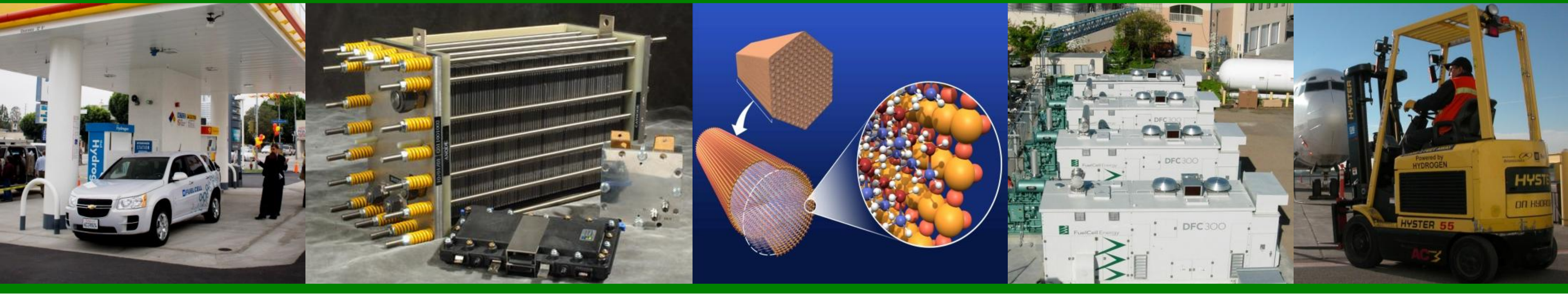
U.S. DEPARTMENT OF ENERGY



Hydrogen Production & Delivery

Sara Dillich

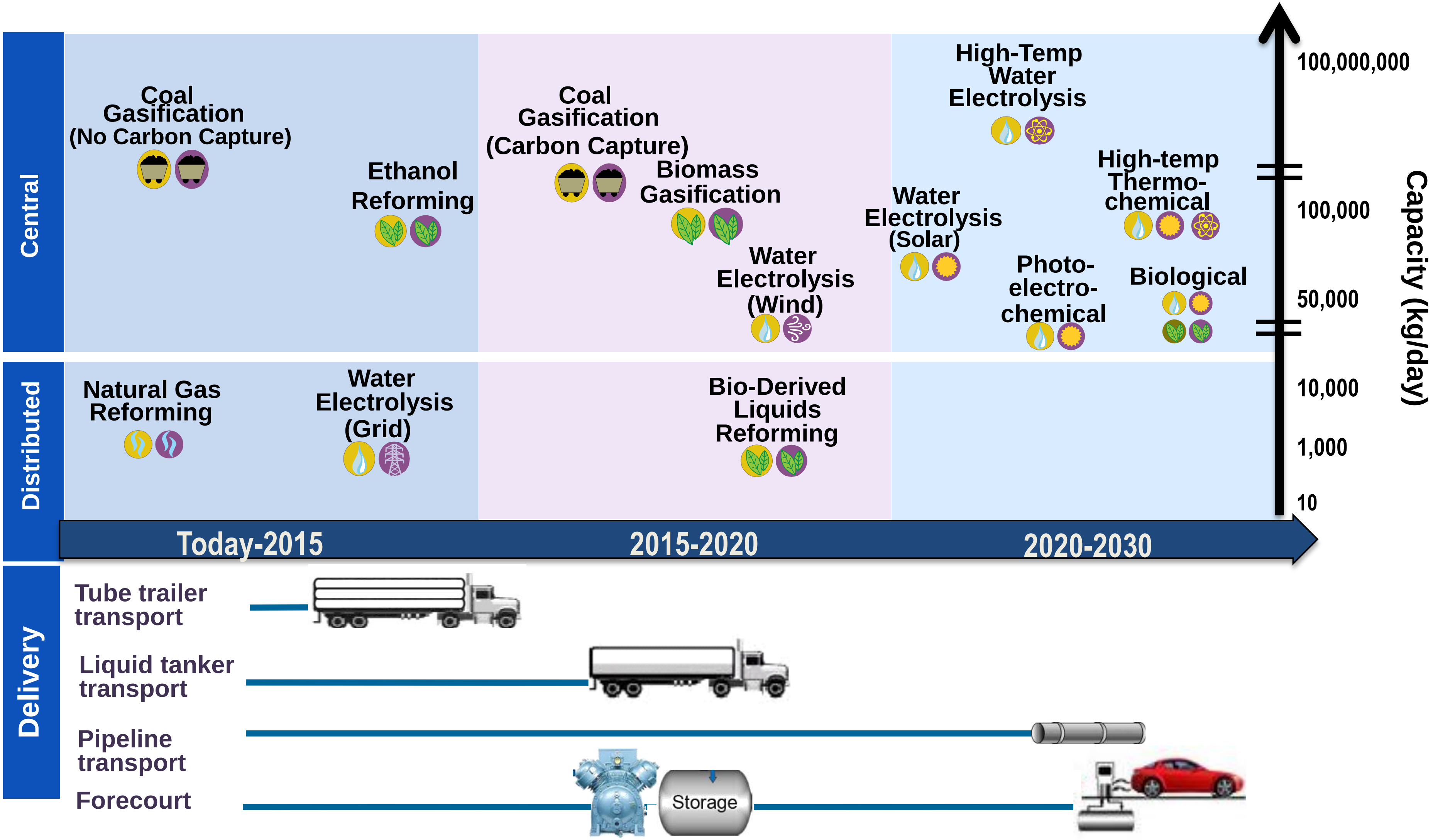
2011 Annual Merit Review and Peer Evaluation Meeting

(May 9, 2011)

Goals and Objectives:

U.S. DEPARTMENT OF ENERGY

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



Central

Coal Gasification (No Carbon Capture)

Ethanol Reforming

Coal Gasification (Carbon Capture)

Biomass Gasification

Water Electrolysis (Wind)

High-Temp Water Electrolysis

Water Electrolysis (Solar)

High-temp Thermo-chemical

Photo-electro-chemical

Biological

Distributed

Natural Gas Reforming

Water Electrolysis (Grid)

Bio-Derived Liquids Reforming

Today-2015

2015-2020

2020-2030

Capacity (kg/day)

100,000,000

100,000

50,000

10,000

1,000

10

Delivery

Tube trailer transport

Liquid tanker transport

Pipeline transport

Forecourt

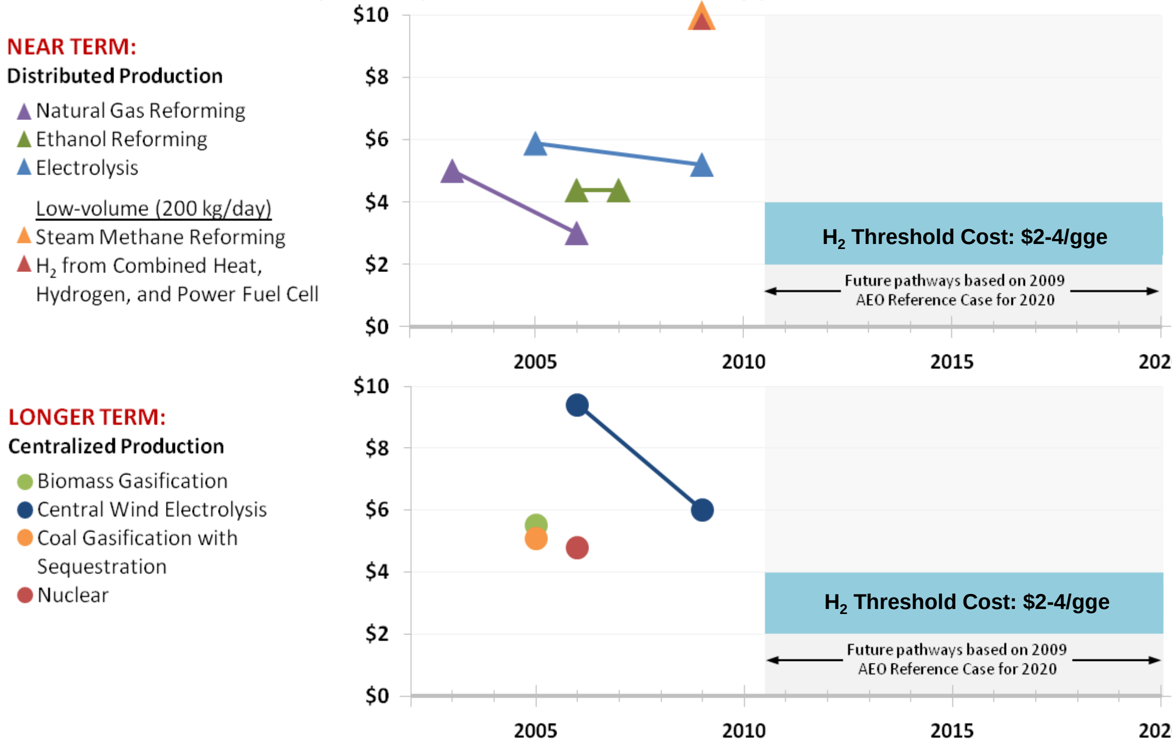
Storage

Challenges: Production

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

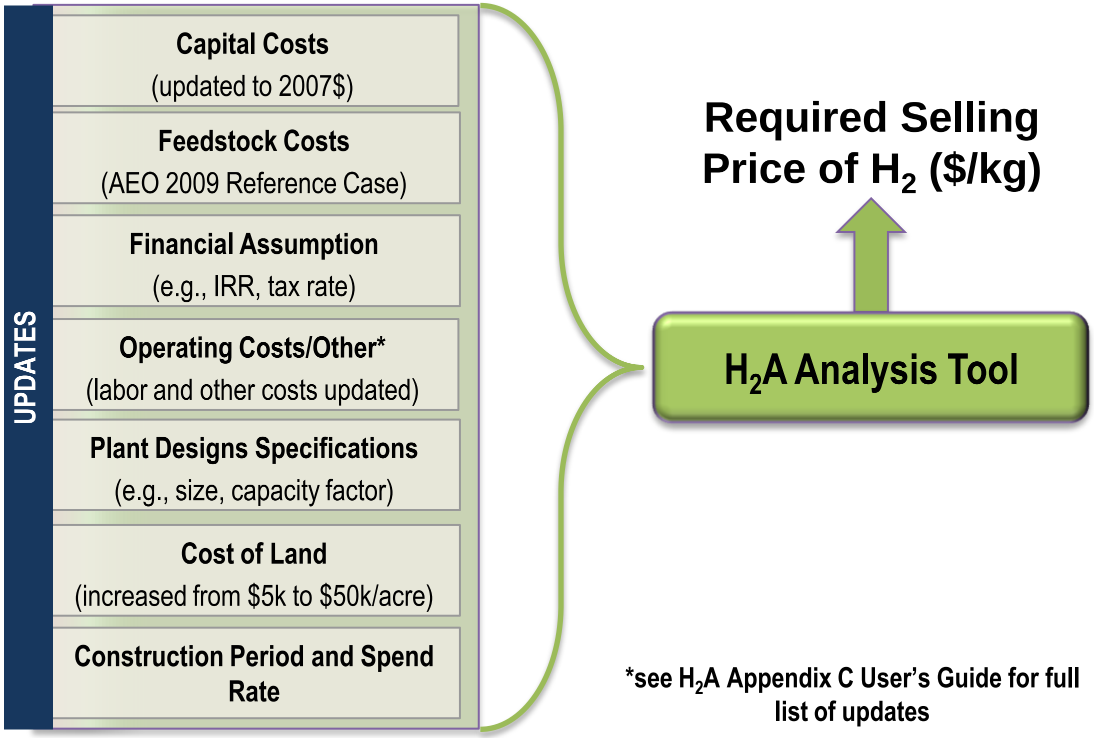

Projected High-Volume Cost of Hydrogen (Dispensed)—Status
($/gallon gasoline equivalent [gge], untaxed)

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



UPDATES

Capital Costs
(updated to 2007$)

Feedstock Costs
(AEO 2009 Reference Case)

Financial Assumption
(e.g., IRR, tax rate)

Operating Costs/Other*
(labor and other costs updated)

Plant Designs Specifications
(e.g., size, capacity factor)

Cost of Land
(increased from $5k to $50k/acre)

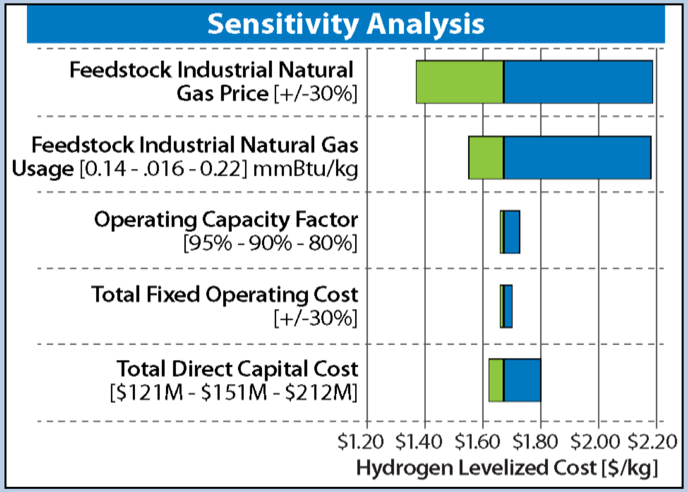
Construction Period and Spend Rate

H_2A Analysis Tool

Required Selling Price of H_2 ($/kg)

*see H_2A Appendix C User's Guide for full list of updates

Examples



Targets and MYPP

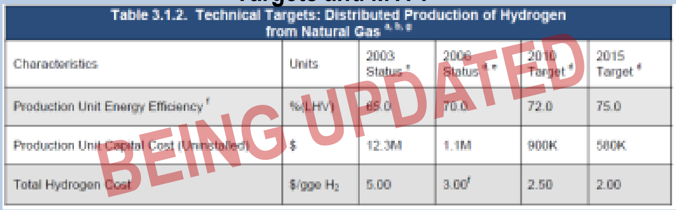
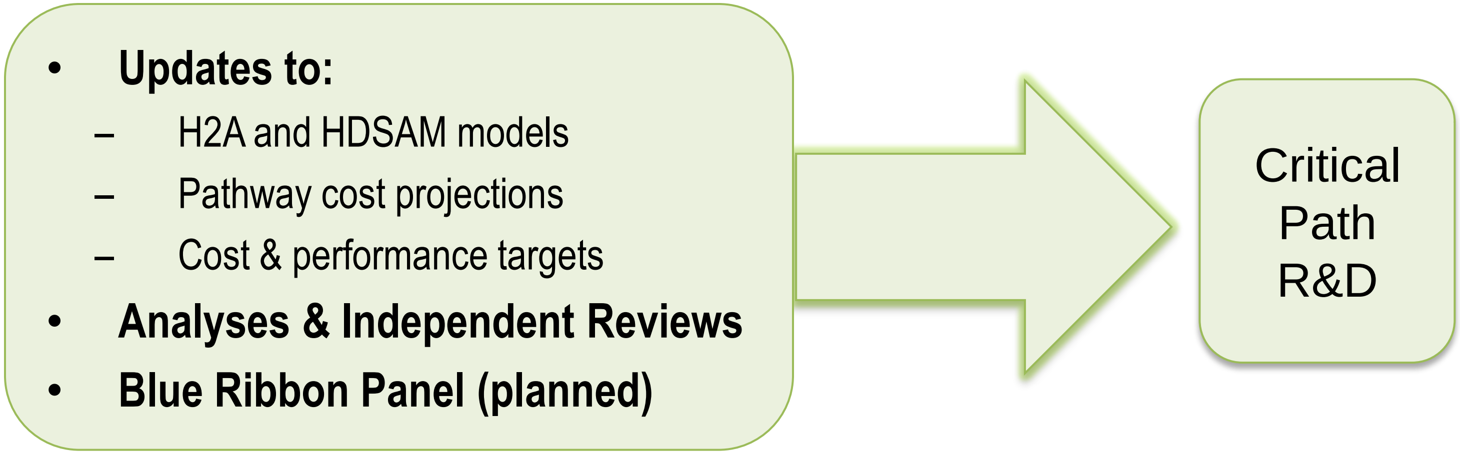


Table 3.1.2. Technical Targets: Distributed Production of Hydrogen from Natural Gas [a, b, c]

Characteristics	Units	2003 Status [d]	2006 Status [d, e]	2010 Target [d]	2015 Target [d]
Production Unit Energy Efficiency [f]	%(LHV)	65.0	70.0	72.0	75.0
Production Unit Capital Cost (Uninstalled)	$	12.3M	1.1M	900K	580K
Total Hydrogen Cost	$/gge H_2	5.00	3.00[f]	2.50	2.00

BEING UPDATED



- **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

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

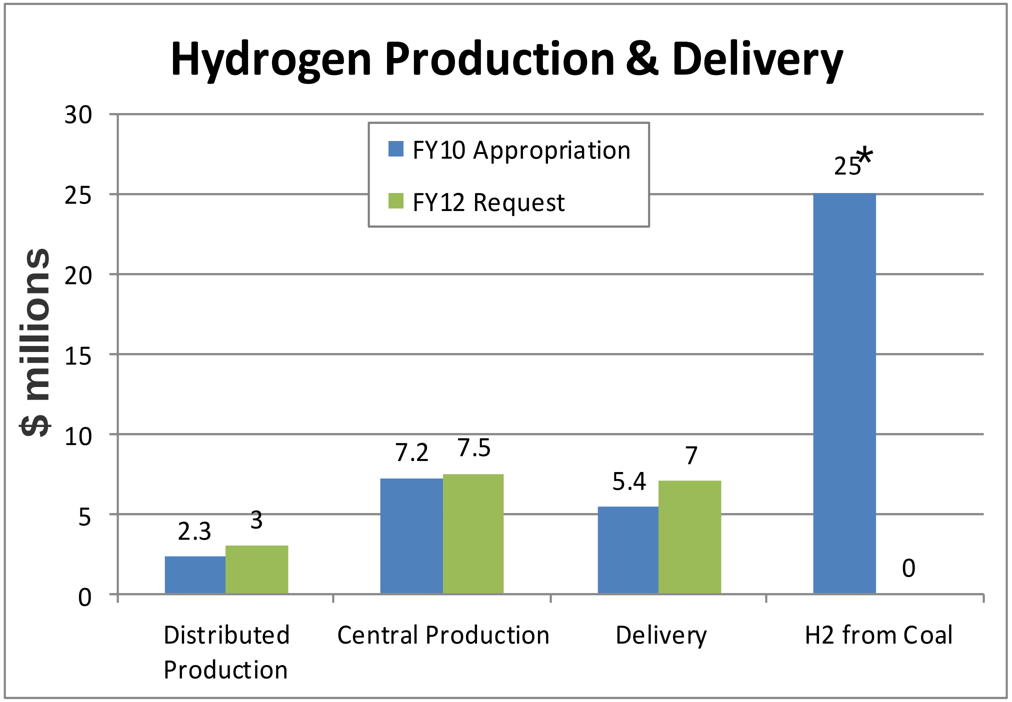
Target and Status costs are 2009 projected high volume costs (Centralized pathway costs do not include dispensing costs, cost targets for STCH, PEC and Biological are technology readiness using H2A assumptions)

5

Budget – P&D subprogram

FY 2012 Request = $17.5M

FY 2010 Appropriation = $15M



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)

2011 Progress: Bio-Derived Liquids – Pyrolysis Oil

Pyrolysis oil : potential low-cost feedstock for distributed production

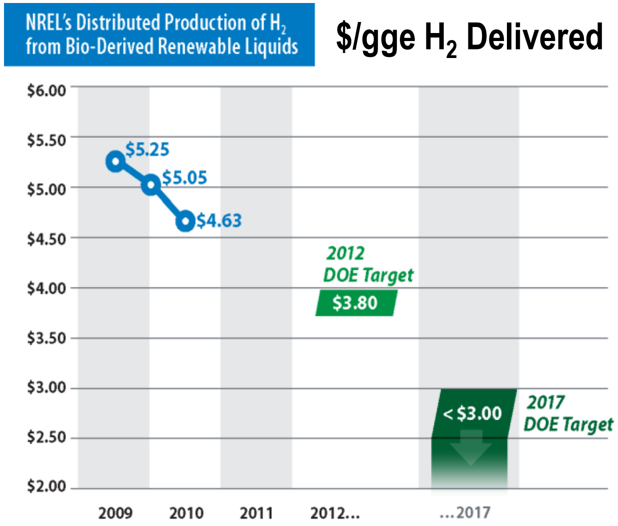
Biomass pyrolysis produces high yields of bio-oil, which could be stored and shipped to a site for renewable hydrogen production.

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

Autothermal Reforming (NREL)

production of H2 by catalytic steam reforming of oil (~ 650 C)

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



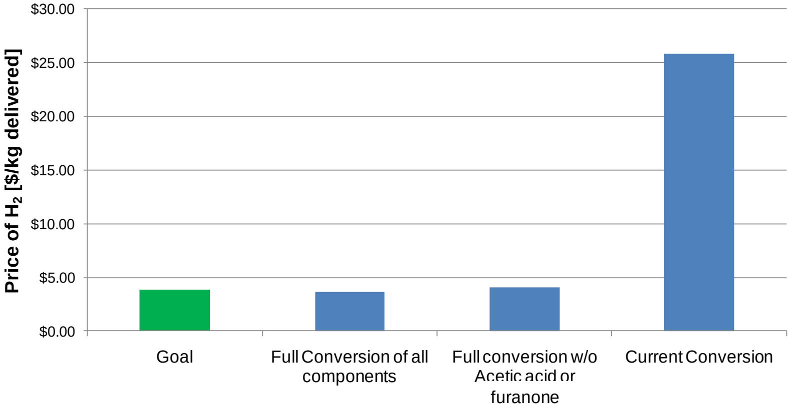
*H2A assumptions: 2005\$, nth plant, 1,500 kg/day, Current projected high volume cost based on 2011 performance

Aqueous Phase Reforming (PNL)

production of H_2 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_2)



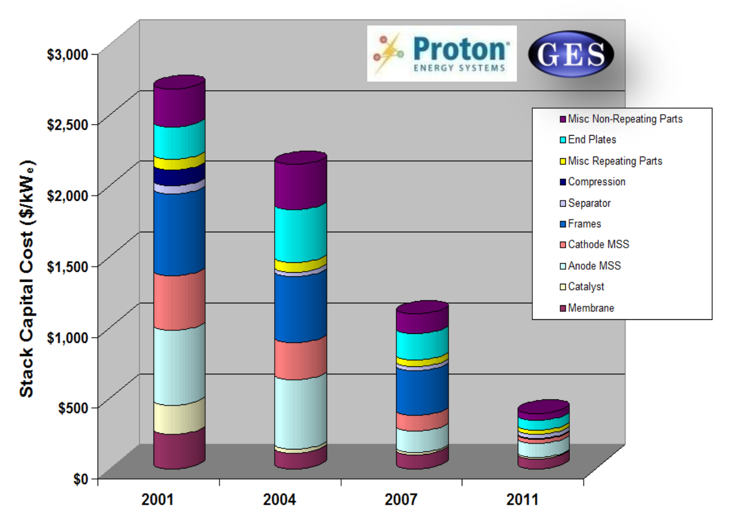
Ongoing Focus:

- **Acetic acid in feed reduces catalyst activity**
- **Consumption of produced H_2 by other molecules in the feed**
- **Further reduction in cost**

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

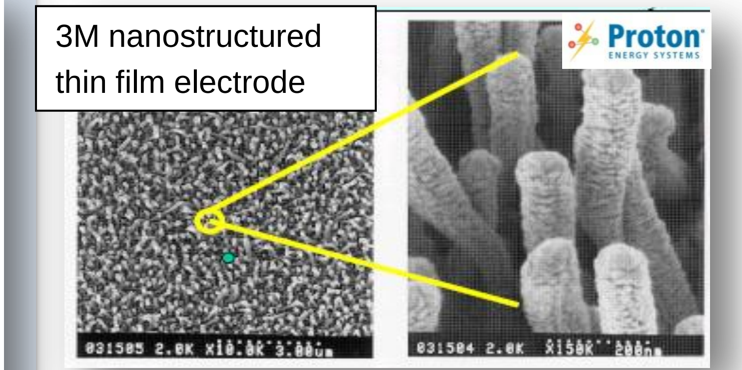
2011 Progress: Electrolysis

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

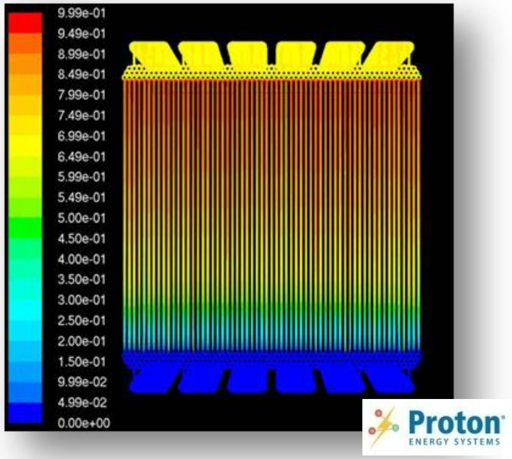


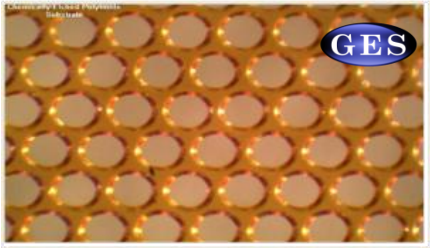
3M nanostructured thin film electrode

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

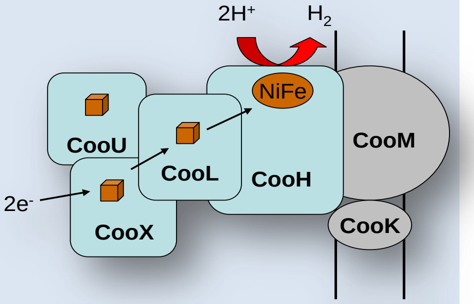




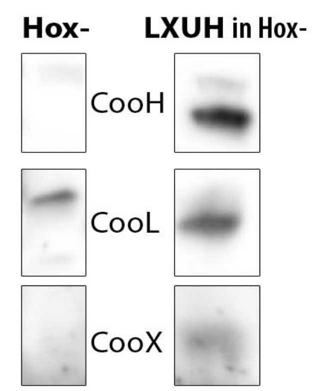
90% cost reduction of the MEAs by fabricating chemically etched supports

2011 Progress: Biological

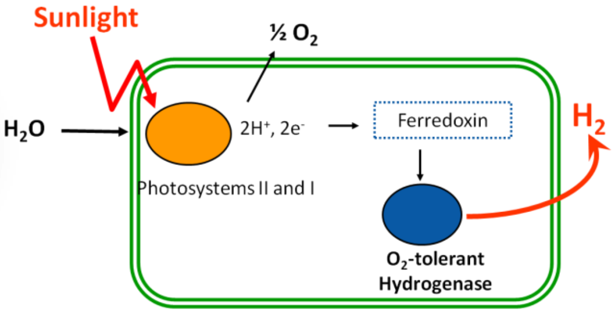
Tools developed to manipulate bacteria genome for O_2 tolerant hydrogen production



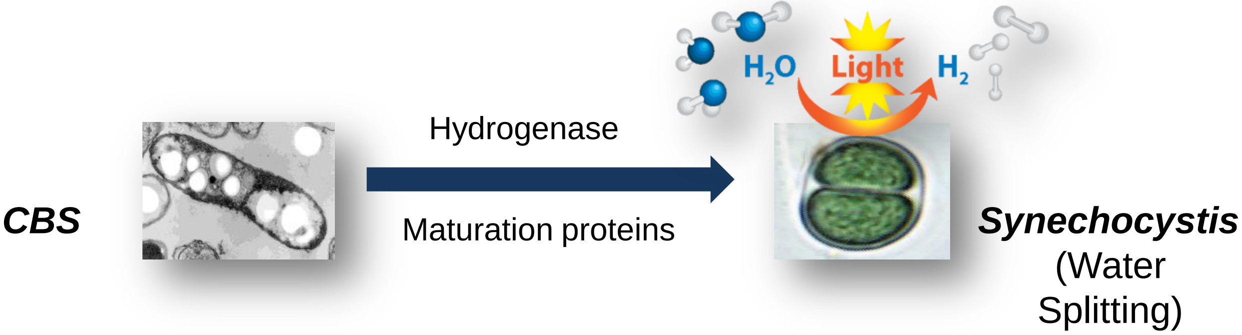
CBS O_2-tolerant hydrogenase protein



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



Goal: Develop an O_2-tolerant cyanobacterial system for continuous light-driven H_2 production from water



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*

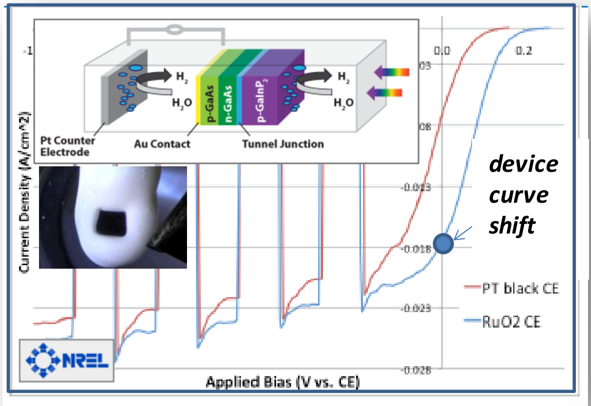
Data provided by Pin-Ching Maness, last updated February 2011

2011 Progress: Photoelectrochemical

New benchmark for solar to hydrogen (STH) efficiency

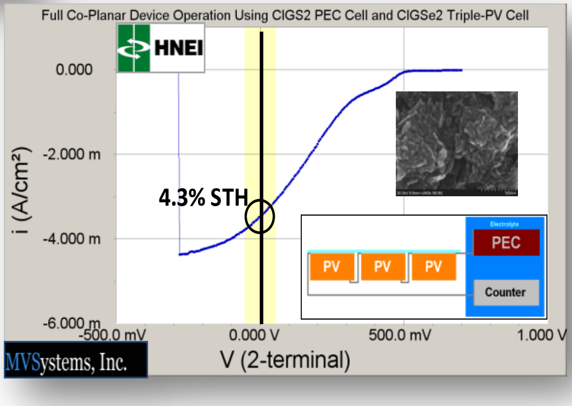
Accomplishments:

- ✓ 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)*

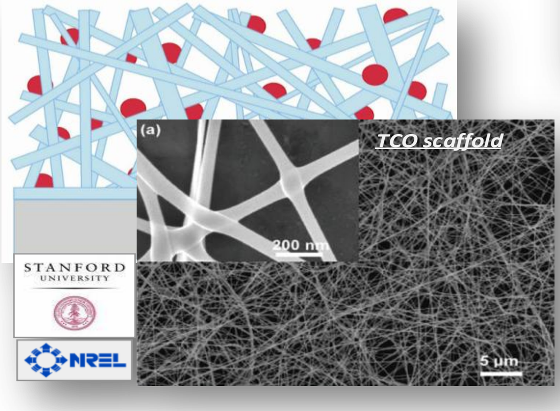


>16% STH efficiency potential demonstrated in crystalline III-V device

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_2 and other materials.

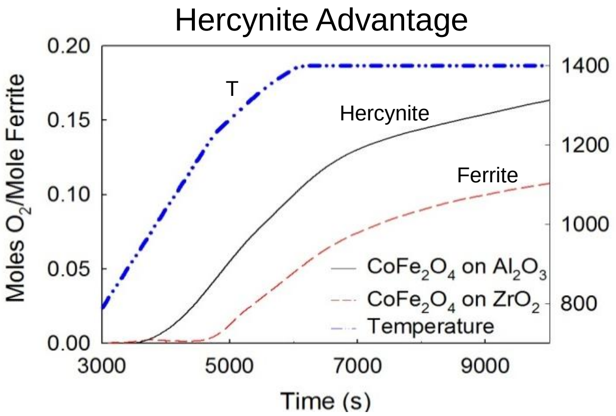
2011 Progress: Solar Driven High Temperature Thermochemical (STCH)

U.S. DEPARTMENT OF ENERGY

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.

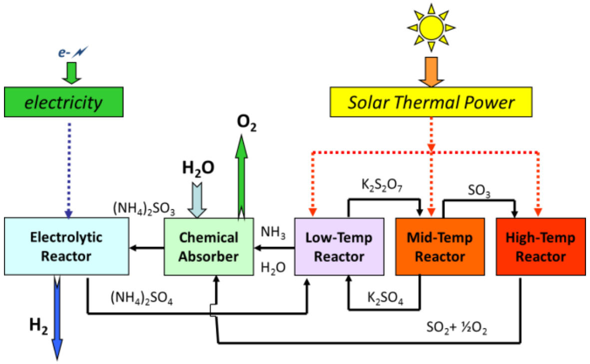


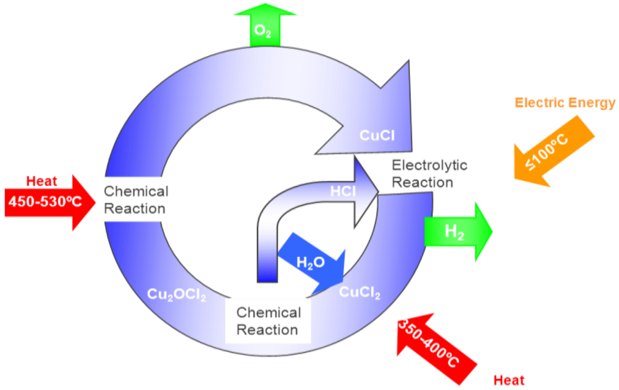
Ferrite Cycle

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)

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 80ºC, close to those previously obtained at 130ºC. (SAIC)





Cu-Cl Cycle

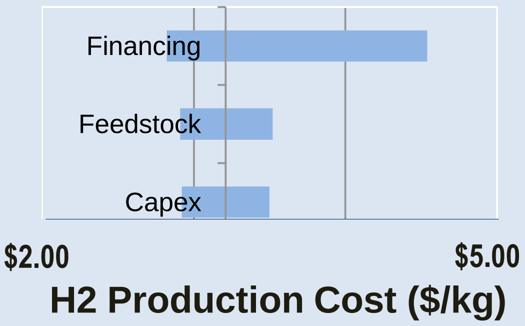
Two best membranes identified for Cu-Cl cycle with Cu diffusivity <10% of Nafion that are chemically and thermally stable at 80 C for over 40 hours. (ANL)

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

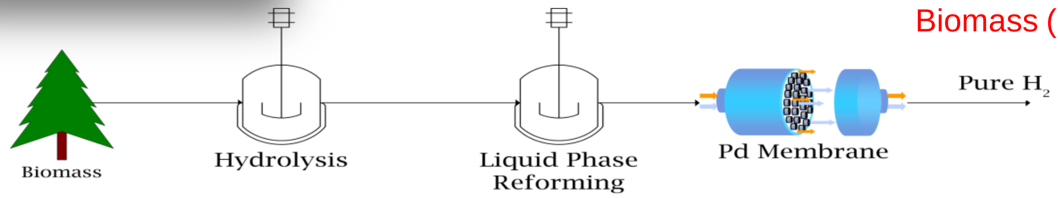


Primary influences on cost include feedstock costs, capital costs, and project financing structure

Biomass to Slurry Approach (UTRC)

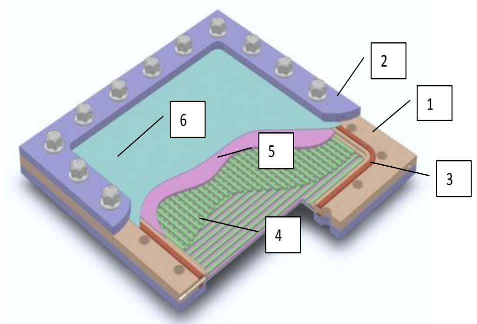
✓ Fuel flexible
✓ Carbon neutral

0.09-0.13 kg H_2/kg Biomass (dry)



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

Biomass Gasifier with Close Coupled Membrane (GTI)

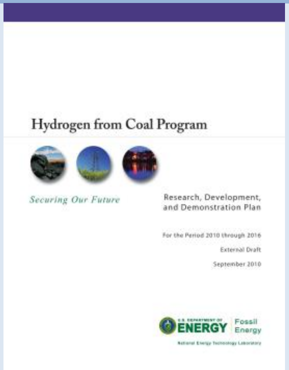


1-base plate
2-clamping frame
3-copper gasket
4-slotted metal support
5-porous support
6-membrane

- Membrane module design completed
- Potential for >40% H_2 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

Securing Our Future

Research, Development, and Demonstration Plan

For the Period 2010 through 2016

External Draft

September 2010

U.S. DEPARTMENT OF ENERGY Fossil Energy

National Energy Technology Laboratory

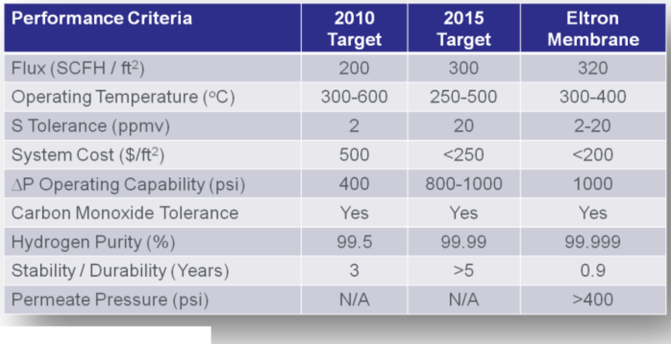
Hydrogen from Coal Program Research, Development and Demonstration Plan (Sept 2009)

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

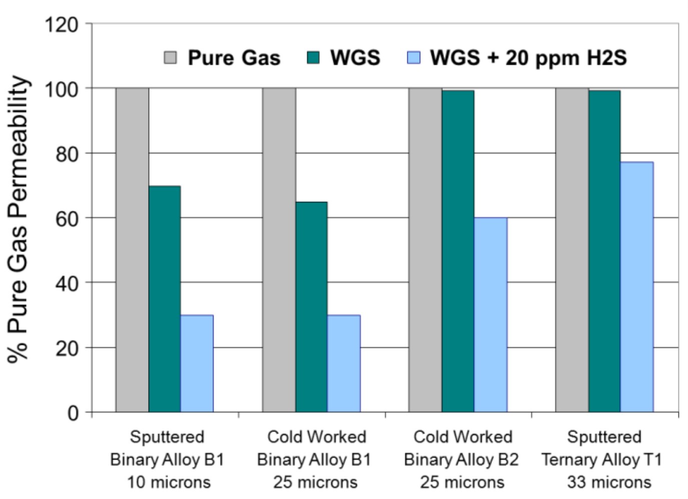
U.S. DEPARTMENT OF ENERGY | Fossil Energy

National Energy Technology Laboratory

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

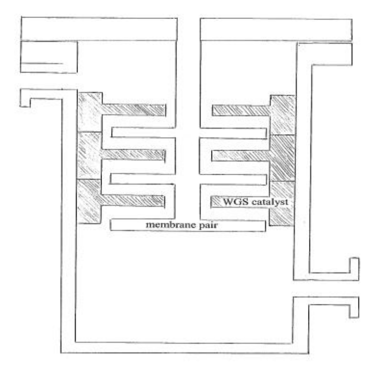


Performance Criteria	2010 Target	2015 Target	Eltron Membrane
Flux (SCFH / ft^2)	200	300	320
Operating Temperature (°C)	300-600	250-500	300-400
S Tolerance (ppmv)	2	20	2-20
System Cost ($/$ft^2$)	500	<250	<200
ΔP Operating Capability (psi)	400	800-1000	1000
Carbon Monoxide Tolerance	Yes	Yes	Yes
Hydrogen 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)



Challenges: Delivery

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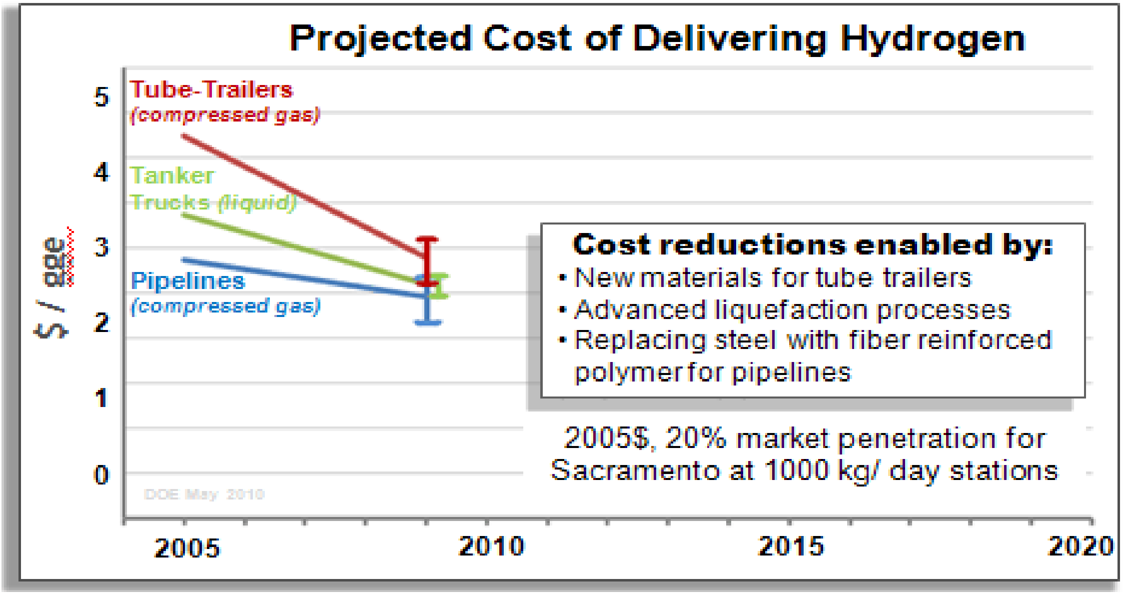
Station costs now dominate delivery costs

Reductions in projected costs of hydrogen delivery:

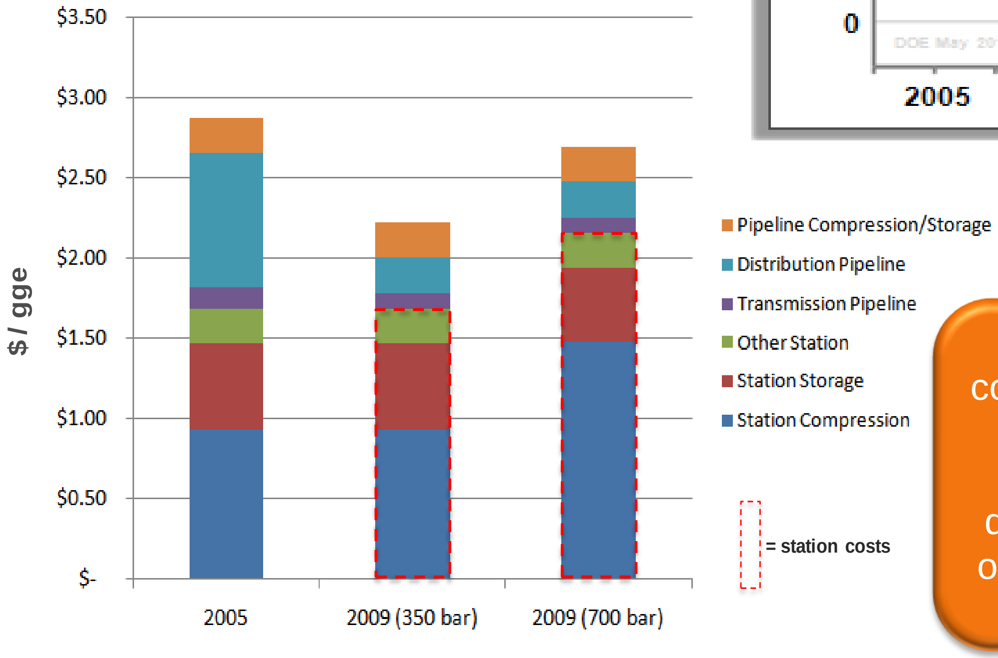
~30% reduction in tube trailer costs

>20% reduction in pipeline costs

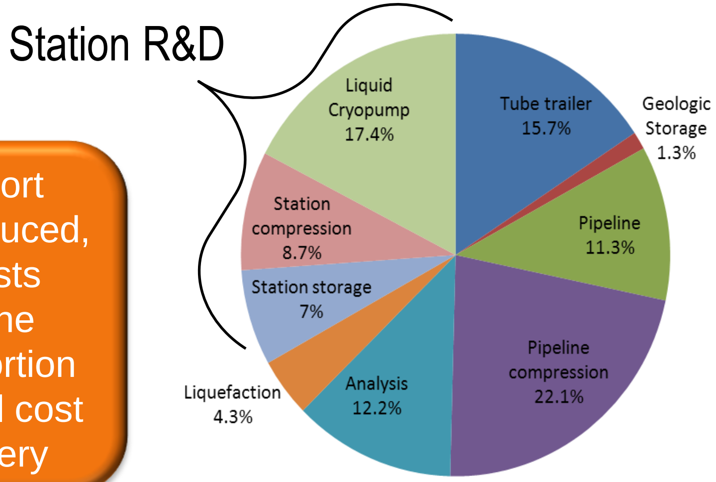
~15% reduction in liquid hydrogen delivery costs



Example: Projected pipeline delivery costs



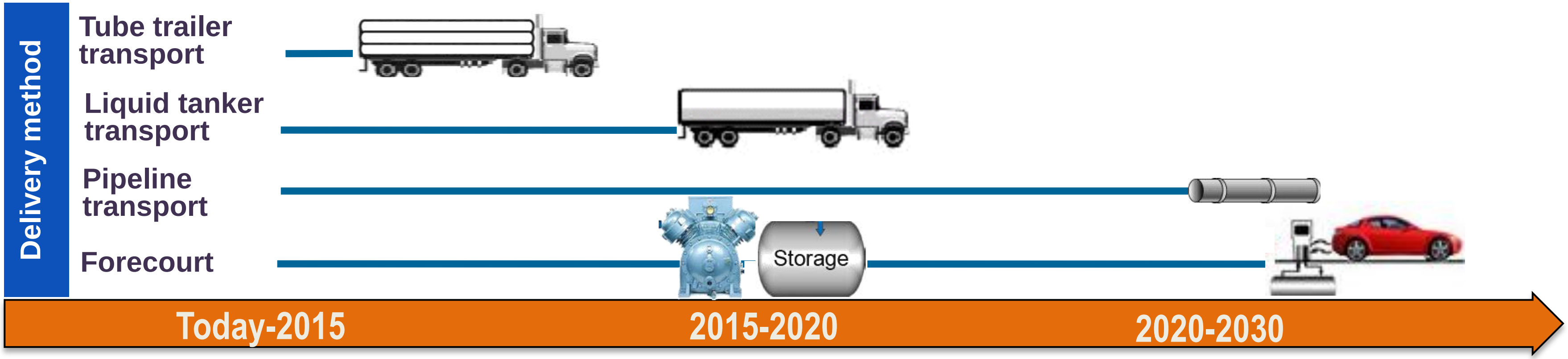
As Transport costs are reduced, station costs become the dominant portion of the overall cost of H_2 delivery



Delivery - FY11

Strategies: Delivery

Long-term emphasis on forecourt technologies



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

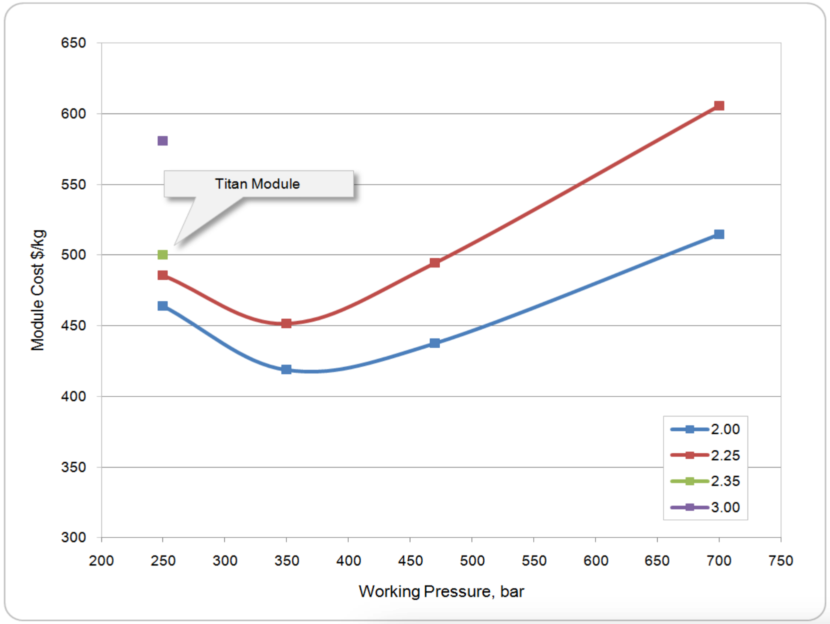
Pathway	Reference	Status (2010)
GH_2 delivery via tube trailer	Based on HDSAM v 3.0: assumes Indianapolis with 15% market penetration, total of 122,000kg/day delivery over the entire city, plant is at city gate. H_2 produced at 20bar. Costs include all processes from the plant gate to dispensing (700bar onboard storage) and are expressed in 2007 dollars. Costs assume mass production and costs for steel pipeline are based on a recent study by Brown et al., Oil & Gas Journal, v. 109, Jan. 2011; results not yet vetted.	$4.6/gge
LH_2 delivery via tanker truck		$3.2/gge
GH_2 delivery via pipeline		$4.1/gge

2011 Progress: Tube Trailer Delivery

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_2
    - 10% reduction in transport costs (Lincoln)
- Successfully fabricated and hydroburst tested a full scale glass fiber wrapped vessel (LLNL)



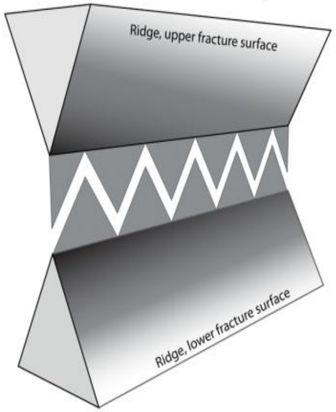
- **Practical limit is likely 350 bar**
    - Higher pressures require thicker walled vessels
    - Availability of low-cost plumbing hardware
    - Availability of low-cost H_2 compressors

LINCOLN COMPOSITES
A Member of Hexagon Composites Group

2011 Progress: Pipelines for Gaseous H_2

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

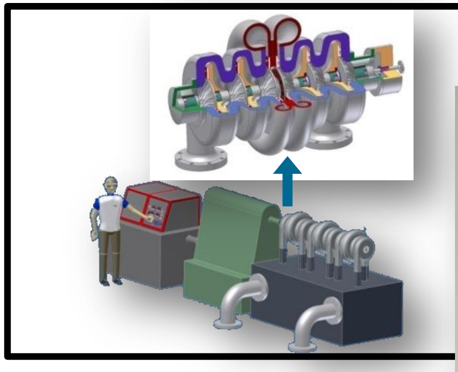
Steel Pipeline Analysis *(SNL/U of Illinois)*



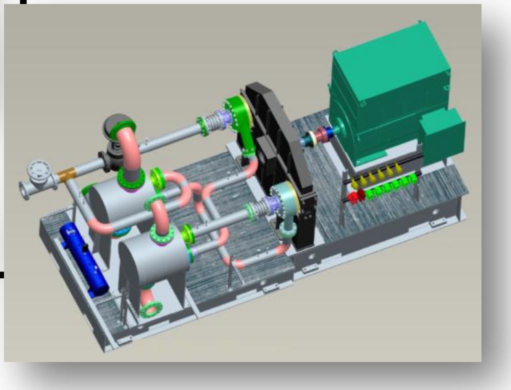
- Developed models to predict the effects of H_2 on the mechanical properties of pipeline steels
- Identified 2 commercial pipeline steel micro-structures that minimize H_2 effects at pressure

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)

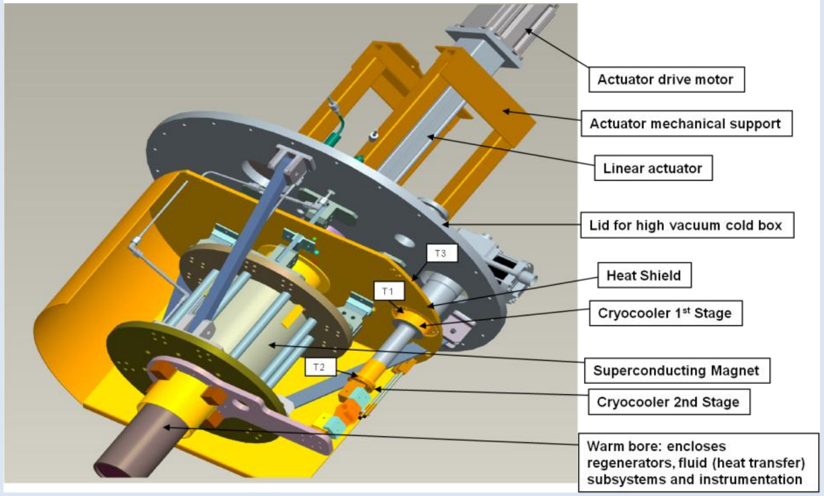
- Initiated fabrication of two compressor designs for prototype testing
- Prototype testing to begin next year

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

2011 Progress: Liquefaction

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

Active Magnetic Regenerative Refrigerator (AMMR)



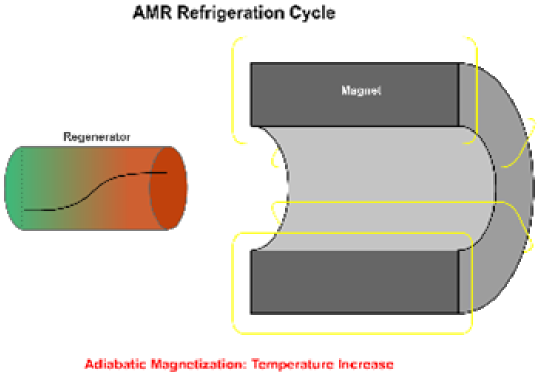
Heracles

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 sub-systems into a prototype AMRR device – currently in testing (Heracles)



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

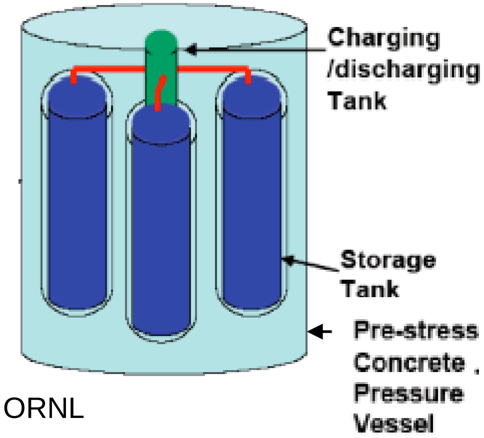
Next Steps: Design test facility for two-stage compression up to 12,000 psi

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_2) for station storage
- ✓ Initiated design trade studies



ORNL

Next Steps: Vessel design, engineering, and demonstration

Hydrogen P&D Collaborations

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_2 Production and Delivery Applied R&D

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

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)

~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

For More Information

U.S. DEPARTMENT OF ENERGY

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