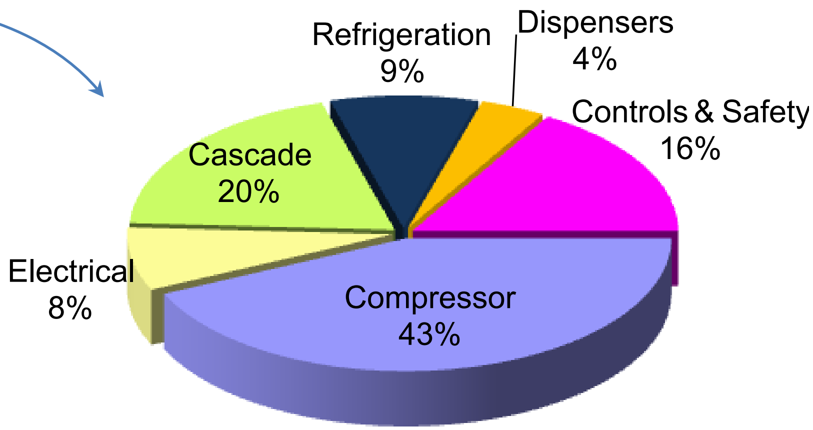
Station costs dominate delivery costs—key focus area.

Pathway Cost

Ex: CGH_2 Transport by Tube Trailer



Refueling Station (2011 Technology)



*Based on preliminary HDSAM (v2.3) analysis assuming 15% market penetration in a city with a population of 1.2M

Fueling Station (CSD) Costs

	2011 Projected Cost*	2020 Projected Cost*
Centralized Production	$1.90/kg	$1.30/kg
Distributed Production	$2.50/kg	$1.70/kg

***The portion of H_2 cost attributed to compression, storage, and dispensing. Projections assume a station capacity of 1500kg/day and mature station design and manufacturing technology (nth plant).**

FY2012 Analysis Focus

- ✓ Identify cost drivers for H_2 delivery in early market applications
- ✓ Evaluate options to improve station compressor reliability
- ✓ Investigate the role of high-pressure tube trailers in reducing station costs

Strategies: Delivery

Near-term emphasis on station technologies

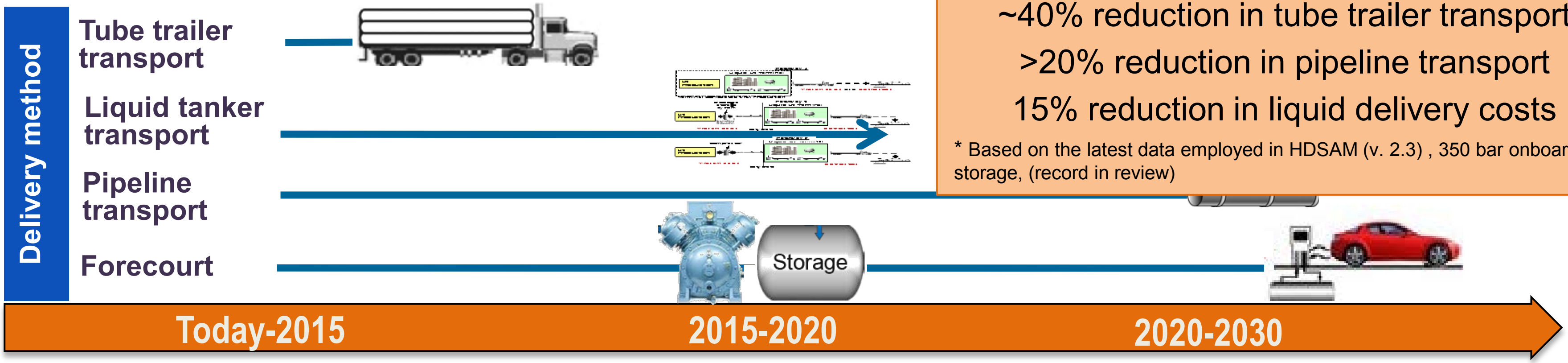
Reductions in projected costs*

~40% reduction in tube trailer transport

>20% reduction in pipeline transport

15% reduction in liquid delivery costs

* Based on the latest data employed in HDSAM (v. 2.3) , 350 bar onboard storage, (record in review)



Delivery method

- Tube trailer transport
- Liquid tanker transport
- Pipeline transport
- Forecourt

Storage

Today-2015

- Advanced tube trailer GH_2 transport
- Conventional LH_2 transport
- Mobile re-fuelers
- Co-sited forecourts
- Forecourt GH_2 production

2015-2020

- Improved liquefaction
- Cold GH_2 transport
- Improved, low-cost forecourt technology (compression & storage)

2020-2030

- Pipeline GH_2 transport
- Advanced energy efficient liquefaction
- Dedicated forecourts with advanced compression/ storage/dispensing technology

Pathway	Reference	2011 Status
GH_2 delivery via tube trailer	Based on HDSAM v 2.3: assumes Indianapolis with 15% market penetration, total of 122,000kg/day delivery over the entire city, plant is 62 mi from city gate. H_2 produced at 20bar. Costs include all processes from the plant gate to dispensing (700bar onboard storage) and are expressed in 2007 dollars. Costs assume mass production. Steel pipeline are based on a recent study by Brown et al., Oil & Gas Journal, v. 109, Jan. 2011. Tube trailer costs assume 560kg H_2 capacity.	$3.7gge
LH_2 delivery via tanker truck		$3.2/gge
GH_2 delivery via pipeline		$4.1/gge

2012 Progress: Tube Trailer Delivery

New trailer system meets DOE's 2015 capacity target.

FY10/11 Achievement

Lincoln Composite's Titan™ ISO System:

- ✓ Capable of transporting 616kg H_2 at 250bar (3625psi)
- ✓ 2x increase in capacity over steel vessels
- ✓ Received DOT special permit approval

FY12 Achievement

Lincoln Composite's Titan 5™ integrated CHG trailer system:

- ✓ Capable of transporting 726kg H_2
- ✓ 18% increase in capacity over Titan™
- ✓ Meets DOE's 2015 capacity target

2012 Progress: Pipelines for H_2(g) Delivery

Fiber reinforced polymer (FRP) pipeline can reduce costs 20%, and new compressor technology can reduce capital costs 20%.

Collaboration on FRP pipeline testing/characterization (SRNL & ORNL)

- ✓ Can reduce installation costs by 20– 40%
- ✓ Presented technical background for codification to ASME pipeline committee
- ✓ Collecting fatigue and burst data on baseline piping and those with intentional introduced flaws
- ✓ Carrying out a study for field testing at Aiken County H_2 Facility

ASME B31.12-2008

Hydrogen Piping and Pipelines

ASME Code for Pressure Piping, B31

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

ASME

Detailed designs for high speed centrifugal H_2 compressors (Mohawk Industries; Concepts NREC)

- ✓ Each designed to meet DOE’s 2015 targets for pipeline compression
- ✓ Potential to reduce capital cost by 20% and O/M costs by 30%
- ✓ Currently building single stage demonstration systems for testing

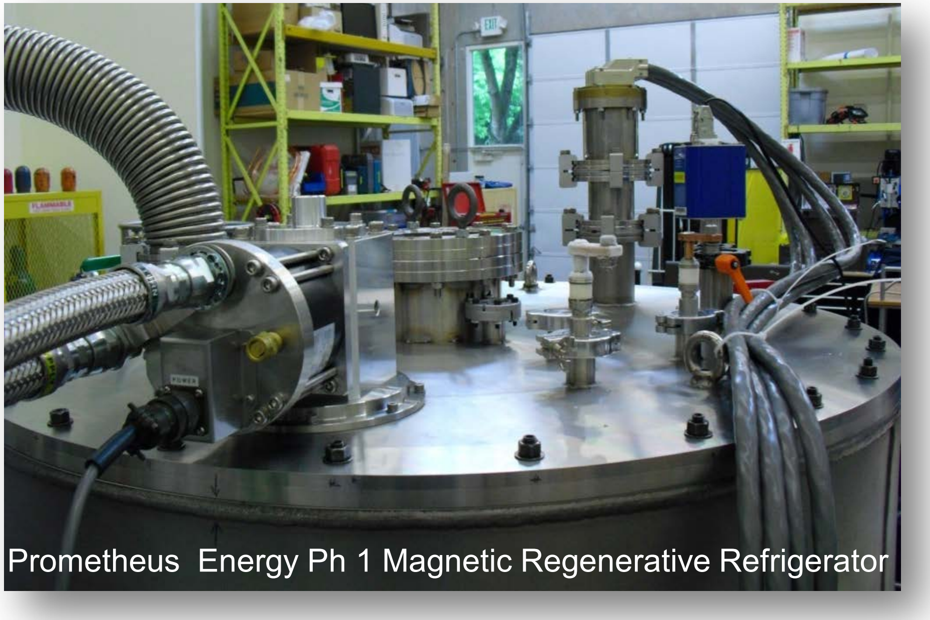
Mohawk Innovative Technology Inc. Single Stage Compressor

2012 Progress: Liquid Delivery & Cryopump

New magnetic liquefier system can potentially reduce energy consumption by 32%.

Developed a magnetic H_2 liquefaction system (Prometheus)

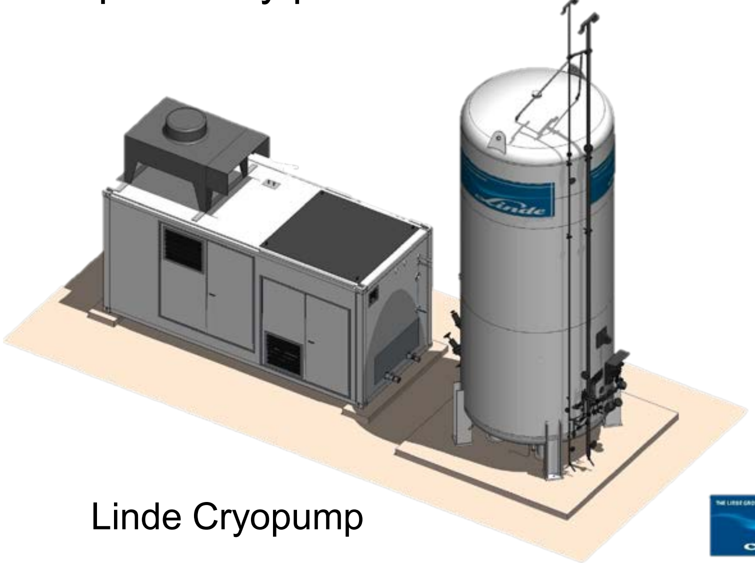
- ✓ Achieved a stable temperature of 120K (met Phase I goal)
- ✓ Is projected to increase H_2 liquefaction efficiency 32% (*reducing the energy cost of liquefaction from ~40% to ~20% of the lower heating value of* H_2)



Prometheus Energy Ph 1 Magnetic Regenerative Refrigerator

Planned installation of a Linde 880bar H_2 cryopump (LLNL)

- ✓ 100kg/hr peak refueling rate
- ✓ Enables cryocompressed storage and refueling testing
- ✓ Contract with Linde signed
- ✓ High pressure dispenser designed
- ✓ Facility construction planning underway (construction begin in Summer 2012)
- ✓ Pump delivery planned in December 2012



Linde Cryopump

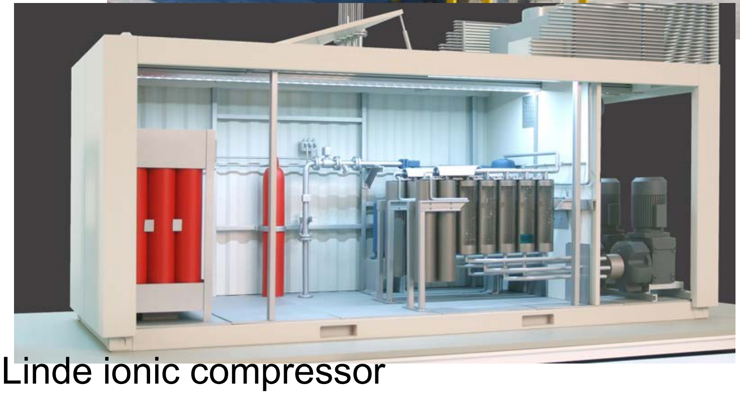
2012 Progress: Fueling Station

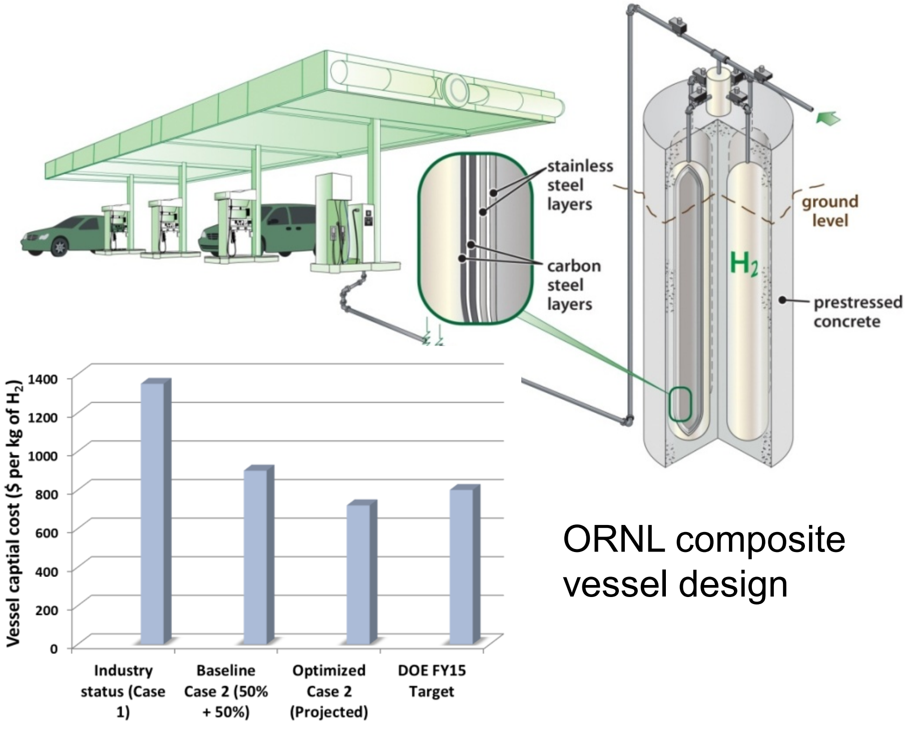
Advanced concepts are key to reduction of forecourt compression and storage costs

Power monitoring by NREL of the Linde IC-50 Ionic Compressor (350bar) at the AC Transit Emeryville refueling station to verify:

- Potential to reduce energy consumption by 20%
- Fast fueling of 5 kg/min
  - Similar to piston compression, but the piston is replaced by an ionic liquid


AC Transit Emeryville, CA Station


Linde ionic compressor

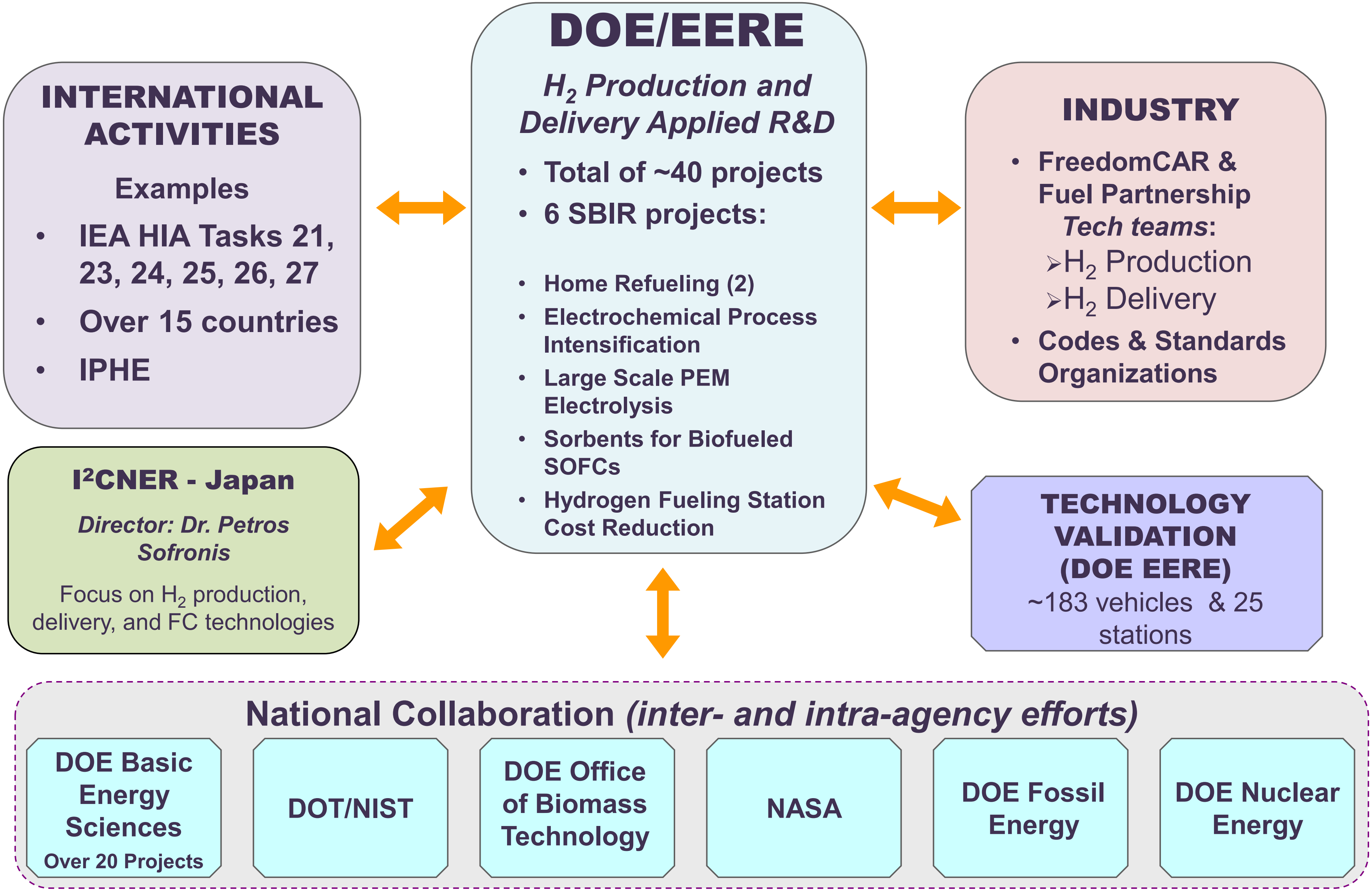


ORNL composite vessel design

Development of composite vessel of 50% steel + 50% concrete that can achieve an estimated 30% cost reduction when compared to current station storage vessel (ORNL)

✓ Conducting detailed design studies to further reduce projected cost prior to carrying out technology development and demonstration

Hydrogen Production & Delivery Collaboration



DOE/EERE

H_2 Production and Delivery Applied R&D

- **Total of ~40 projects**
- **6 SBIR projects:**

- **Home Refueling (2)**
- **Electrochemical Process Intensification**
- **Large Scale PEM Electrolysis**
- **Sorbents for Biofueled SOFCs**
- **Hydrogen Fueling Station Cost Reduction**

INTERNATIONAL ACTIVITIES

Examples

- **IEA HIA Tasks 21, 23, 24, 25, 26, 27**
- **Over 15 countries**
- **IPHE**

INDUSTRY

- **FreedomCAR & Fuel Partnership *Tech teams*:**
  - H_2 Production
  - H_2 Delivery
- **Codes & Standards Organizations**

I²CNER - Japan

Director: Dr. Petros Sofronis

Focus on H_2 production, delivery, and FC technologies

TECHNOLOGY VALIDATION (DOE EERE)

~183 vehicles & 25 stations

National Collaboration *(inter- and intra-agency efforts)*

- **DOE Basic Energy Sciences**
  Over 20 Projects
- **DOT/NIST**
- **DOE Office of Biomass Technology**
- **NASA**
- **DOE Fossil Energy**
- **DOE Nuclear Energy**

HTAC Hydrogen Production Expert Panel*

The Panel focused on R&D priorities for H_2 production and opportunities for coordination with other agencies/offices to optimize effectiveness of the H_2 production portfolio.

- May 10-12, 2012
- Over two dozen participants from academia, industry, and national laboratories in the field of hydrogen production
- Evaluated current status and future prospects for viable hydrogen production technologies for near and long term applications.
- Recommendations will be provided in a report to DOE through HTAC

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*"Hydrogen and Fuel Cell Technical Advisory Committee", DOE federal advisory committee per the Energy Policy Act of 2005
 - Expert Panel being held as subcommittee of HTAC with strict adherence to all FACA requirements

For More Information

U.S. DEPARTMENT OF ENERGY

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