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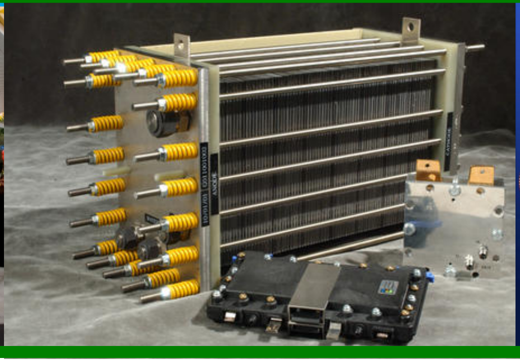
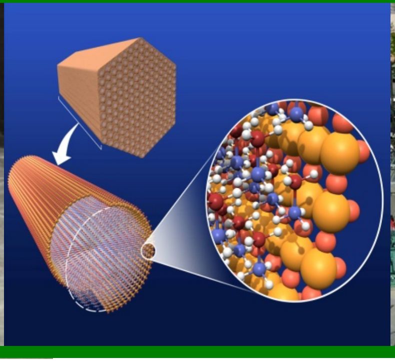
ENERGY


Hydrogen Production & Delivery Program Area
- Plenary Presentation -

Sara Dillich
Fuel Cell Technologies Office

2014 Annual Merit Review and Peer Evaluation Meeting
June 16, 2014

Goals and Objectives

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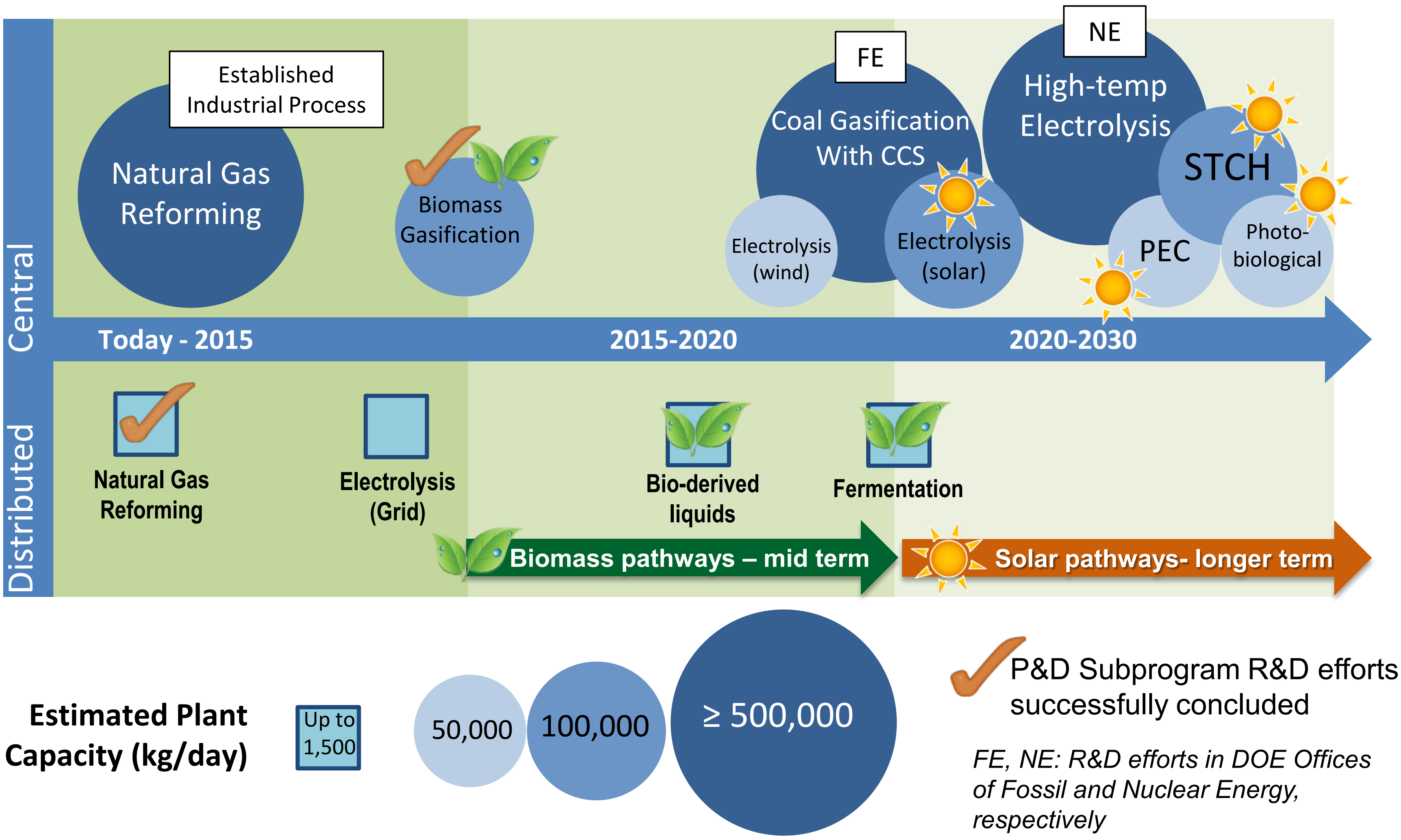
Objective: Develop technologies to produce hydrogen from clean, domestic resources at a delivered and dispensed cost of < $4/kg H_2 by 2020



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

Challenges and Strategies

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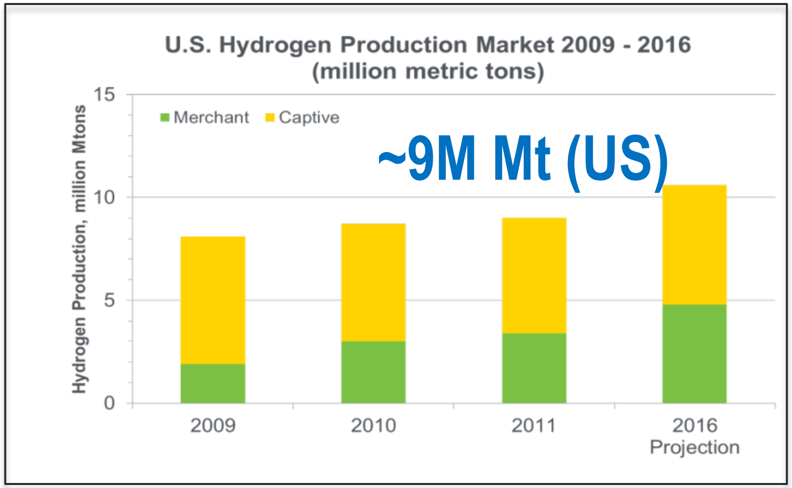
Cars are ready now!

Hyundai FC vehicles launched in CA this Spring. Toyota and Honda FC vehicles coming soon.

- Fueling infrastructure is needed in the immediate near-term
- Traditional sources (natural gas) meet near-term hydrogen demand, but large-scale production from renewable sources will be needed in long-term

Number of Fuel Cell Cars Served	Hydrogen Demand (metric tons)	
	Daily [1]	Yearly
1 million	~780	**0.29 M** (<<9)
250 million	~137,000	**~50 M** (>>9)

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



Global Hydrogen Generation Market, MarketsandMarkets, 2011

Challenges & Strategy

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

Barriers

Production and delivery cost of renewable & low-carbon hydrogen

- Feedstock costs
- Capital costs
- O&M costs

Strategy

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.

R&D Focus

- Reliability and cost of compression, storage and dispensing
- Renewable integration
- Balance of plant improvements
- Technoeconomic analysis

R&D Focus

- Innovations in materials, devices and reactors for renewable H_2 production
- Advanced materials and systems for H_2 delivery
- Technoeconomic analysis

Key Areas

Delivery

- Polymers & composites for delivery technologies
- Liquefaction technologies
- Compressor reliability
- Low cost onsite storage

Production

- Electrolysis
- Bio-Derived Liquids
- Hybrid fossil/renewable approaches
- Solar Water Splitting: PEC, STCH, Biological
- Microbial Biomass Conversion

Challenges and Strategies

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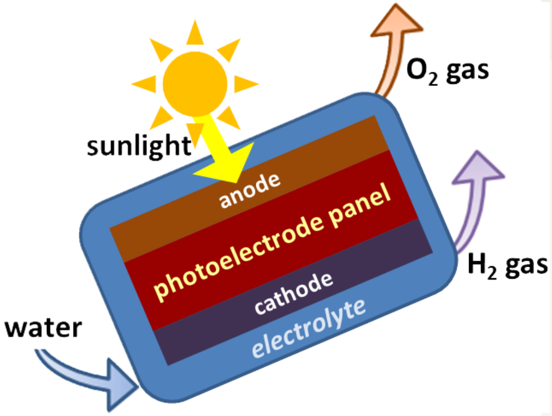
Lowering the Cost of Forecourt Compression, Storage and Dispensing (CSD) is an urgent immediate need



Near-term (*~3 years)*

- Improve cost, reliability & efficiency of forecourt components (e.g., compressors, hoses, seals)
- Decrease the footprint and cost of storage at the forecourt through advanced composite designs
- Improve durability of low-PGM catalysts for electrolytic hydrogen production

Longer-term (*beyond 3 years)*

- Advanced technologies for forecourt compressors, dispensers and detectors for high reliability and throughput
- Demonstrate continuous production of hydrogen at reactor scales (≥ 10 liters) from microbial biomass conversion technologies
- Demonstrate PEC and STCH devices/cycles with modeled capabilities for STH efficiencies > 15%, 20%, respectively

Strategy

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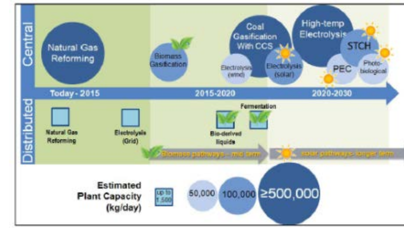
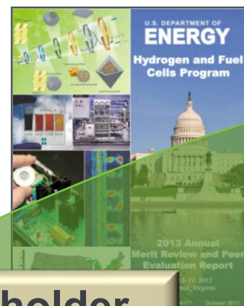
Techno-economic analyses, stakeholder input, inform programmatic decisions

Workshops:
- BioHydrogen
- Delivery
- Electrolysis
- Infrastructure

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



U.S. DRIVE
Tech Team
Roadmaps

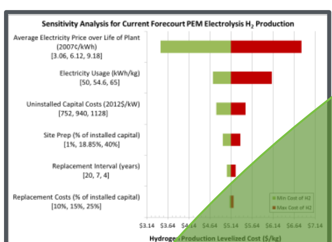


SBIR / STTR
Small Business Innovation Research
Small Business Technology TRansfer

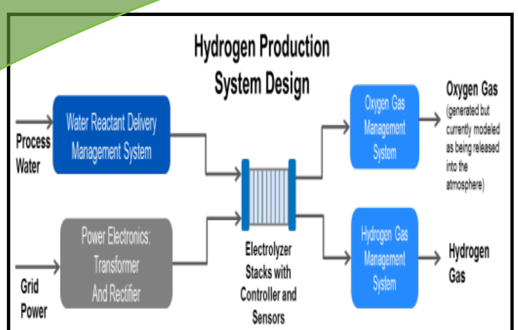
Collaboration & Coordination

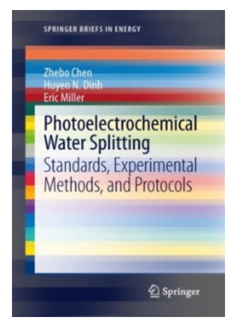
RD&D Portfolio

Priorities, Metrics, Targets



Stakeholder Input





Pathway Working Groups

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

Characteristics	Units	2011 Status	2015 Target	2020 Target	Ultimate Target
Solar-Driven High-Temperature Thermochemical Cycle Hydrogen Cost [b]	$/kg	NA	14.80	3.70	2.00
Chemical Tower Capital Cost (installed cost) [c]	$/TPD H_2	NA	4.1MM	2.3MM	1.1MM
Annual Reaction Material Cost per TPD H_2 [d]	$/yr.-TPD H_2	NA	1.47M	89K	11K
Solar to Hydrogen (STH) Energy Conversion Ratio [e,f]	%	NA	10	20	26
1-Sun Hydrogen Production Rate [g]	kg/s per m^2	NA	8.1E-7	1.6E-6	2.1E-6

Analysis & Studies

Collaboration with DOE-SBIR Office: Electrolysis Projects

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Year Ending	Organization	Project
SBIR Phase II		
FY15	Giner Electrochemical Systems	High-Performance, Long-Lifetime Catalysts for PEM Electrolysis
FY15	Proton On-Site	Low Noble Metal Content Catalysts/Electrodes for Electrolysis
FY15	Proton On-Site	High Efficiency Electrocatalysts for Alkaline Membrane Electrolysis
SBIR Phase I *		
FY14	Giner Electrochemical Systems	High Temperature, High Efficiency PEM Electrolysis
FY14	Tetramer Technologies, LLC	New Approaches to Improved PEM Electrolyzer Ion Exchange Membranes
FY14	Amsen Technologies, LLC	High Performance Proton Exchange Membranes for Electrolysis Cells

**Electrolyzer membrane projects recently selected for negotiation from BES topic*

Stakeholder Input: Electrolytic H_2 Production Workshop Results

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Commercial Technologies (e.g., PEM, Alkaline)

Challenges

- Improved stack performance
- High pressure stack/system components
- Increase stack size
- Market issues (manufacturing investment vs market size)
- Grid integration

RD&D Needs

- Improved catalysts & membranes
- Better anode support media
- Studies of high P electrolysis vs. compression
- Demonstrate large scale viability (MEA, power conversion, etc.)
- Low cost hardware
- MW scale demonstration

Pre-commercial Technologies (Solid Oxide, Alkaline Membrane, Reversible)

Challenges

- Material & systems durability
- Scale-Up: large format cells
- Efficiency at high current density (cell performance)
- Production volume
- BOP/pressurized operation

RD&D Needs: Near Term

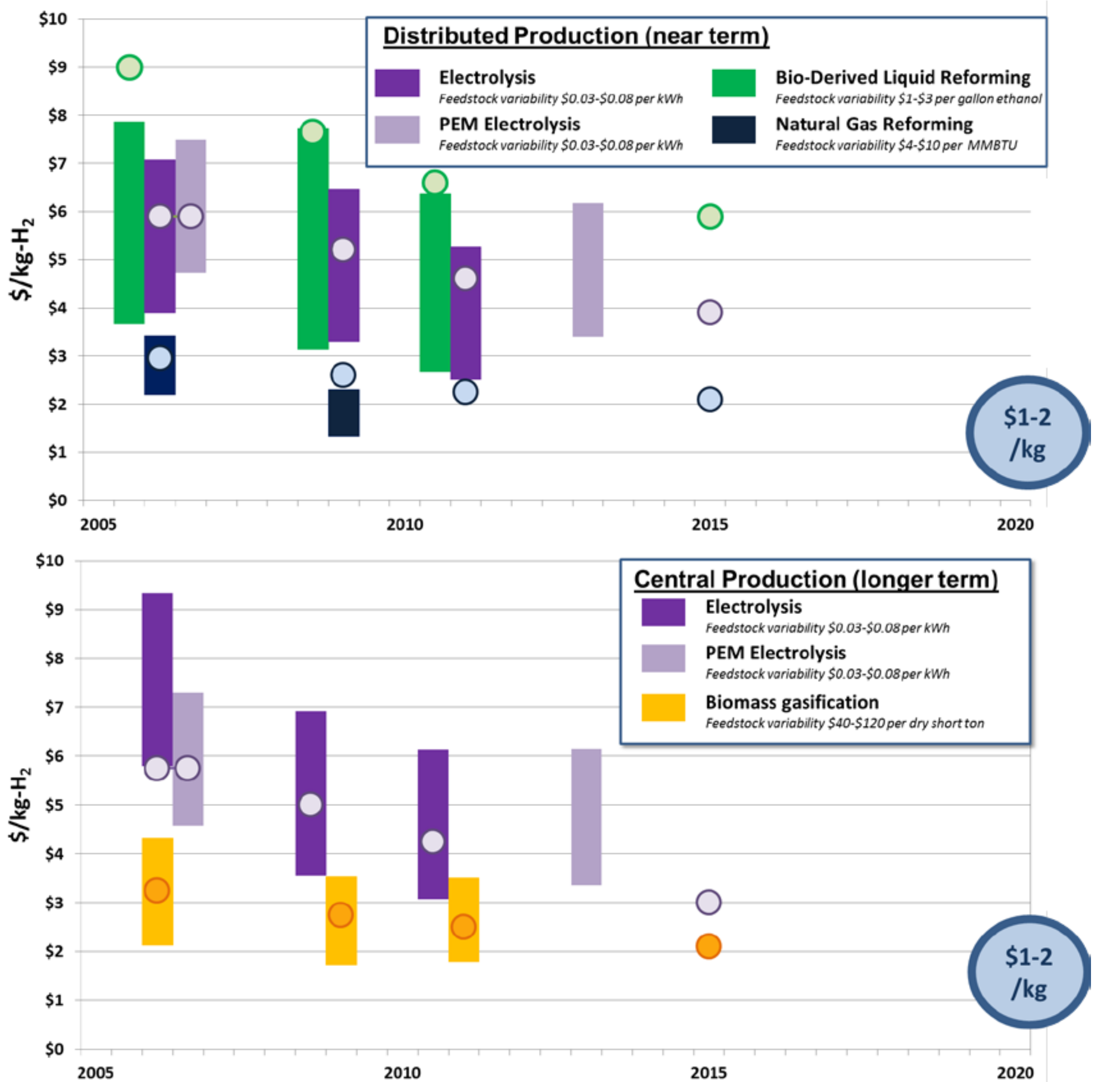
- Materials durability: mechanisms, accelerated tests
- Scale-up: multi-kW pilot plant (advance TRL)
- Efficiency at high current density
- New., more active catalyst materials (AEM)
- Lower temperature SOEC materials

RD&D Needs: Long Term

- Long-term integrated system testing

Production Cost Status for Near/Mid-Term Pathways

Projected high-volume cost of hydrogen for near-term production pathways



- Status of hydrogen cost (production only, does not include delivery or dispensing costs) is shown in vertical bars.
- Targets for hydrogen cost are shown in circles.
- Targets shown are normalized for consistency in feedstock assumptions and year-cost basis (2007 dollars)
- *Targets prior to 2015 are extrapolated based on 2015 and 2020 targets in the FCT Office's Multi-year RD&D Plan.*
- Cost ranges are shown in 2007 dollars
- Projections of costs assume Nth-plant construction, distributed station capacities of 1,500 kg/day, and centralized station capacities of ≥50,000 kg/day.

Delivery Pathways

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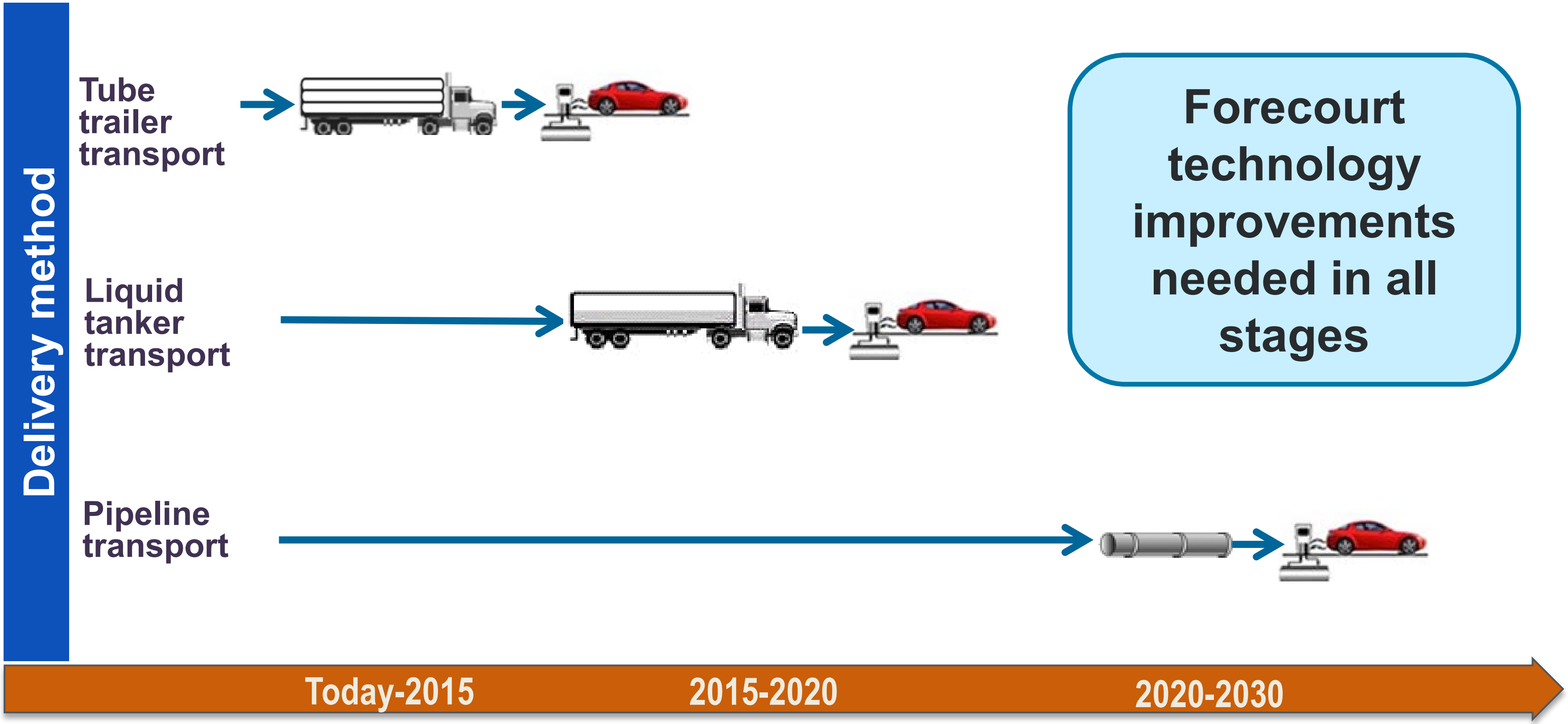


Today-2015

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

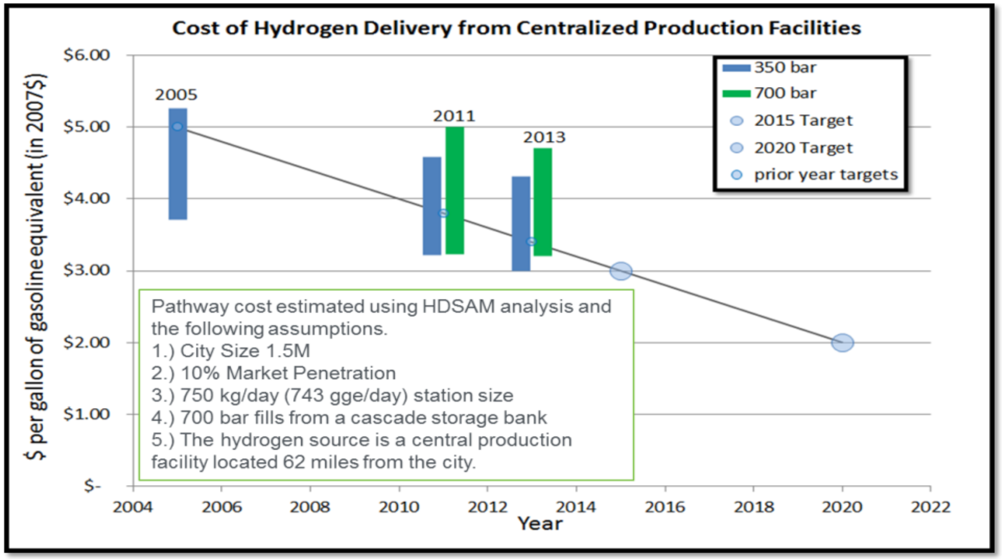
2015-2020

- 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

Delivery: Compression, Storage and Dispensing (CSD) Cost Reduction

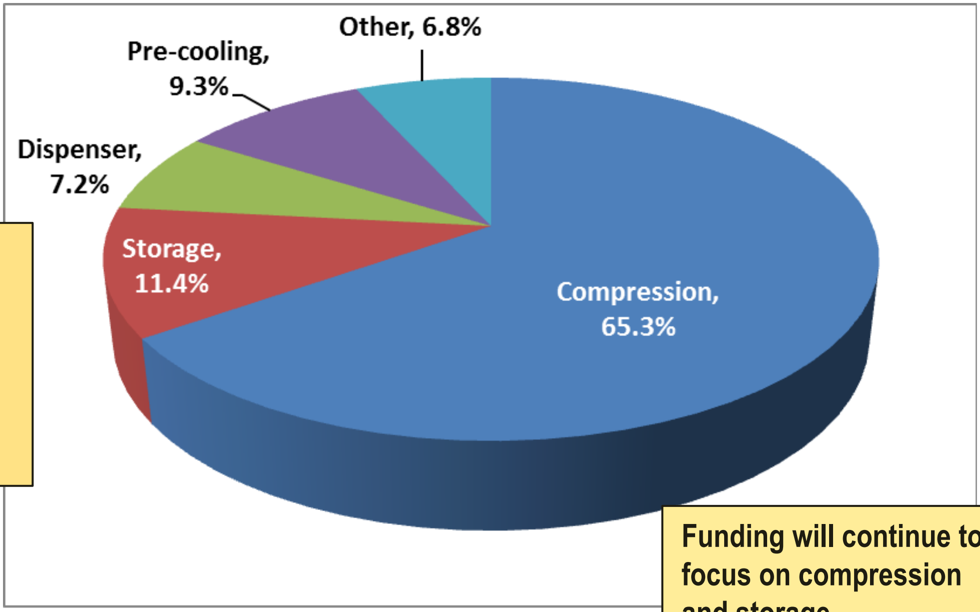


Range of HDSAM projected costs of hydrogen delivery from central production facilities in 2005, 2011, and 2013 along with the relevant targets.

See Fuel Cell Technologies Office Record 13013 for details : http://hydrogen.energy.gov/program_records.html

Hydrogen station cost distribution by component based on the pipeline delivery scenario[1]

Station CSD costs adds between $1.00 - $3.00 to the cost of dispensed hydrogen, ~70% of which can be attributed to Compression and Storage



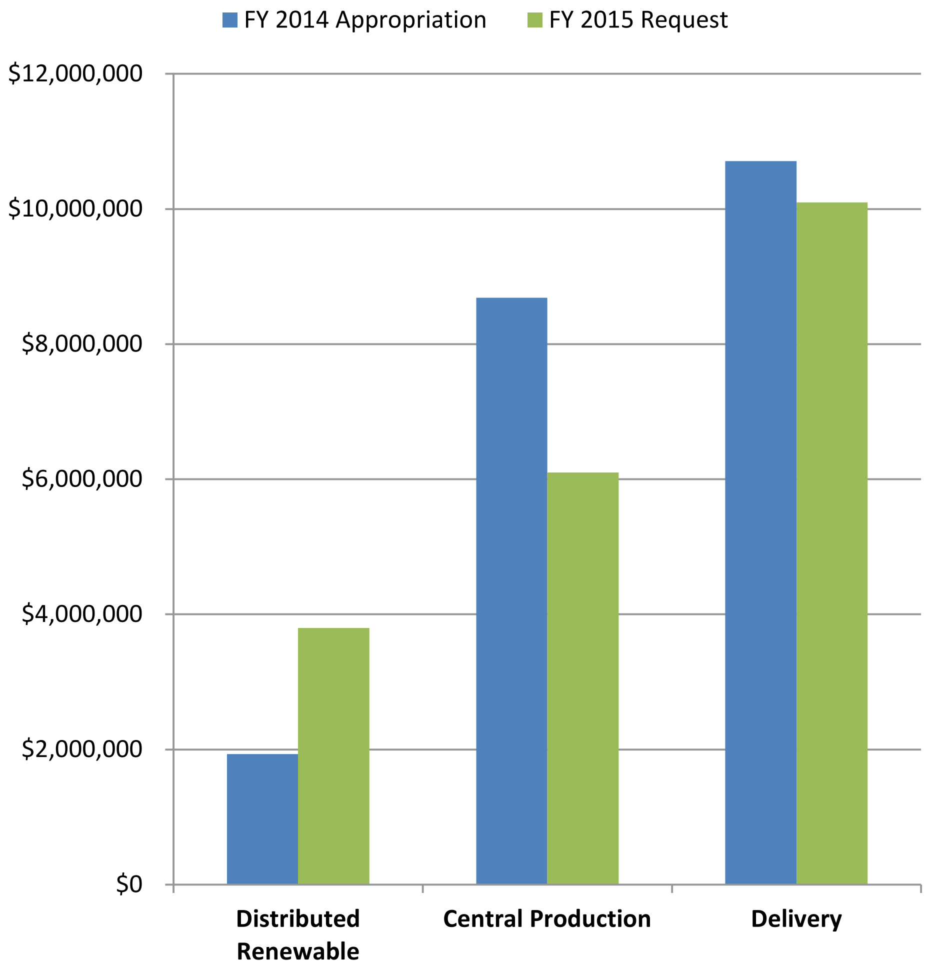
Funding will continue to focus on compression and storage

1.) Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs, May 2014, ttp://www.hydrogen.energy.gov/pdfs/58564.pdf

Budget

U.S. DEPARTMENT OF ENERGY

FY 2014 Appropriation = $21M
FY 2015 Request = $20 M



EMPHASIS

- Continued Analysis of Production & Delivery Pathways
  - Fermentative H_2 Production
  - High Temperature Electrolysis
  - Cost of Early Market Production & Delivery
- 2014 New Starts: Balance of Near/Mid Term and Long Term Activities
- Infrastructure R&D a Near-Term Focus
- Demonstration of New Forecourt Components for 700 bar Refueling
- Demonstration of Renewable Production from Integrated Systems
- Continued Cross-Office Coordination and Collaboration
- Continued International Collaborations and Communications

Accomplishments: Production Analysis

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Completed industry-vetted case study of H_2 production costs via PEM electrolysis

Four PEM Electrolysis cases developed in H2A v3[a]

Case	Start Date	Production of H_2 (kg/day)	Plant Life (years)
Current[b] Forecourt	2010	1,500	20
Future Forecourt	2025	1,500	20
Current Central	2010	50,000	40
Future Central	2025	50,000	40

Results:

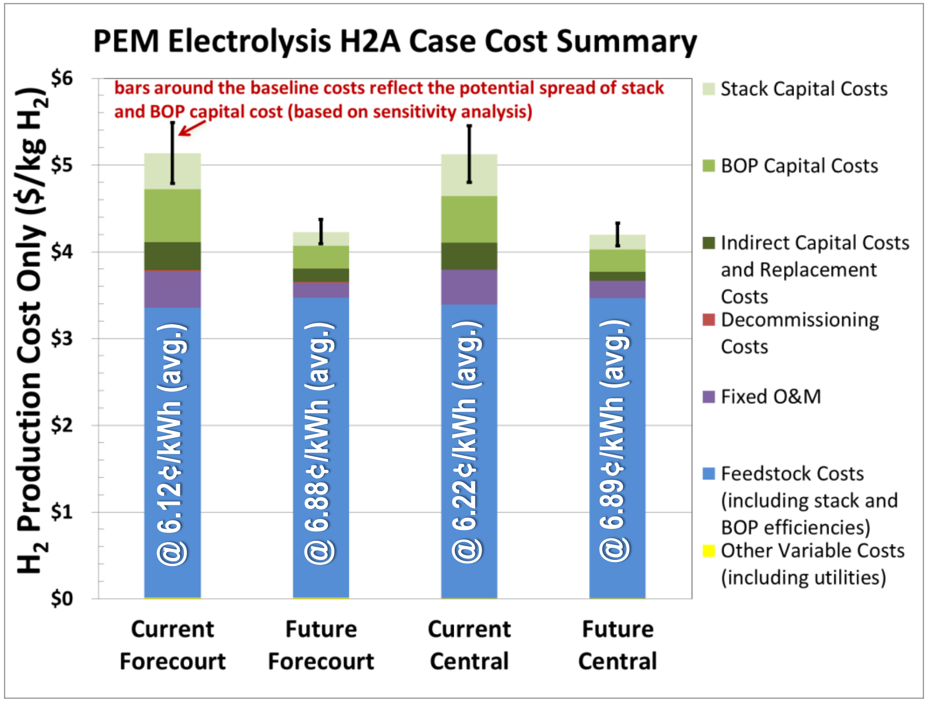
- Baseline costs & cost ranges established for the four PEM cases;
- Key cost drivers identified and quantified, including:
  –*Electricity cost; electrolyzer efficiency; capital cost*

	Low Range ($/kg H_2)	Baseline Cost ($/kg H_2)	High Range ($/kg H_2)
Forecourt			
Current Case	$4.80	$5.10	$5.50
Future Case	$4.10	$4.20	$4.40
Central			
Current Case	$4.80	$5.10	$5.40
Future Case	$4.10	$4.20	$4.30

Methodology:

Representative PEM electrolyzer systems based on input from several key industry collaborators with commercial experience were evaluated using the process:

- *Solicited relevant detailed information from the companies*
- *Synthesized data, amalgamated into base parameters for cases*
- *Base parameters & sensitivity limits vetted by the companies*
- *Four H2A v3 Cases Populated and models run to project H_2 cost*



[a] Discounted cash flow model using technoeconomic inputs to project H_2 production costs incorporating economies of scale:
[b] Current case based on demonstrated technology manufactured at volume; different from existing costs based on low production commercially available electrolyzers

Accomplishments: Electrolysis

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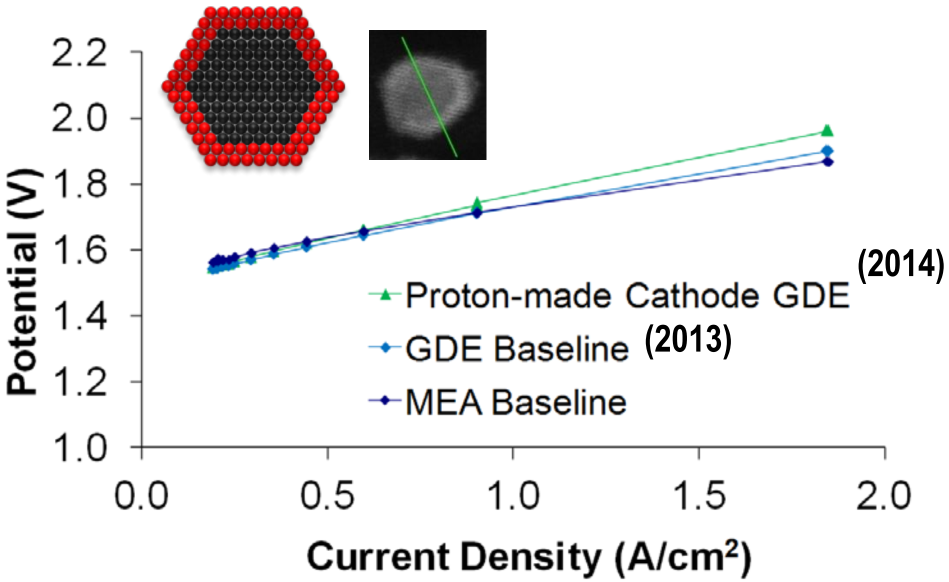
Leveraging recent fuel cell catalyst advances, demonstrated equivalent electrolysis MEA performance with ≥10x lower PGM electrode loading than baseline cells

Adapted two different electrocatalysis approaches originally investigated for lowering PGM loading in PEM fuel cells

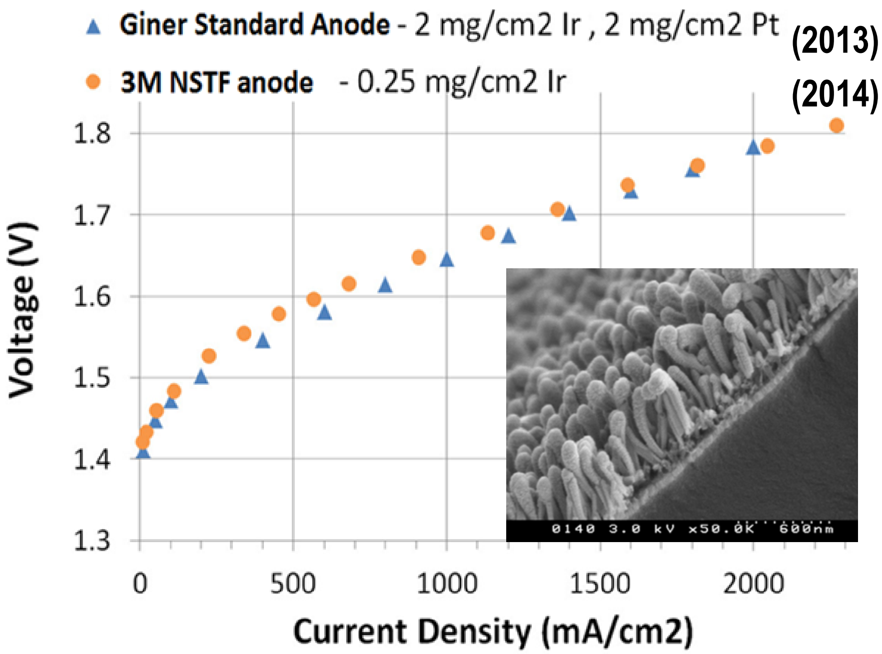
Proton OnSite: BNL Core-Shell Catalyst (PD098)

Proton OnSite successfully transferred the manufacture of BNL-developed core shell catalyst technology to its facilities and achieved equivalent cathode performance at 1/10th of the cathode PGM loading relative to 2013 baseline.



Giner: 3M NSTF Anodes (PD103)

Giner's testing of 3M NSTF anode technology under electrolysis conditions demonstrated comparable performance at 1/16th of the anode PGM loading relative to 2013 baseline.



Accomplishments: Solar-thermochemical: 2-step, metal oxide cycles

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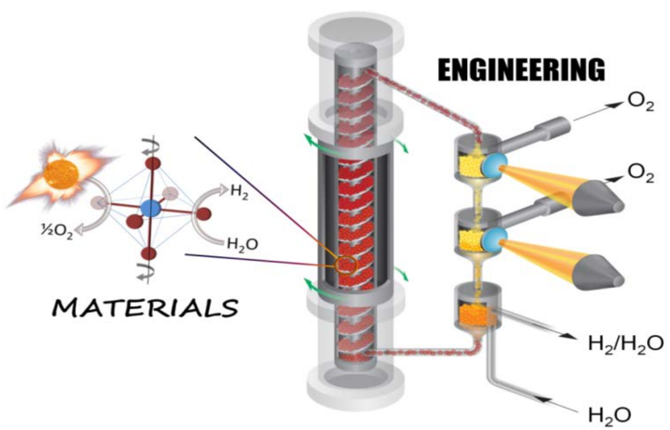
Thermodynamic models, advanced materials and new reactor designs for maximum solar to hydrogen (STH) efficiencies

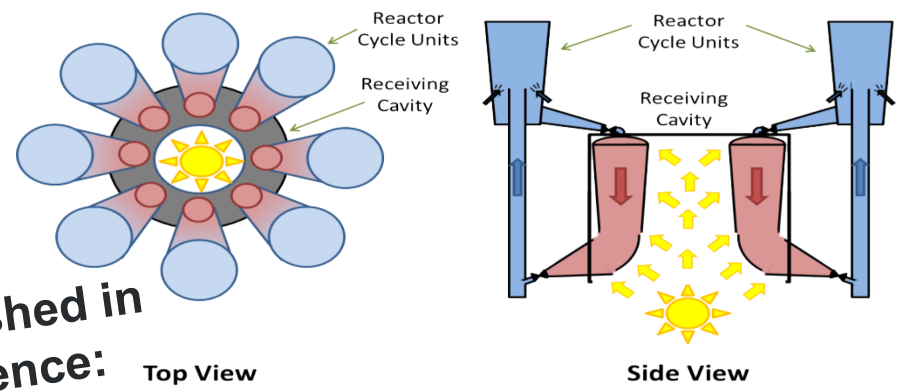
2013: SLMA perovskite cycle: 9x more H_2 than CeO_2 at 150 °C lower T_{TR}
2014: 15 additional perovskite formulations with T_{TR} < CeO_2 and δ > CeO_2
(SNL PD081)

2013: Isothermal (ΔT=0) hercynite Red/Ox; Demonstrated ~100 µmole H_2/g active material
2014: Pseudo-isothermal (ΔT≤150C) Demonstrated 400 µmole H_2/g active material
(CU-Boulder PD028)

- ✓ Model to predict/optimize STH
- ✓ Ideal, non-stoichiometric oxide: Δδ large (≥0.3); H_2O/H_2 small (<20)
- ✓ New pressure -cascade reactor concept: multiple reduction chambers, p_{TR} <10Pa



- ✓ Pseudo-isothermal operation allows for high reduction efficiency, rapid oxidation kinetics
- ✓ New particle flow, "beam-up" reactor concept: flexible ΔT, decoupled Red/Ox reactions, times
- ✓ Engineered, attrition-resistant, flow particles



Published in Science:

Efficient generation of H_2 by splitting water with an isothermal redox cycle. Muhich et al. Aug 2, 2013

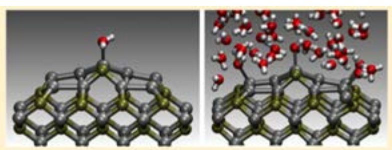
Accomplishments: Photoelectrochemical

Demonstrated surface treatment stabilization at 1.7x higher current densities; Published seminal work on standard method in PEC R&D

Theory-guided enhancement of III-V PEC durability at high H_2 production rates

(NREL / UNLV / LLNL PD035/PD058)

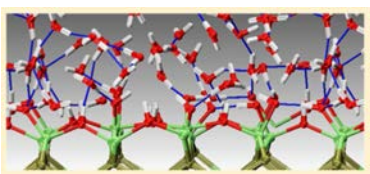
Important theoretical models of III-V PEC interfaces published, including detailed water interactions and corrosion mechanisms



JPC Publication:

Journal of Physical Chemistry C 118, 1062 (2014)

Surface Chemistry of GaP(001) and InP(001) in Contact with Water Brandon C. Wood,* Eric Schwegler, Woon Ih Choi, and Tadashi Ogitsu



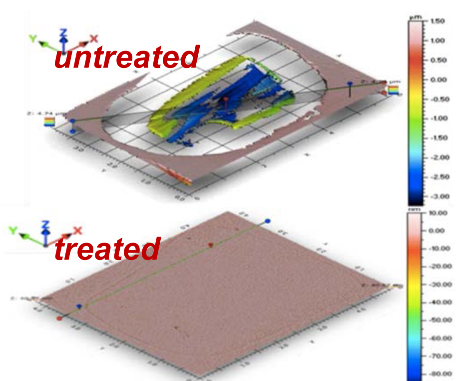
JACS Publication:

Journal of the American Chemical Society 135, 15774 (2013)

Hydrogen-Bond Dynamics of Water at the Interface with InP/GaP(001) and the Implications for Photoelectrochemistry
Brandon C. Wood,* Eric Schwegler, Woon Ih Choi, and Tadashi Ogitsu

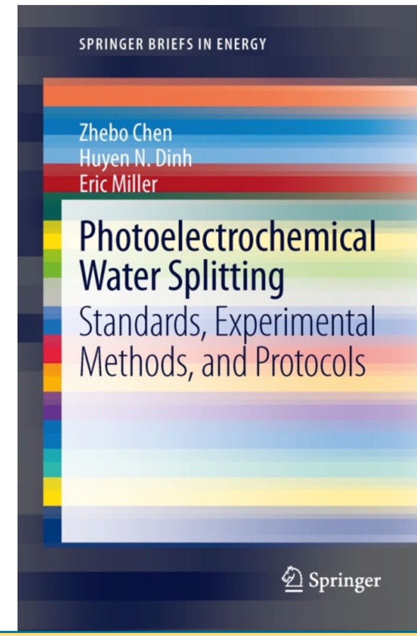
Verified corrosion mitigation of advanced InP III-V semiconductors as a result of ion surface treatment. Treated InP surfaces operated for over 24hrs at high production rates of 25mA/cm² (compared to 15mA/cm² in wider bandgap $GaInP_2$ in 2013) (NREL)

Surface treated InP show little degradation after 24hr PEC operations at 25mA/cm²



Key publication of consolidated standards for PEC R&D

(DOE PEC Working Group)



- Detailed experimental protocols and reporting standards vetted by national and international experts

www.springer.com/chemistry/electrochemistry/book/978-1-4614-8297-0

- Summary paper in the Journal of Materials Research cited nearly 200x to date

Journal of Materials Research / Volume 25 / Issue 01 / 2010, pp 3-16

Accomplishments: Microbial Biomass Conversion

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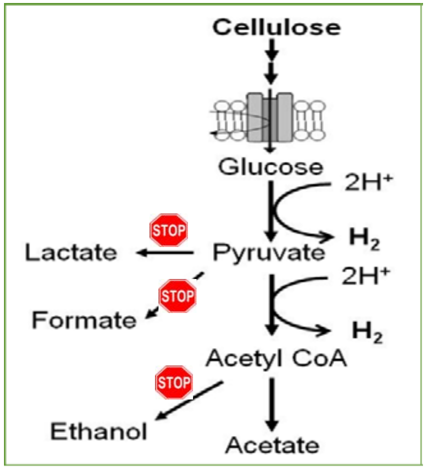
Since May 2013: Developed microbial H_2 production systems to utilize lower-cost lignocellulosic feedstocks (fermentation) and scaled-up reactors (MRECs)

Demonstrated an average H_2 production rate of 466 mL/$L_{reactor}$/day from fermentation of pretreated corn stover (NREL PD038)

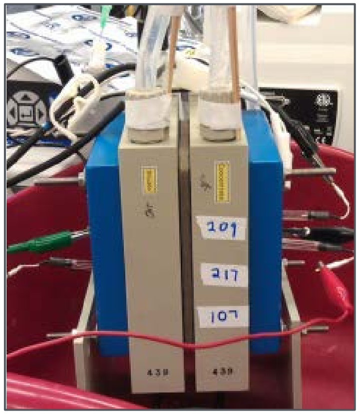
- ✓ No inhibition from lignin accumulation, even at bioreactor concentrations of 14-16 g/L
- ✓ Achieved 62% of the H_2 production rate observed for the higher-cost, less complex, refined cellulose feedstock used previously, with minimal system modifications.
- ✓ Next steps: Further increase production, e.g., removing competing pathways

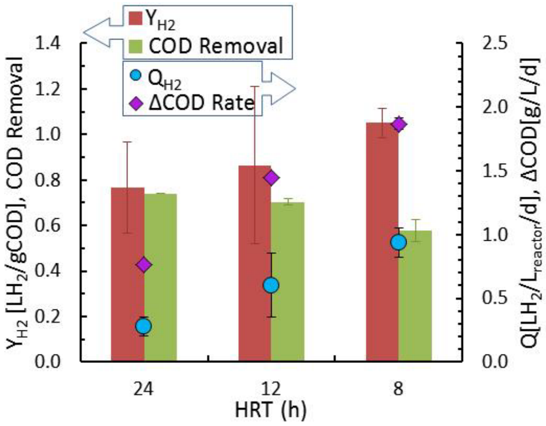


Demonstrated larger, more scalable, Microbial Reverse-Electrodialysis Cell (MREC), generating H_2 with salinity gradient instead of grid electricity (Penn State PD038)

- ✓ Scaled-up system >5x in FY14: from 60 ml total volume in FY13 to 315 ml, increasing net hydrogen production from 48 ml/day to 280 ml/day.
- ✓ Demonstrated H_2 production up to 0.9 L/$L_{reactor}$/day while treating synthetic fermentation waste water at a Chemical Oxygen Demand (COD) reduction of 1.9 g/L/day.
- ✓ Next steps: Develop methods to improve conversion of protein and fatty acid waste water components

315 ml MREC reactor





Accomplishments: Delivery Analysis for Tube Trailer Consolidation

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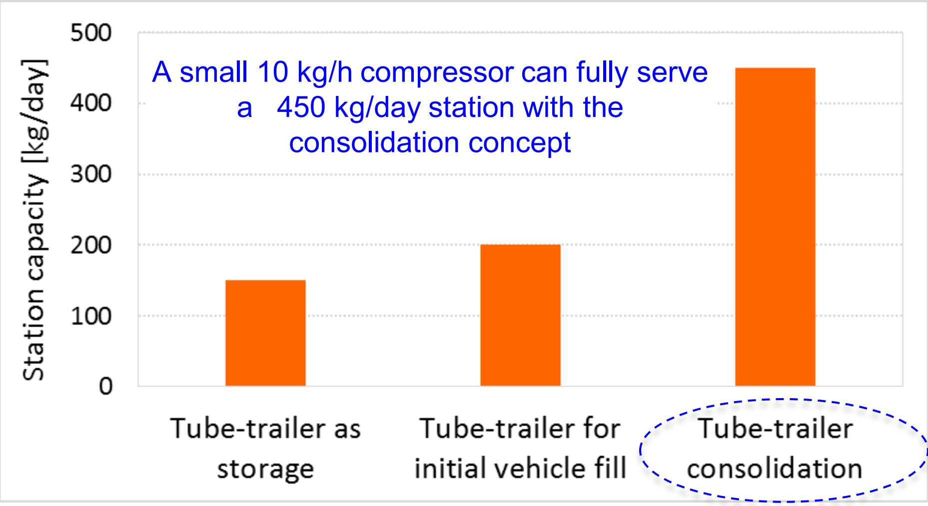
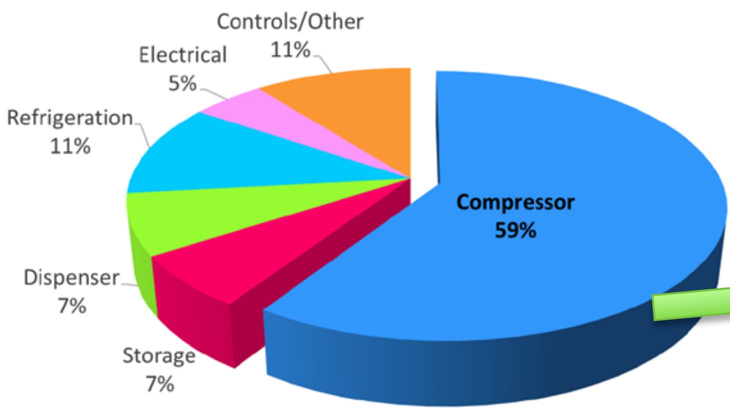
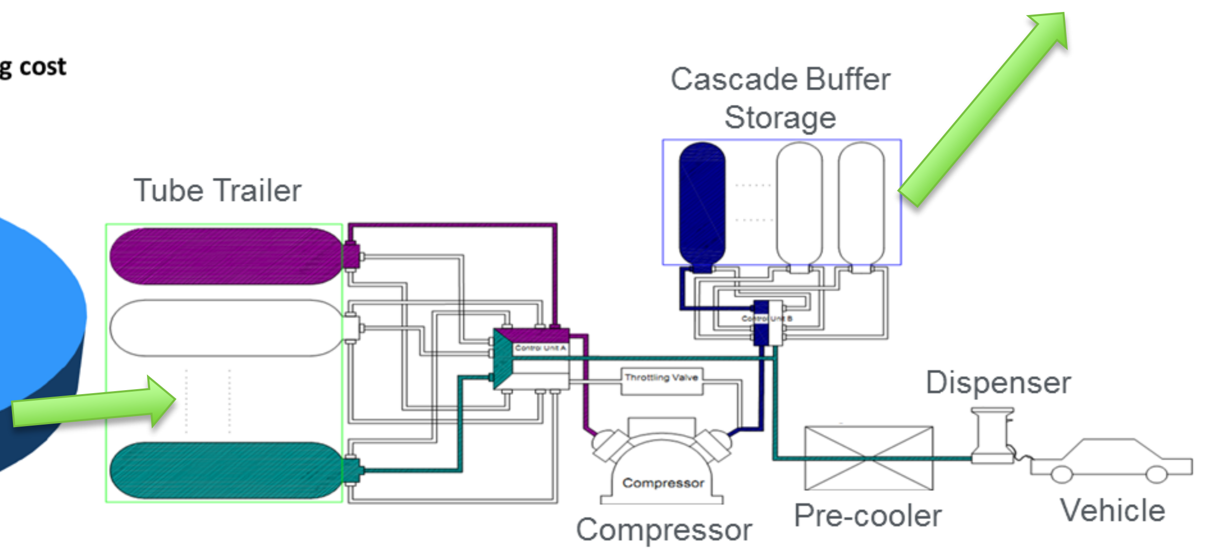
Tube trailer delivery with consolidation at the forecourt can reduce station costs by more than 50% relative to the 2013 estimate for pipeline delivery.

- By using the compressor to consolidate the remaining hydrogen on board the tube trailer during off peak hours a smaller compressor can be used at the forecourt to meet the same demand.
- This greatly reduces the cost of the compressor and this lowers the station cost contribution. (ANL PD014)



Compressor contributes more than half of refueling cost





Accomplishments: Pipelines

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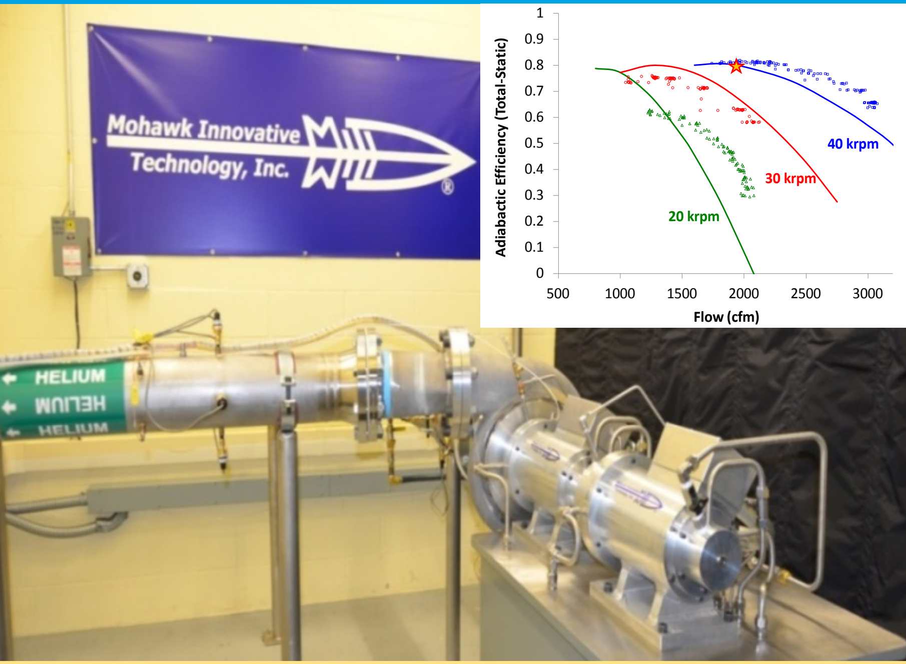
Improved centrifugal pipeline compression and fiber reinforced polymer (FRP) pipeline technologies to reduce the cost of hydrogen delivery via pipeline.



Verified the potential of improved centrifugal pipeline compression to reduce compression capital cost to $2M from $2.7M in 2013. *Based on a 3,000 kW motor rating*

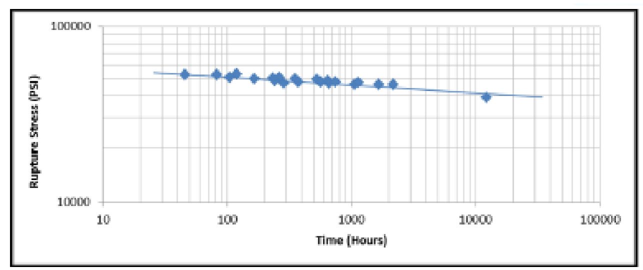
- Completed prototype testing in He at 40,000 RPM to verify the oil-free centrifugal hydrogen compressor performance as designed

(Mohawk Innovative Technology, Inc. PD016)

Increasing the design life of FRP from 20 years (FY13) to 50 years (FY14)

- A data set from ASTM D2992 was used to calculate the reduction in design stress to support a 50 year design life.
- A decrease in the fiber stress level by 4.3% will provide the desired increase in design life.

(SRNL PD022)



ASTM D2992 Data set for FRP

Years	Time (hours)	Rupture Stress (psi)
1	8,760	42113
20	175,200	36465
50	438,000	34894

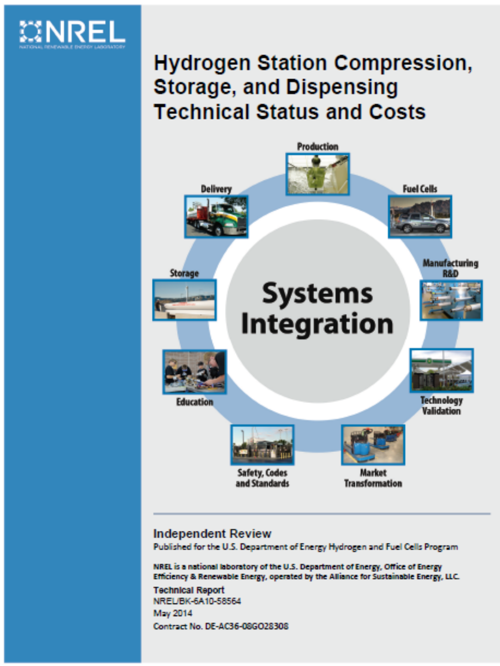
Stress Levels vs. Time

Accomplishments: Forecourt

U.S. DEPARTMENT OF ENERGY

The cost and reliability of compression and dispensing equipment and components remains a key area of focus at the forecourt

Published an Independent Panel Report on H_2 Station Compression, Storage, and Dispensing Technical Status and Costs (NREL)



The projected compression storage and dispensing cost in 2007$ for 700 bar fueling from hydrogen delivered via pipeline, onsite SMR, 500 bar tube trailer in a mature market scenario is between \$2.20 - \$2.80/kg, \$2.30-\$3.20/kg, and \$1.00-\$1.20/kg respectively.

Initiated a SBIR project to develop a new highly reliabile700 bar hydrogen dispensing hose. (Nanosonic PD101)

- Down-selected materials for hose construction, which exhibited an ultra-low hydrogen permeance after severe 180° bending three times in a -50°C chamber.
- Design has a predicted burst pressure of 2560-bar and an innovative path to dissipate static electricity.

Hydrogen P&D Collaborations

U.S. DEPARTMENT OF ENERGY

DOE/EERE

H_2 Production and Delivery Applied R&D

- **~ 20 projects**
- **>12 SBIR projects:**

- **Membranes**
- **Electrolysis**
- **Separations**
- **Components for Fueling Station**

INTERNATIONAL ACTIVITIES

Examples:

- IEA HIA Tasks
- Infrastructure Workshops
- IPHE

INDUSTRY

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

I²CNER - Japan

Director: Dr. Petros Sofronis

Focus on H_2 production, delivery, and FC technologies

TECHNOLOGY VALIDATION (DOE EERE)

>180 vehicles & 25 hydrogen stations

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

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

Recent and Upcoming Activities

U.S. DEPARTMENT OF ENERGY

Summary of recent activities and upcoming milestones

- **3 Funding Opportunity Announcements released for Hydrogen Production Analysis, Production RD&D, Delivery RD&D; Joint FOA with NSF addressing Solar Water Splitting**
- **Springer Brief in Energy: "Photoelectrochemical Water Splitting: Standards, Experimental Methods, and Protocols".**
- **New SBIR projects on sensors, seals, hoses, electrolysis**
- **Independent Panel Report: Hydrogen Station CSD Technical Status and Costs**

2Q 2014
Reduce electrolyzer cathode catalyst PGM loading by 90% compared to commercial MEA.

3Q 2014
Announce Selections from FOAs

4Q 2014
Start waste to energy demo of bio-fueled SOFC and clean-up system

4Q 2014
Complete data analysis and reporting to ASME B31.12 for inclusion of FRP into the code

4Q 2014
Complete Go/No-Go on the use of liquid hydrogen carriers

2Q 2015
New starts in Production and Delivery

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

2Q 2016
Joint FOA with NSF, subject to appropriations

4Q 2016
Design a reactor/receiver system for solar-based central production of > 50,000 kgH_2 /day.

4Q 2016
Complete development of advanced H_2 metering technology.

FY 2014 | FY 2015 | FY 2016

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