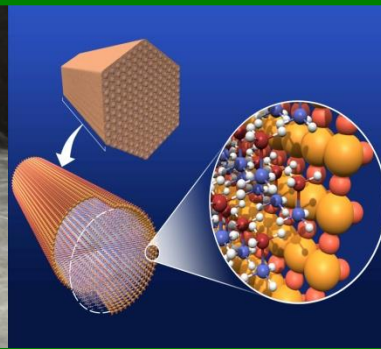




U.S. DEPARTMENT OF  
**ENERGY**



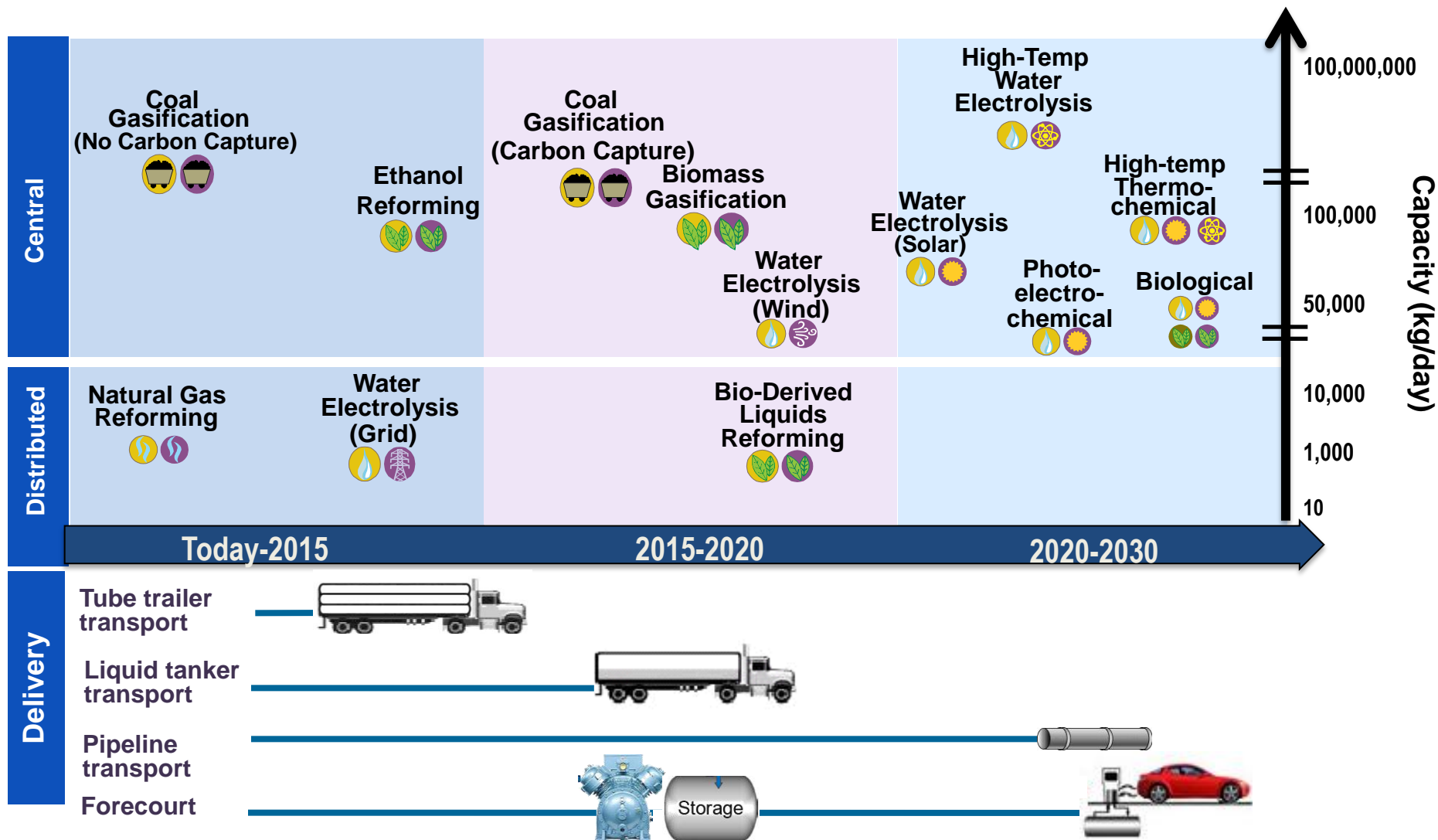
# Hydrogen Production & Delivery

*Sara Dillich*

*2011 Annual Merit Review and Peer Evaluation Meeting  
(May 9, 2011)*

# Goals and Objectives:

*Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of \$2-\$4/gge H<sub>2</sub>*



## Reduction of feedstock and capital equipment cost

### Pathway Challenges

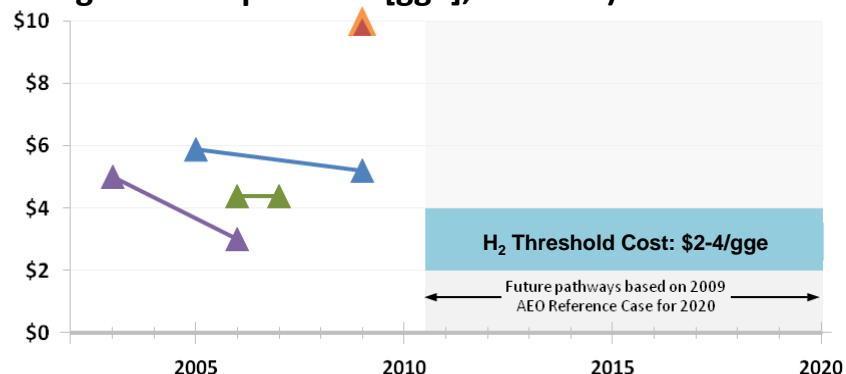
- **Near to Mid-Term :**
  - Electricity & feedstock costs
  - Capital equipment costs
  - Catalysts and membranes
  - Integration with grid
  - Forecourt CSD
- **Long-Term:**
  - Capital costs
  - Durable materials of construction
  - Feedstock costs
  - Operation and maintenance
  - Pipeline Infrastructure

### Projected High-Volume Cost of Hydrogen (Dispensed)—Status (\$/gallon gasoline equivalent [gge], untaxed)

#### NEAR TERM:

##### Distributed Production

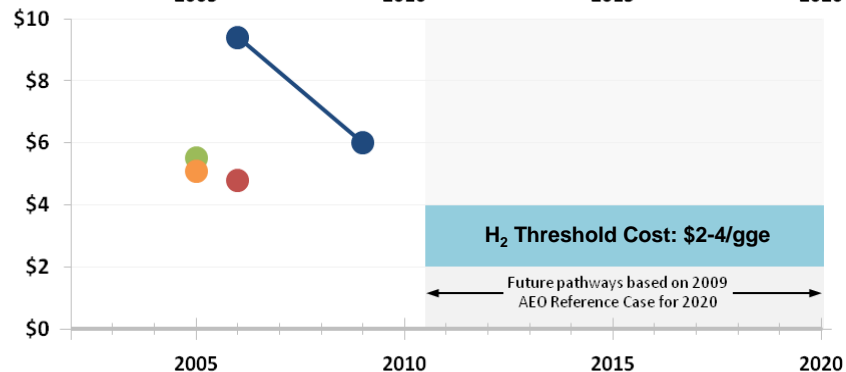
- ▲ Natural Gas Reforming
  - ▲ Ethanol Reforming
  - ▲ Electrolysis
- Low-volume (200 kg/day)
- ▲ Steam Methane Reforming
  - ▲ H<sub>2</sub> from Combined Heat, Hydrogen, and Power Fuel Cell



#### LONGER TERM:

##### Centralized Production

- Biomass Gasification
- Central Wind Electrolysis
- Coal Gasification with Sequestration
- Nuclear

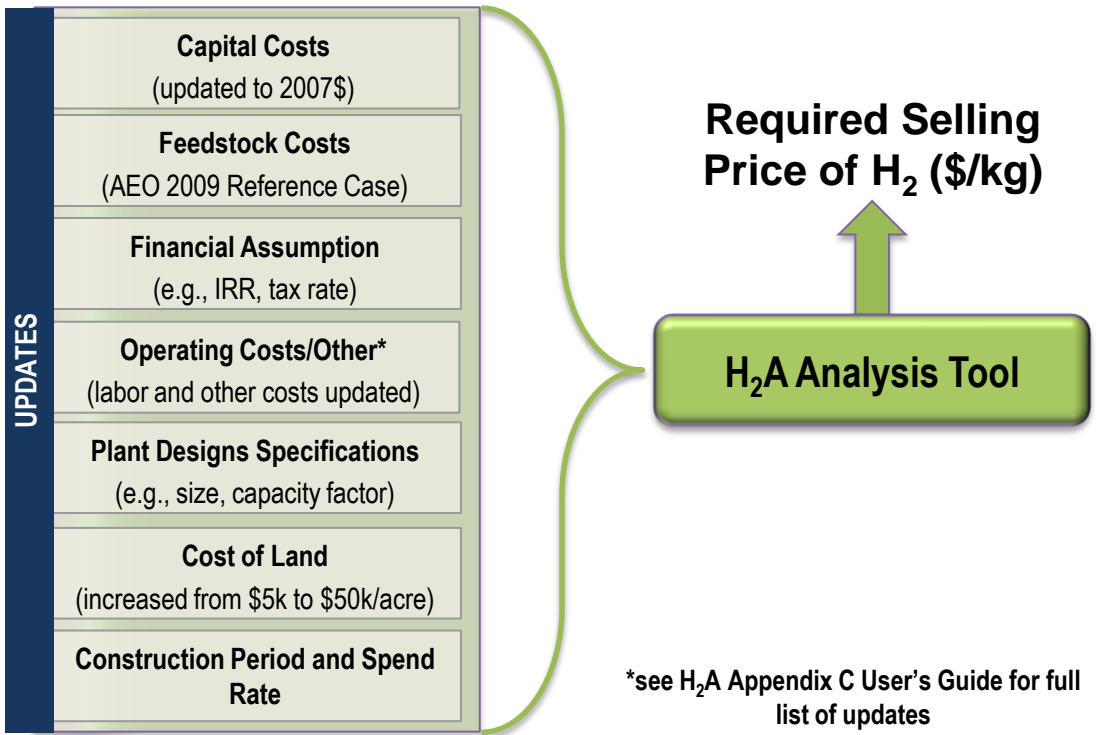


Hydrogen cost range reassessed – includes gasoline cost volatility and range of vehicle assumptions.

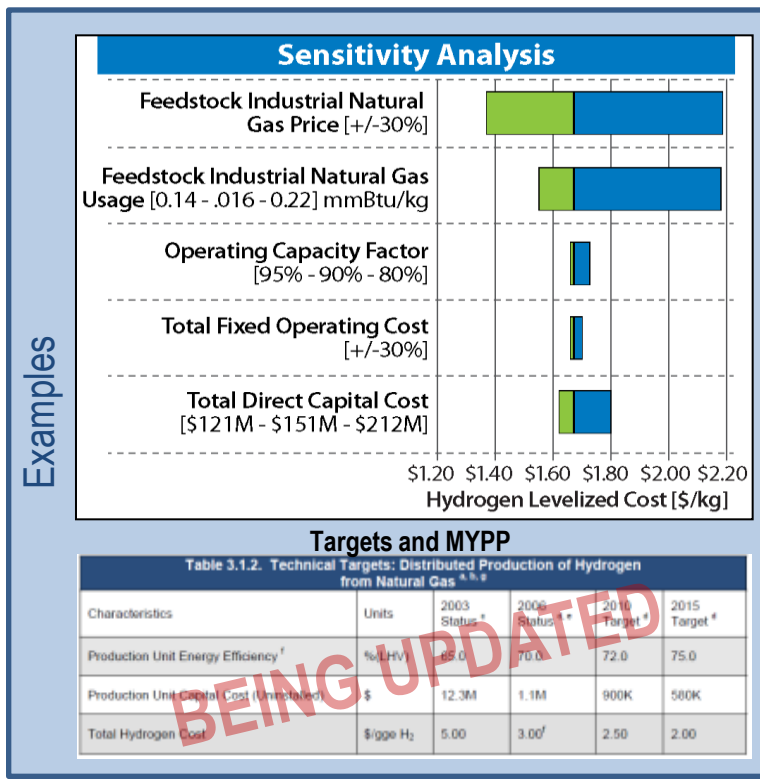
Hydrogen threshold costs have been updated from \$2-\$3/gge to \$2-\$4/gge. High volume projected costs for hydrogen production technologies continue to decrease. Low volume/early market costs are still high

Cost data points are being updated to the 2009 AEO reference case.

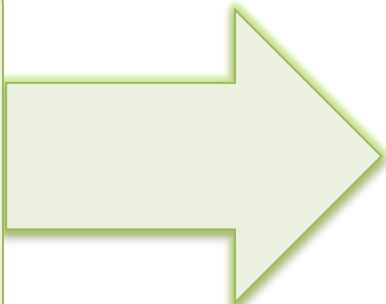
# Strategies: Update Targets and R&D Plan



\*see H<sub>2</sub>A Appendix C User's Guide for full list of updates



- **Updates to:**
  - H2A and HDSAM models
  - Pathway cost projections
  - Cost & performance targets
- **Analyses & Independent Reviews**
- **Blue Ribbon Panel (planned)**



**Critical Path R&D**

# Production Strategies

## *Targets and projected costs informed by independent analysis*

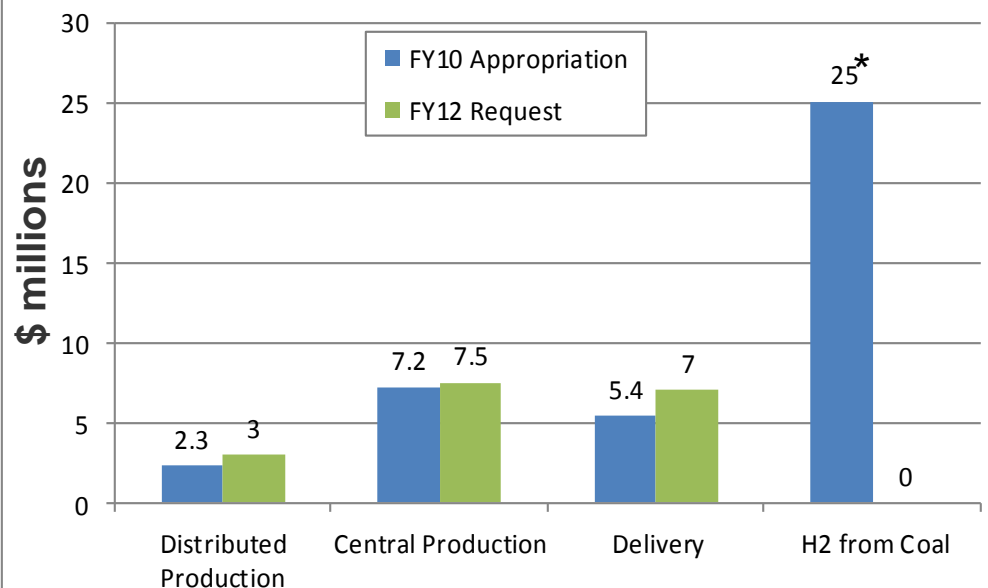
<b>Pathway</b>	<b>Report</b>	<b>Status</b>
Steam Methane Reforming	<i>Distributed Hydrogen Production from Natural Gas</i> , NREL, October, 2006	\$2.75-\$3.05/gge
Electrolysis - Distributed  - Central (Wind)	<i>Current (2009) State -of-the-Art Hydrogen Production Cost Estimate Using Water Electrolysis</i> , NREL, September, 2009.	\$4.90-\$5.70/gge ~ 75% membrane efficiency(PEM)  \$2 .70-\$3.50/gge ~75% membrane efficiency (PEM)
Photoelectro-chemical (PEC)	<i>Technoeconomic Analysis of Photoelectrochemical (PEC) Hydrogen Production</i> , Directed Technologies Inc., December, 2009.	\$4-\$10/gge (projected cost assuming technology reaches technology readiness). Promising PEC materials identified, but durability issues remain.
Biological	<i>Technoeconomic Boundary Analysis of Biological Pathways to Hydrogen Production</i> , Directed Technologies Inc., September, 2009.	\$3-\$12/gge (projected cost assuming technology reaches technology readiness). 15% solar-to-chemical energy efficiency by microalgae
Biomass Gasification	<i>Hydrogen Production Cost Estimate Using Biomass Gasification</i> , Independent Panel Review, NREL, <b>Draft</b> , April, 2011	Preliminary results: feedstock costs, capital costs, and financing structure are primary influences on cost.
Solar Thermochemical	<i>Cost Analyses on Solar-Driven High Temperature Thermochemical Water-Splitting Cycles</i> , TIAx, February, 2011	Hybrid Cycles: \$3.9 -\$5.4 (2025) Hi Temp Cycles: \$2.4-\$4.7 (2025) H2A, <b>\$2007</b>

Target and Status costs are 2009 projected high volume costs (Centralized pathway costs do not include dispensing costs, cost targets for STCH, PEC and Biological are technology readiness using H2A assumptions)

**FY 2012 Request = \$17.5M**

**FY 2010 Appropriation = \$15M**

## Hydrogen Production & Delivery



**FY11 appropriation to be determined**

\*Includes coal-biomass-to-liquids R&D

Nuclear Hydrogen Initiative was discontinued at end of FY 2009 as a separate program. Development of high temperature electrolysis is continuing under the NGNP project, which is also looking at other end-use applications and energy transport systems

## Emphasis

- Update cost projections and 2015 and 2020 targets

## Distributed Production

- Develop production and forecourt technologies for early markets
- Reduce capital costs by 10% from 2010 baseline

## Central

- Continue R&D on solar and bio-based renewable technologies
- Address key materials needs for P&D: Membranes, Catalysts, PEC Devices, Reactors, and Tanks

## Hydrogen from Coal

- Complete laboratory-scale development of separation and purification technologies for coal-derived syngas;
- Continue engineering-scale development of these technologies (FE)



## Pyrolysis oil : potential low-cost feedstock for distributed production

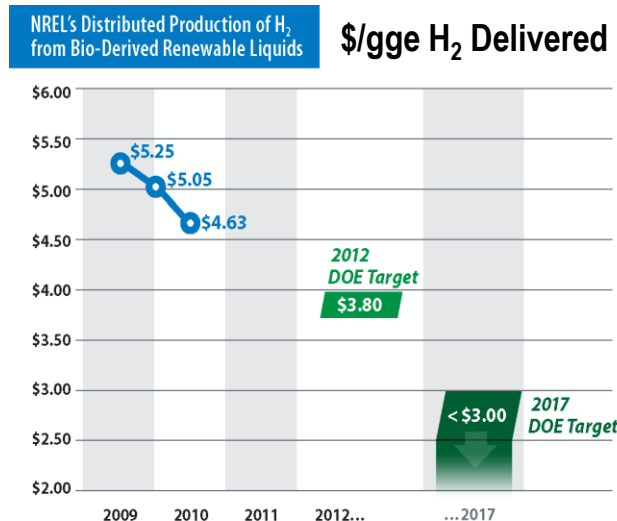


Biomass pyrolysis produces high yields of bio-oil, which could be stored and shipped to a site for renewable hydrogen production.

Pyrolysis oil has a significantly lower cost than sugars or sugar alcohols

**Autothermal Reforming (NREL)**  
production of H<sub>2</sub> by catalytic steam reforming of oil (~ 650 C)

- Increased hydrogen yield by 65%
- Reduced production cost to an estimated \$4.63/gge delivered\*

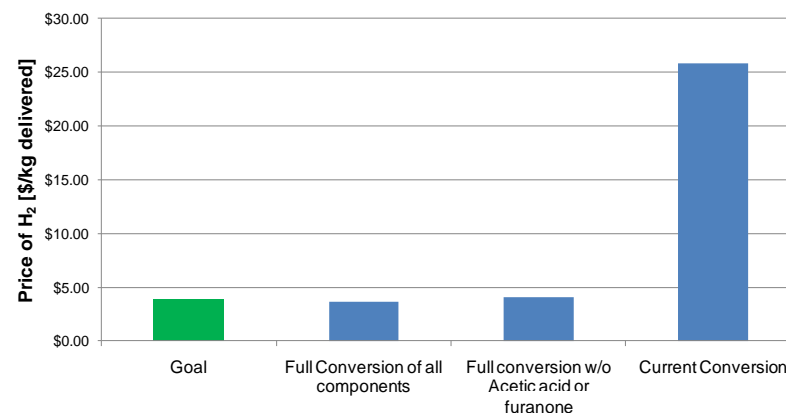


\*H2A assumptions: 2005\$, nth plant, 1,500 kg/day, Current projected high volume cost based on 2011 performance

**Aqueous Phase Reforming (PNL)**  
production of H<sub>2</sub> from bio-oil in water phase at moderate temperatures (< 275 C)

H2A analysis demonstrates economic feasibility

**Cost of Hydrogen From Bio-oil Conversion**  
(Relative to 2012 Target of \$3.80/kg H<sub>2</sub>)



**Ongoing Focus:**

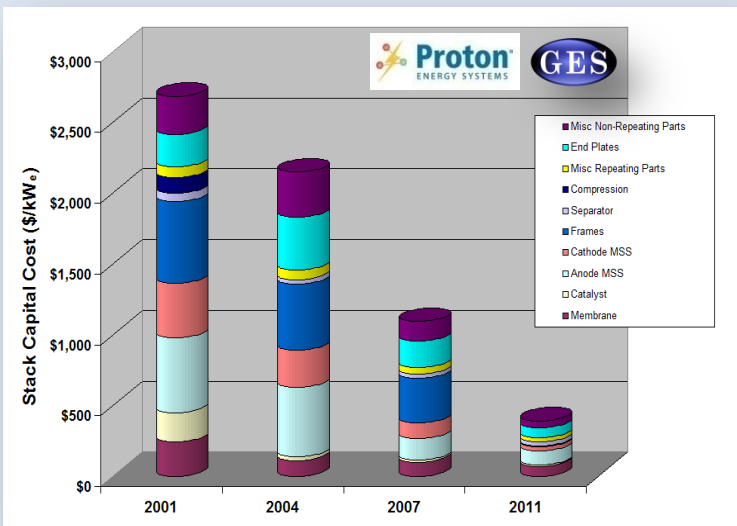
- Acetic acid in feed reduces catalyst activity
- Consumption of produced H<sub>2</sub> by other molecules in the feed
- Further reduction in cost

\*H2A assumptions: \$0.65/gallon bio-oil delivered (\$0.50-0.80 range ) 7



# 2011 Progress: Electrolysis

*Stack capital costs reduced through design and manufacturing innovations*

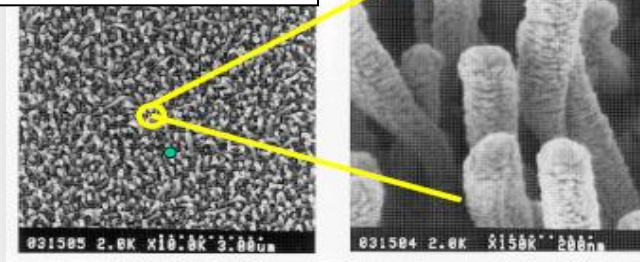


*Historical capital cost reduction*

➤ **Demonstrated 15% stack capital cost reduction using optimized designs (Proton, Giner):**

- Optimized catalysts, membranes, bipolar plates and gas diffusion layers (GDL)
- Reduced cell- and stack- part count

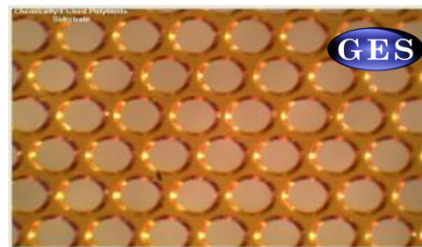
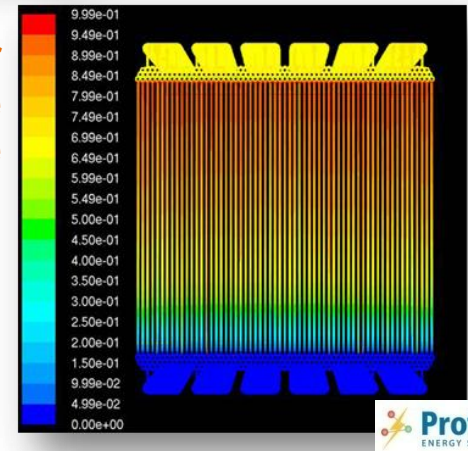
3M nanostructured thin film electrode



Reduction of noble metals with catalyst optimization:

- 50% loading reduction on anode
- >90% reduction on cathode

Designed electrolyzer cell model for more accurate performance prediction

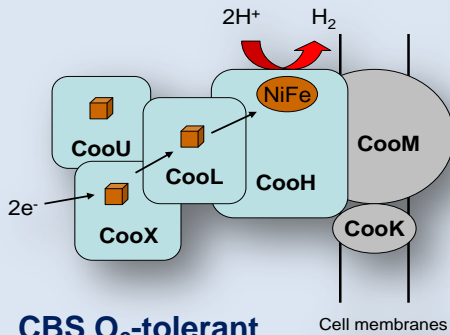


90% cost reduction of the MEAs by fabricating chemically etched supports

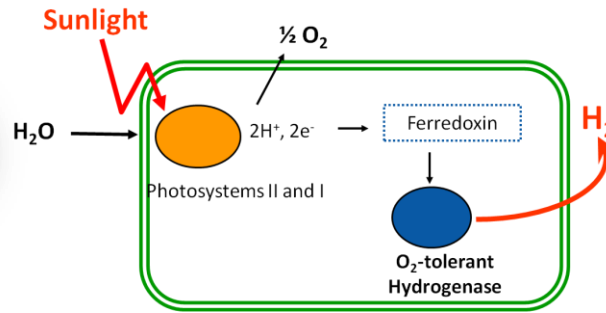


# 2011 Progress: Biological

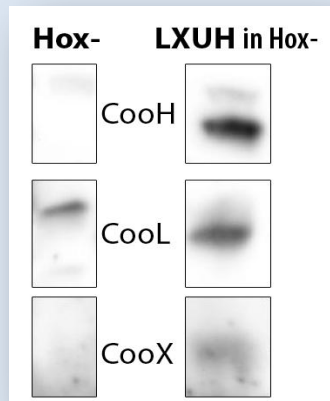
## Tools developed to manipulate bacteria genome for O<sub>2</sub> tolerant hydrogen production



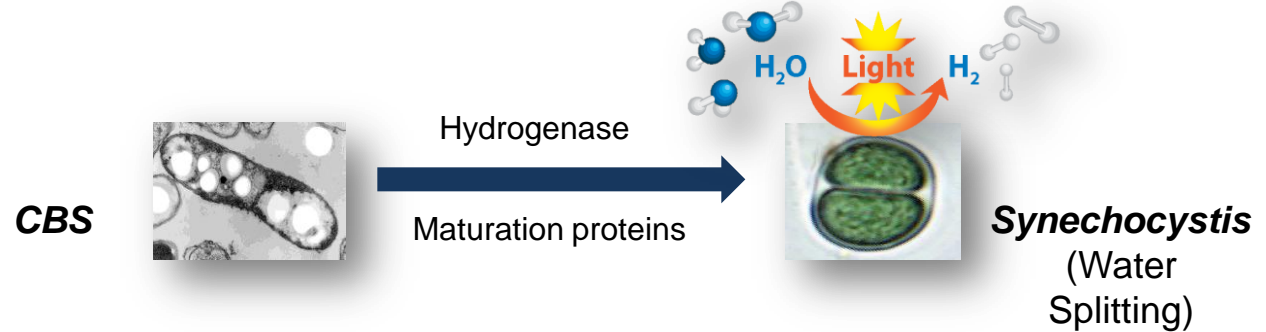
**CBS O<sub>2</sub>-tolerant hydrogenase protein**



**Goal:** Develop an O<sub>2</sub>-tolerant cyanobacterial system for continuous light-driven H<sub>2</sub> production from water



Three of the four CBS hydrogenase subunits were expressed in *Synechocystis* Hox-. The figure above show the presence of CooLXH CBS proteins in the *Synechocystis* recombinant, but not in the Hox- control (left column)



**NREL** developed the genetic tools necessary to manipulate the genome of the bacteria *Rubrivivax gelatinosus* CBS and demonstrated introduction of hydrogen producing machinery, Hydrogenase, from CBS into *Synechocystis*.

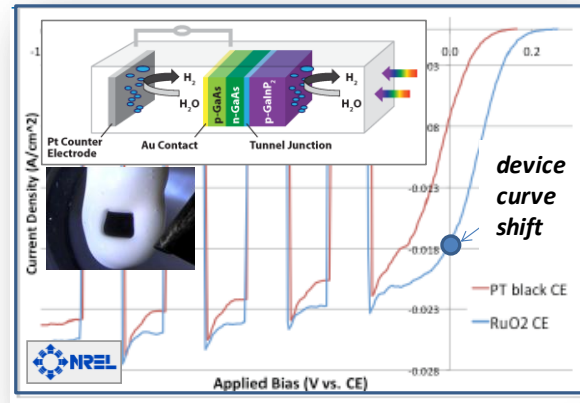
**Next step:** Confirm expression of the CBS hydrogenase maturation proteins in *Synechocystis*

# 2011 Progress: Photoelectrochemical

## New benchmark for solar to hydrogen (STH) efficiency

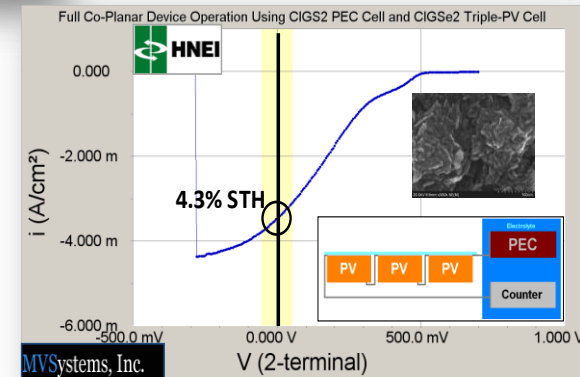
### Accomplishments:

- ✓ Set new performance benchmarks in crystalline material systems (NREL)
- ✓ Set new performance benchmarks in thin-film material systems (MV Systems)
- ✓ Demonstrated novel approach for utilizing nano-particle photocatalysts (Stanford)

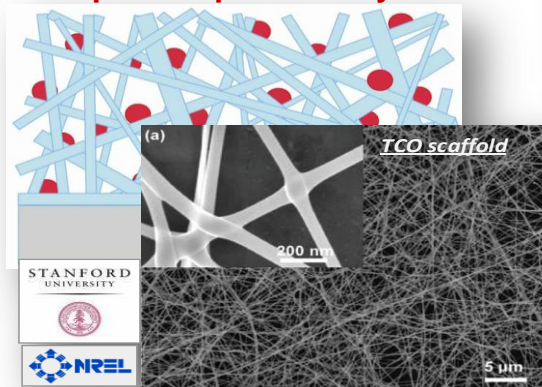


>16% STH efficiency potential demonstrated in crystalline III-V device

4.3% STH efficiency demonstrated in multi-junction thin-film CGSe device



### nano-particle photocatalysts



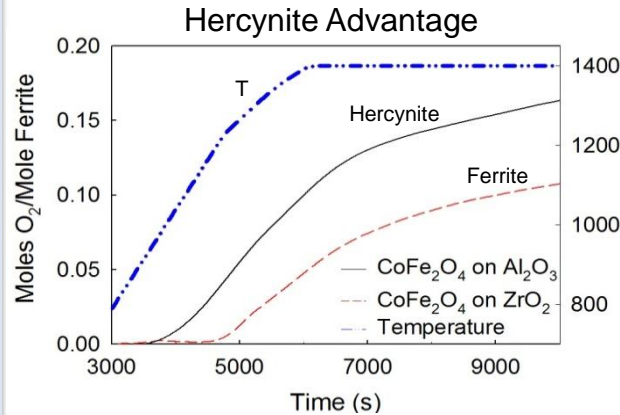
Developed a macroporous scaffold that is transparent, conducting and high surface area – an ideal PEC substrate for MoS<sub>2</sub> and other materials.

## Advanced materials: key to progress in STCH production



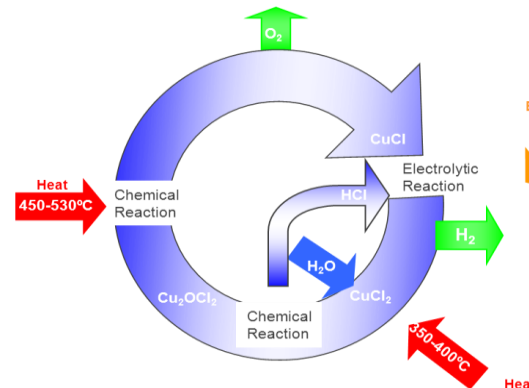
A solar concentrator uses mirrors and a reflective or refractive lens to capture and focus sunlight to produce temperatures up to 2,000°C. This high-temperature heat can be used to drive chemical reactions that produce hydrogen.

Hydrogen production by thermochemical water splitting is a chemical process that accomplishes the decomposition of water into hydrogen and oxygen using heat or a combination of heat and electrolysis.



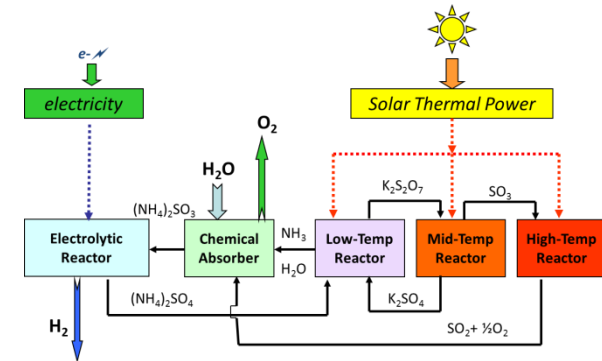
### Sulfur Ammonia Cycle

Down-select of electrode and catalyst materials for high T, P testing. Voltage of the electrolytic cell has been reduced to values at 80°C, close to those previously obtained at 130°C. (SAIC)



### Ferrite Cycle

Using ALD Ferrite, increased thin film peak production rate ~100x faster than bulk. Hercynite route shows advantages in reduced reduction temperature and larger operating window. (U of Colorado)



### Cu-Cl Cycle

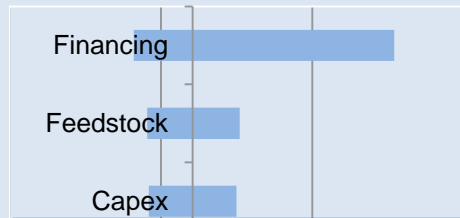
Two best membranes identified for Cu-Cl cycle with Cu diffusivity <10% of Nafion that are chemically and thermally stable at 80 C for over 40 hours. (ANL)

# 2011 Progress: Biomass Gasification

*Efficiency improvements through membrane design (GTI); aqueous phase reforming approach (UTRC)*

## Independent Panel Review: Preliminary Conclusions

### Nth 2,000 T/Day Plant

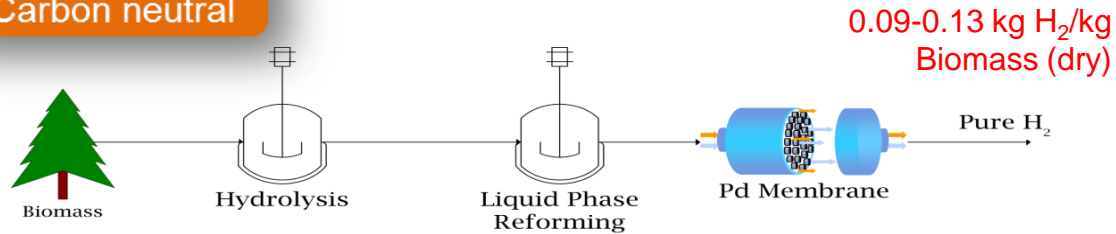


\$2.00 \$5.00  
**H2 Production Cost (\$/kg)**

Primary influences on cost include feedstock costs, capital costs, and project financing structure

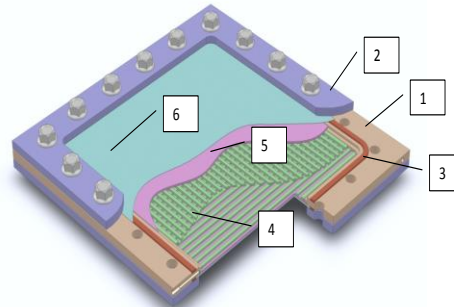
## Biomass to Slurry Approach (UTRC)

- ✓ Fuel flexible
- ✓ Carbon neutral



Characteristics	Units	2012 Target	Current Status
Hydrogen Cost (Plant Gate) <sup>a</sup>	\$/gge	1.60	1.54 (1.31–2.11)
Total Capital Investment	\$M	150	170 (117–304)
Energy Efficiency <sup>b</sup>	%	43	51.1

## Biomass Gasifier with Close Coupled Membrane (GTI)



- 1-base plate
- 2-clamping frame
- 3-copper gasket
- 4-slotted metal support
- 5-porous support
- 6-membrane

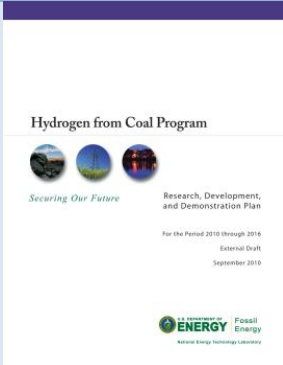
- Membrane module design completed
- Potential for >40% H<sub>2</sub> production efficiency improvement over current gasification technologies



# 2011 Progress: Hydrogen from Coal

## Engineering scale testing of purification and separation technologies in FY11

*Hydrogen from Coal Program Research, Development and Demonstration Plan (Sept 2009)*

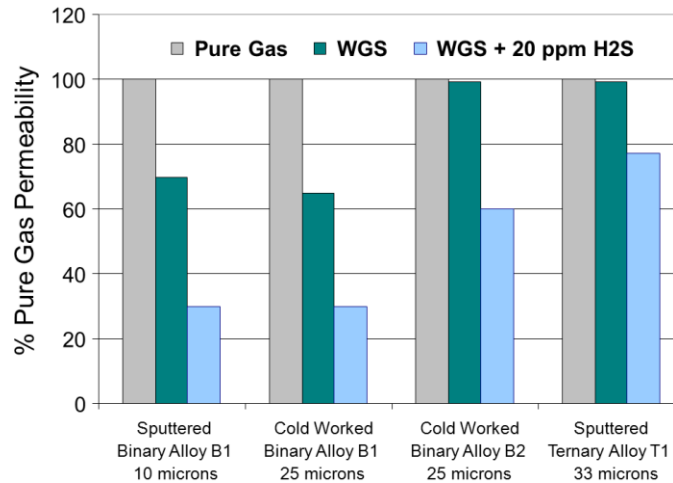


Part of FE's mission is to prove the feasibility of a near-zero emissions, high-efficiency plant that will produce both hydrogen and electricity from coal and reduce the cost of hydrogen from coal by 25 % compared with current technology



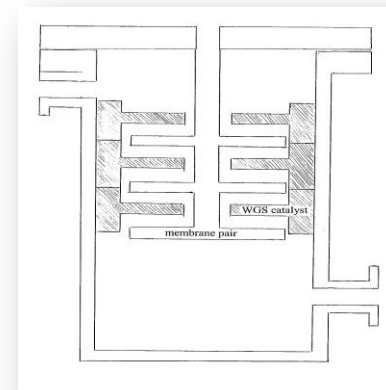
Construction, installation, and mechanical shakedown of the 12 lb/day Hydrogen Transport Membrane. (Eltron)

Performance Criteria	2010 Target	2015 Target	Eltron Membrane
Flux (SCFH / ft <sup>2</sup> )	200	300	320
Operating Temperature (°C)	300-600	250-500	300-400
S Tolerance (ppmv)	2	20	2-20
System Cost (\$/ft <sup>2</sup> )	500	<250	<200
ΔP Operating Capability (psi)	400	800-1000	1000
Carbon Monoxide Tolerance	Yes	Yes	Yes
Hydrogen Purity (%)	99.5	99.99	99.999
Stability / Durability (Years)	3	>5	0.9
Permeate Pressure (psi)	N/A	N/A	>400



Identified, produced, and tested alloys with good sulfur resistance and high flux. Plan to begin sulfur testing in 2Q11. (Praxair)

Currently constructing a stainless steel pressure vessel with stacked donut shaped composite membranes and ceramic water gas shift (WGS) catalyst. (WRI)



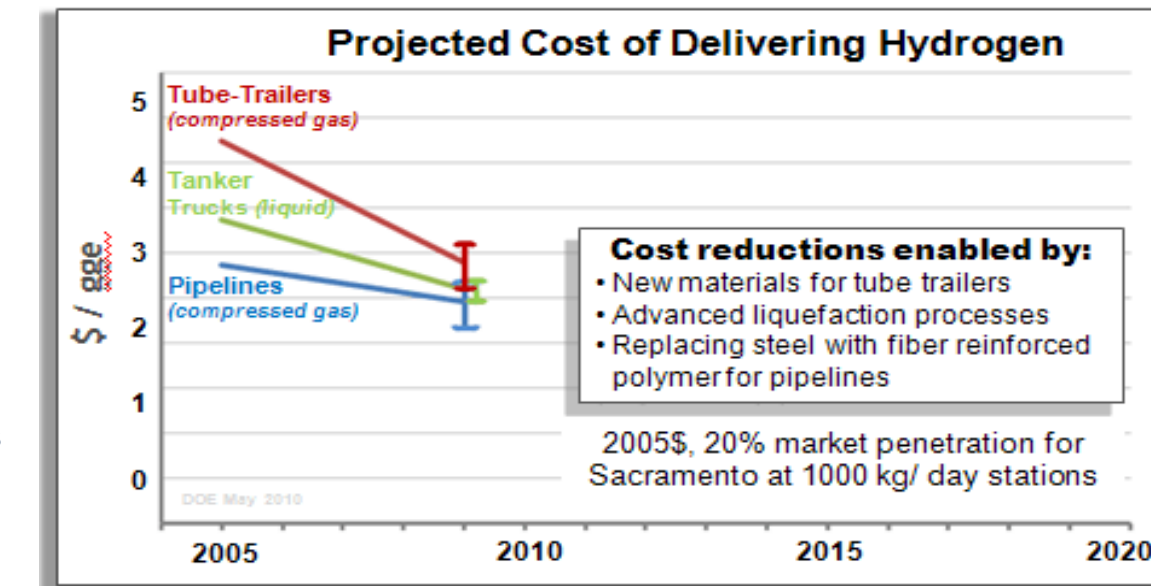
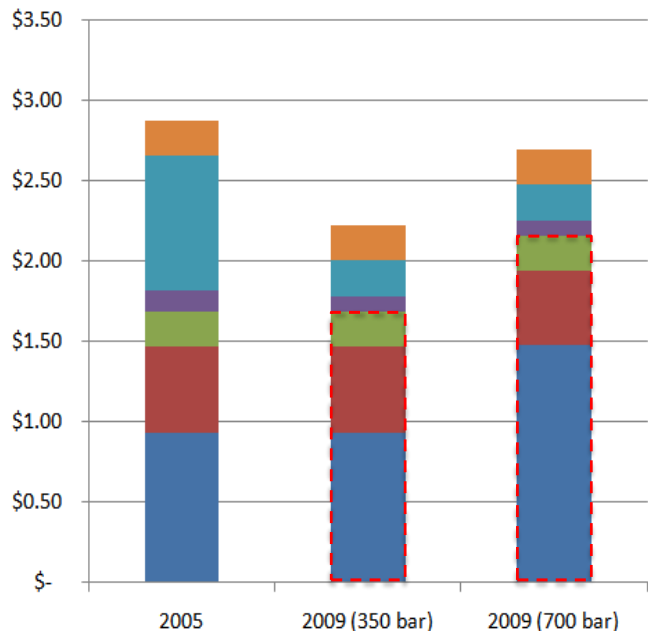


## Station costs now dominate delivery costs

### Reductions in projected costs of hydrogen delivery:

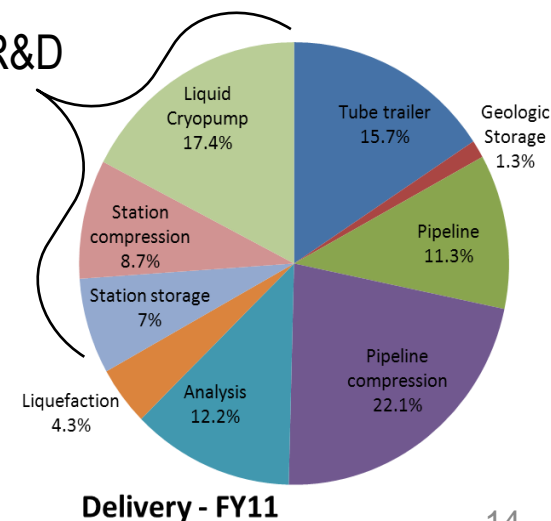
- ~30% reduction in tube trailer costs
- >20% reduction in pipeline costs
- ~15% reduction in liquid hydrogen delivery costs

### Example: Projected pipeline delivery costs

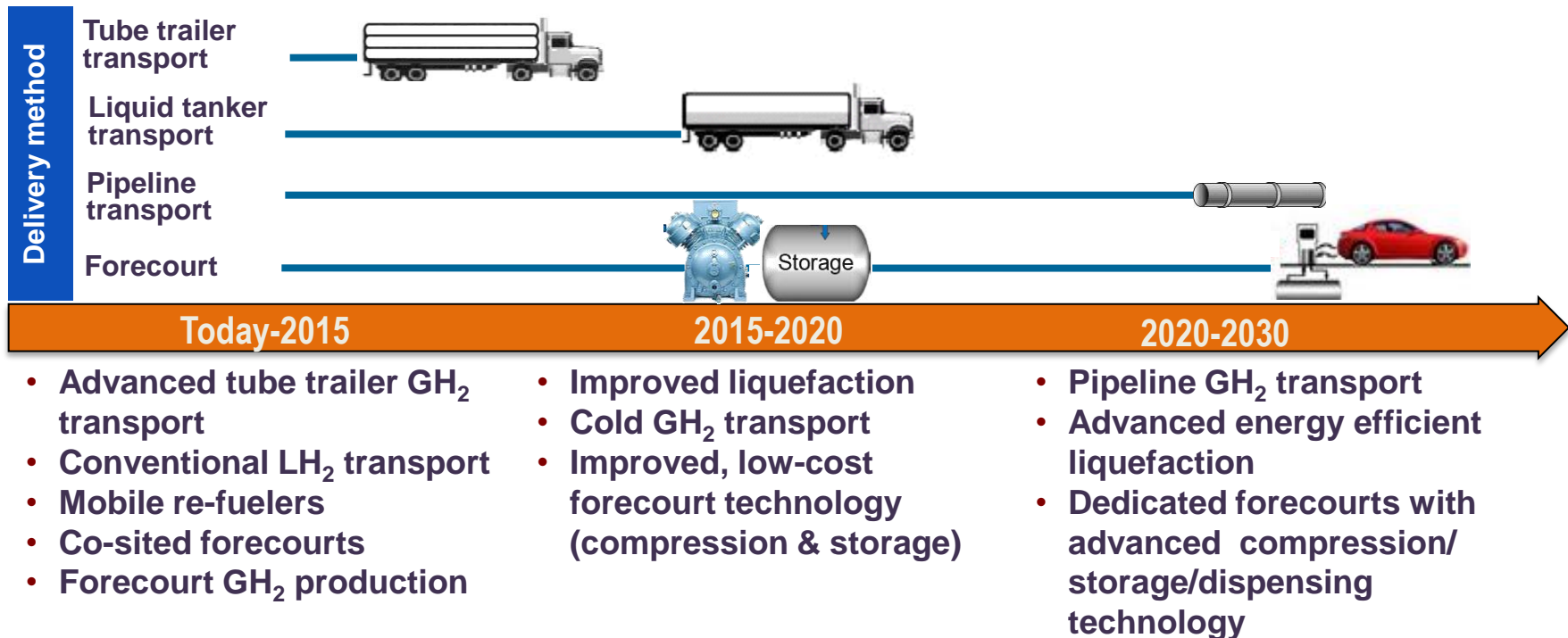


### Station R&D

As Transport costs are reduced, station costs become the dominant portion of the overall cost of H<sub>2</sub> delivery



## Long-term emphasis on forecourt technologies

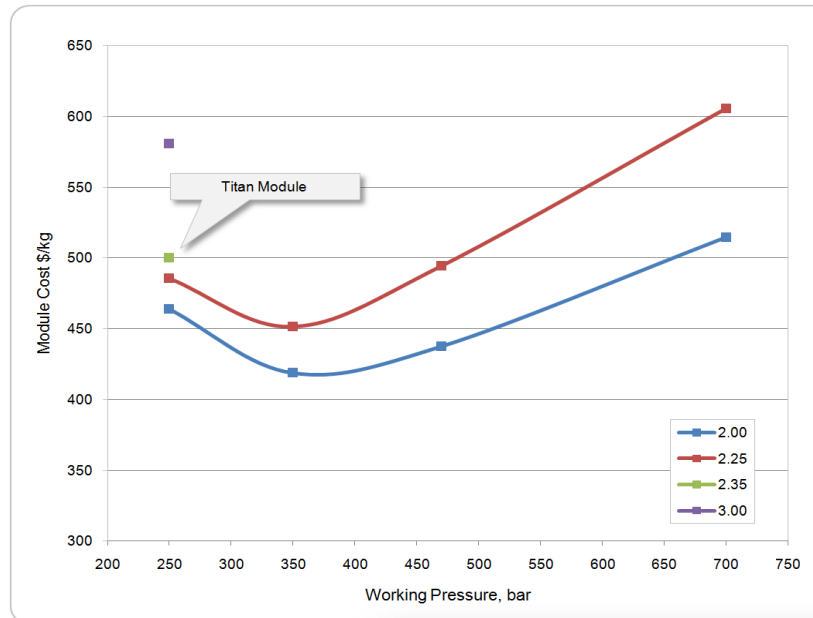


Pathway	Reference	Status (2010)
GH <sub>2</sub> delivery via tube trailer	Based on HDSAM v 3.0: assumes Indianapolis with 15% market penetration, total of 122,000kg/day delivery over the entire city, plant is at city gate. H <sub>2</sub> produced at 20bar. Costs include all processes from the plant gate to dispensing (700bar onboard storage) and are expressed in 2007 dollars. Costs assume mass production and costs for steel pipeline are based on a recent study by Brown et al., <u>Oil &amp; Gas Journal</u> , v. 109, Jan. 2011; results not yet vetted.	\$4.6/gge
LH <sub>2</sub> delivery via tanker truck		\$3.2/gge
GH <sub>2</sub> delivery via pipeline		\$4.1/gge

## *New design parameters increase trailer capacity*

### **Accomplishments:**

- Completed a design trade study on carbon fiber wrapped vessels that shows the potential for:
  - ▶ 100 bar increase in vessel pressure to 350 bar
  - ▶ 33% increase in carrying capacity to 800 kg H<sub>2</sub>
  - ▶ 10% reduction in transport costs (Lincoln)
- Successfully fabricated and hydroburst tested a full scale glass fiber wrapped vessel (LLNL)



- **Practical limit is likely 350 bar**
  - ▶ Higher pressures require thicker walled vessels
  - ▶ Availability of low-cost plumbing hardware
  - ▶ Availability of low-cost H<sub>2</sub> compressors

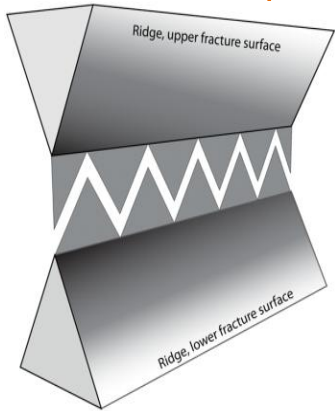


**LINCOLN  
COMPOSITES**  
A Member of Hexagon Composites Group

# 2011 Progress: Pipelines for Gaseous H<sub>2</sub>

*Projected reduction in installed pipeline costs of 15% and pipeline compressor costs of 20%*

## Steel Pipeline Analysis (SNL/U of Illinois)

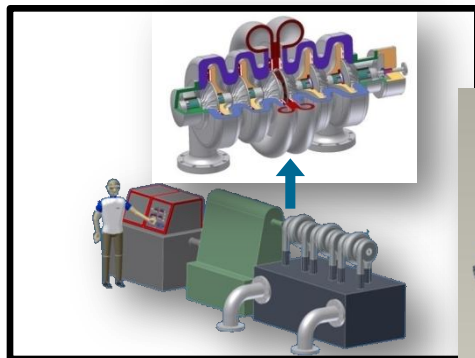


- Developed models to predict the effects of H<sub>2</sub> on the mechanical properties of pipeline steels
- Identified 2 commercial pipeline steel micro-structures that minimize H<sub>2</sub> effects at pressure

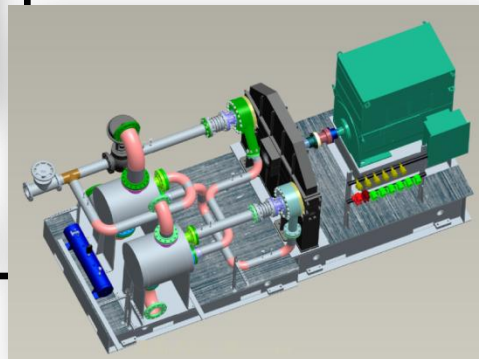
## FRP Pipeline Analysis (ORNL/SRNL)



- Demonstrated 3x safety factor in fiber reinforced polymer (FRP) pipeline via flaw tolerance testing
- Projected 15% reduction in installed pipeline cost



Concepts NREC



Mohawk Innovative Technology, Inc.

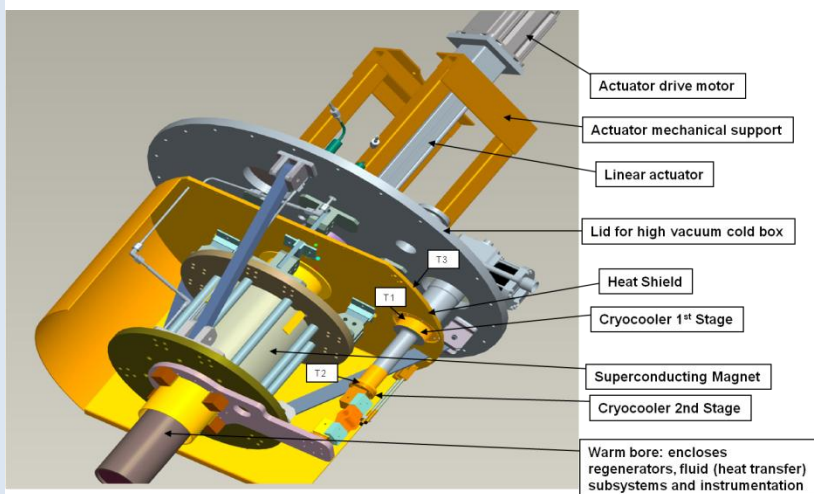
## Compression (Mohawk/Concepts NREC)

- Initiated fabrication of two compressor designs for prototype testing
- Prototype testing to begin next year

Potential to reduce capital cost by >20% and O/M costs by >30%

## Projected increase in $H_2$ liquefaction efficiency of 23% through active magnetic regenerative refrigeration (AMRR)

### Active Magnetic Regenerative Refrigerator (AMMR)



Heracles

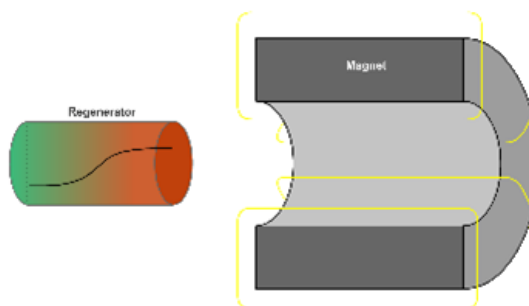
The “refrigerant” is a solid magnetic material whose entropy can be manipulated by an external magnetic field. Rejection and absorption of heat are accomplished by the temperature changes upon magnetization/demagnetization.

Largest cost factor in liquid transport is the liquefaction process. Focused on reducing operating and equipment costs.

### Accomplishments:

- ✓ Improved ortho-para conversion performance and reduced total power required for liquefaction by 2.4% (Praxair)
- ✓ Fabricated a continuous catalytic heat exchanger for improved liquefaction efficiency (GEECO)
- ✓ Fabricated and integrated all subsystems into a prototype AMRR device – currently in testing (Heracles)

### AMR Refrigeration Cycle



Adiabatic Magnetization: Temperature Increase





# 2011 Progress: Refueling Station

## *Reduced forecourt compression and storage costs*

### Electrochemical Hydrogen Compressors (FuelCell Energy)

*Improving reliability and reducing operating cost for forecourt compression at 12000 psi*

#### Accomplishments:

- ✓ Projected a 5x reduction in energy consumption.
- ✓ Developed 2-stage EHC system concept
- ✓ Validated 2-stage EHC hardware feasibility at 2,000/6,000 psi level



FuelCell Energy

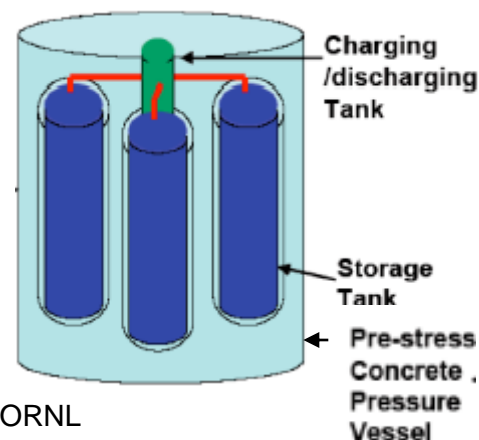
*Next Steps:* Design test facility for two-stage compression up to 12,000 psi

### Concrete Pressure Storage Vessels (ORNL)

*Increasing capacity and reducing forecourt storage cost*

#### Accomplishments:

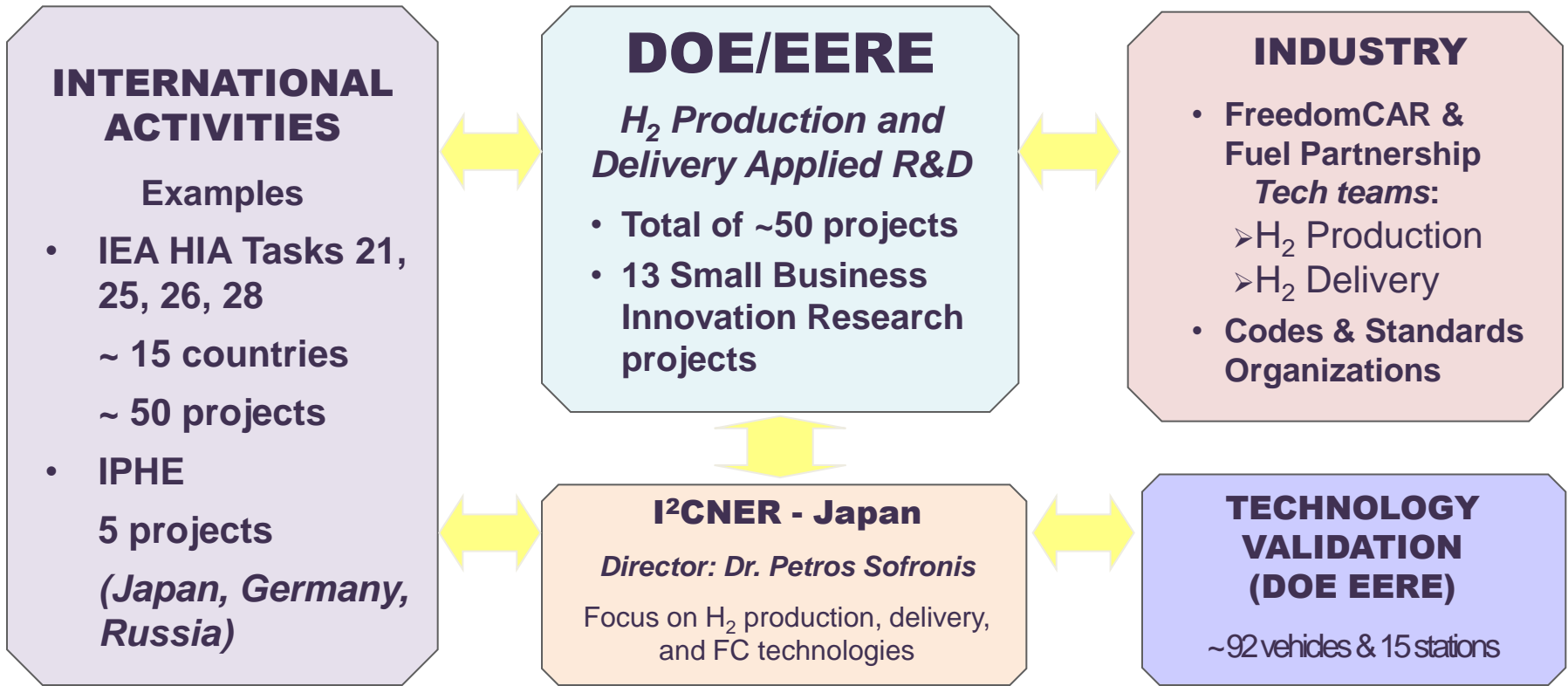
- ✓ Preliminary cost projections indicate the concept can meet the DOE 2015 cost target (\$300/kg H<sub>2</sub>) for station storage
- ✓ Initiated design trade studies



ORNL

*Next Steps:* Vessel design, engineering, and demonstration

**BES**  
2011 AMR Featured Guest



## INTERNATIONAL ACTIVITIES

### Examples

- IEA HIA Tasks 21, 25, 26, 28  
~ 15 countries  
~ 50 projects
- IPHE  
5 projects  
(Japan, Germany, Russia)

## DOE/EERE

### *H<sub>2</sub> Production and Delivery Applied R&D*

- Total of ~50 projects
- 13 Small Business Innovation Research projects

## INDUSTRY

- FreedomCAR & Fuel Partnership  
*Tech teams:*
  - H<sub>2</sub> Production
  - H<sub>2</sub> Delivery
- Codes & Standards Organizations

## I<sup>2</sup>CNER - Japan

*Director: Dr. Petros Sofronis*  
Focus on H<sub>2</sub> production, delivery, and FC technologies

## TECHNOLOGY VALIDATION (DOE EERE)

~92 vehicles & 15 stations

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

DOE – Basic Energy Sciences  
~30 Projects

DOT/NIST

DOE – Office of Biomass Tech.

NASA

DOE – Fossil Energy  
6 projects

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