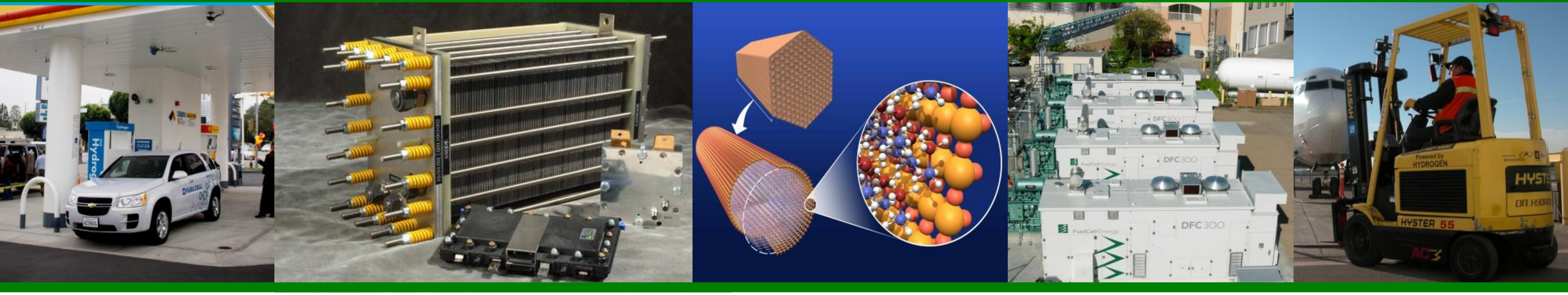
U.S. DEPARTMENT OF
ENERGY



Hydrogen Production & Delivery Program

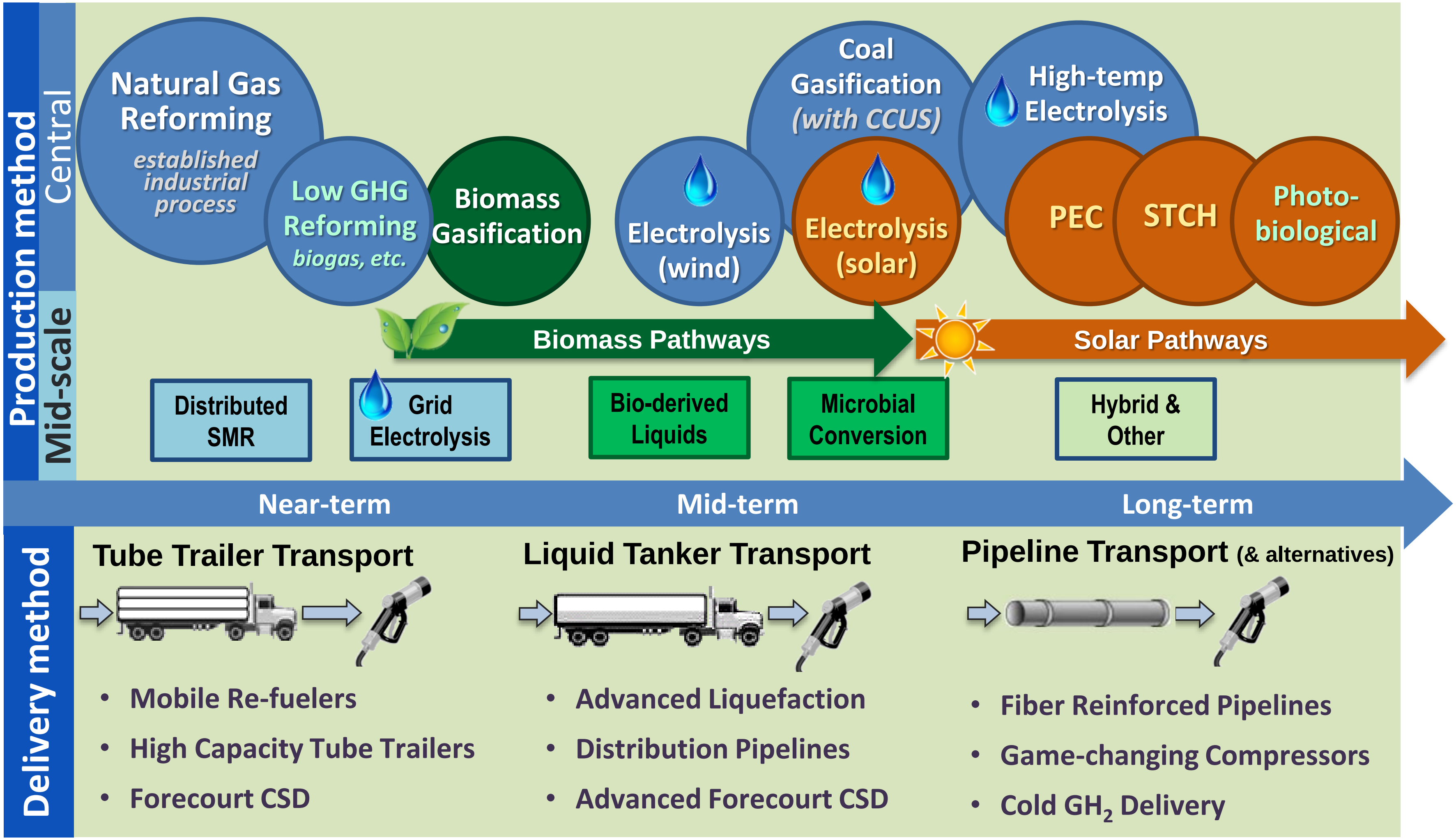
- Plenary Presentation-

Eric L. Miller

2016 Annual Merit Review and Peer Evaluation Meeting

June 6 - 10, 2016

Hydrogen Production & Delivery Roadmap

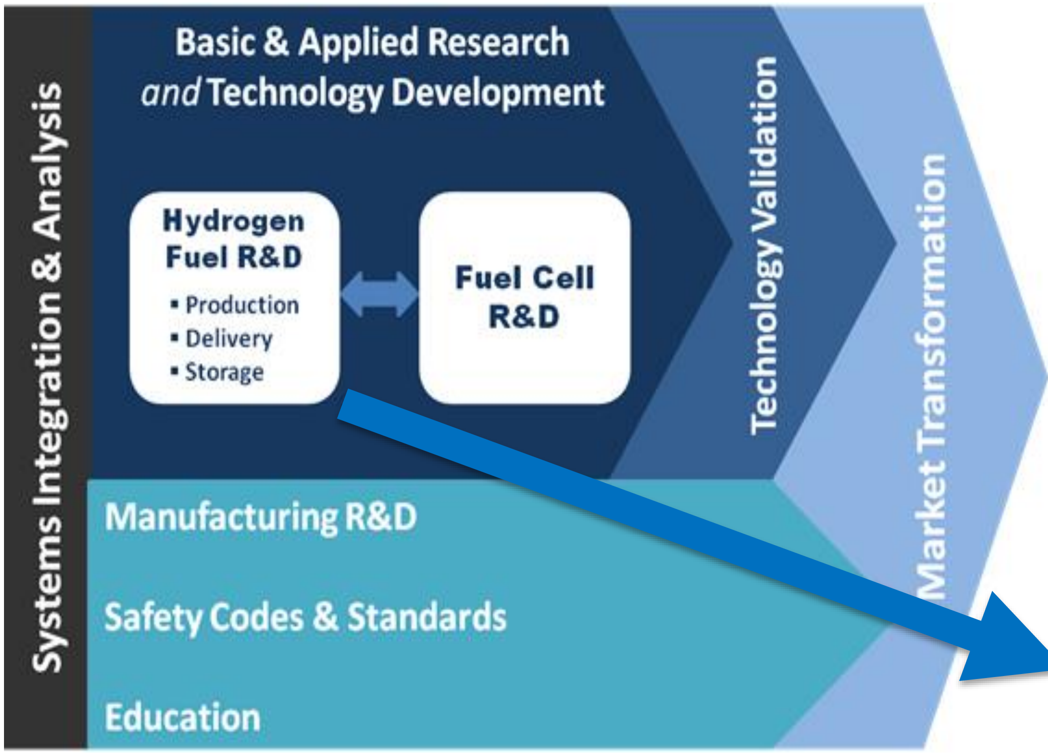


Goal: affordable H_2 from diverse renewable domestic resources

DOE Hydrogen and Fuel Cells Program

Mission

To enable the widespread commercialization of hydrogen and fuel cell technologies



2020 Targets by Application

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

H_2 Storage Cost (On-Board)	$10/kWh 1.8 kWh/L, 1.3 kWh/kg
H_2 Cost at Pump	<$4/gge <$7/gge (early market)

*For Natural Gas **For Biogas

Target-driven approach to accelerate H_2 & fuel cells market penetration

Hydrogen Cost Status and Targets

Targets

Early Market Target

$7/kg

$4/kg

High-Volume Target

Dispensed H_2 Cost Status

(untaxed)

Low-Volume
early markets using NG

$16/kg to $13/kg

High-Volume*
renewable technologies

$7.5/kg to $5/kg

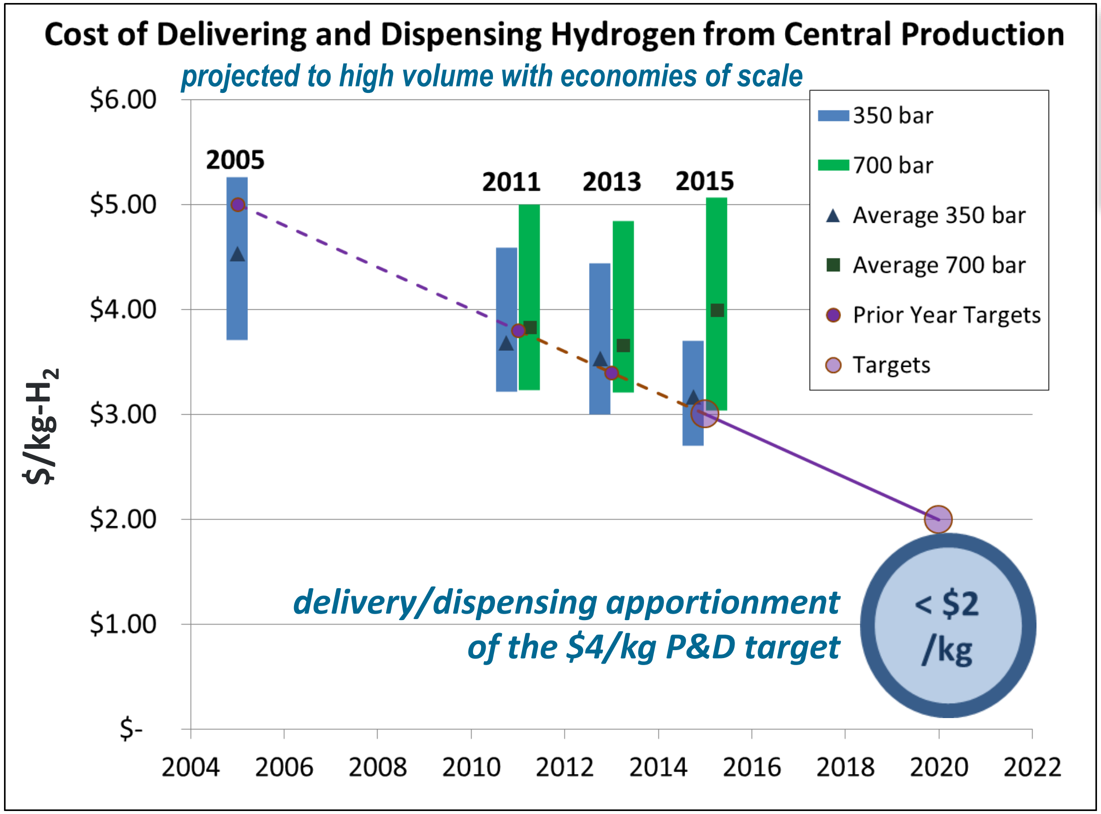
*high-volume projections assume economies of scale

- **LOW-VOLUME, early market cost status is based on low-cost H_2 from NG (<$2/kg) plus >$11/kg for delivery & dispensing**
- ***Developing delivery/dispensing infrastructure is immediate need***

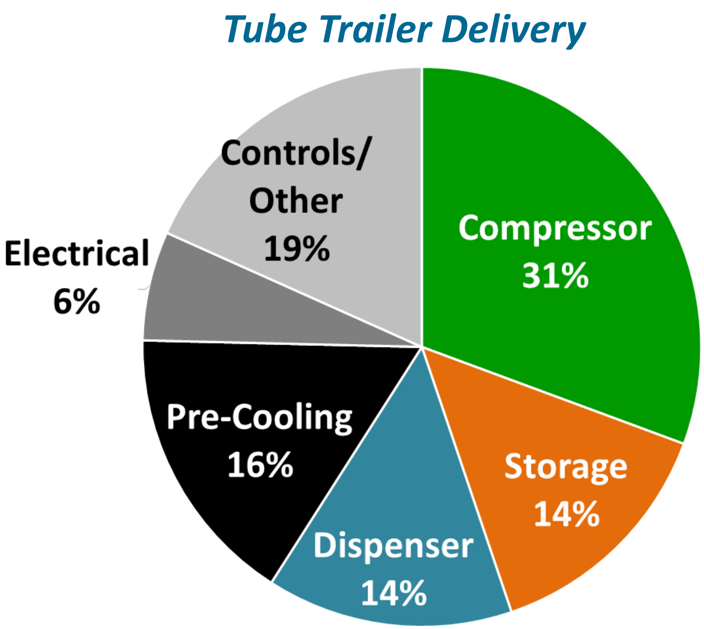
- **HIGH-VOLUME projected cost status is based on ~$2.5-5/kg H_2 (biomass gasification- water electrolysis) plus ~$2.50/kg delivery & dispensing**
- ***RD&D of diverse renewable H_2 technology pathways is vital***

Continued RD&D is needed for renewable H_2 production & delivery

H_2 Delivery and Dispensing Cost Trajectories



HDSAM 3.0 released in 2015!
Techno-economic analysis quantifies delivery/dispensing cost drivers



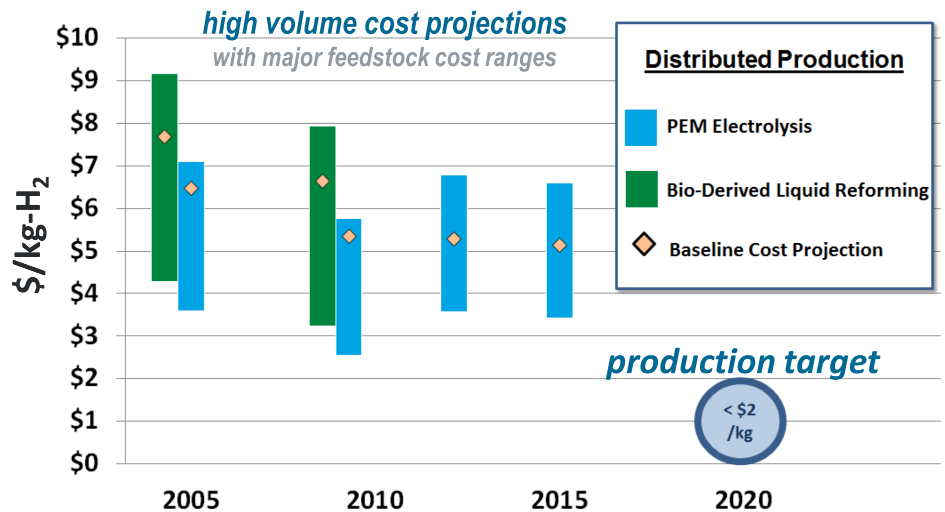
Key Assumptions:

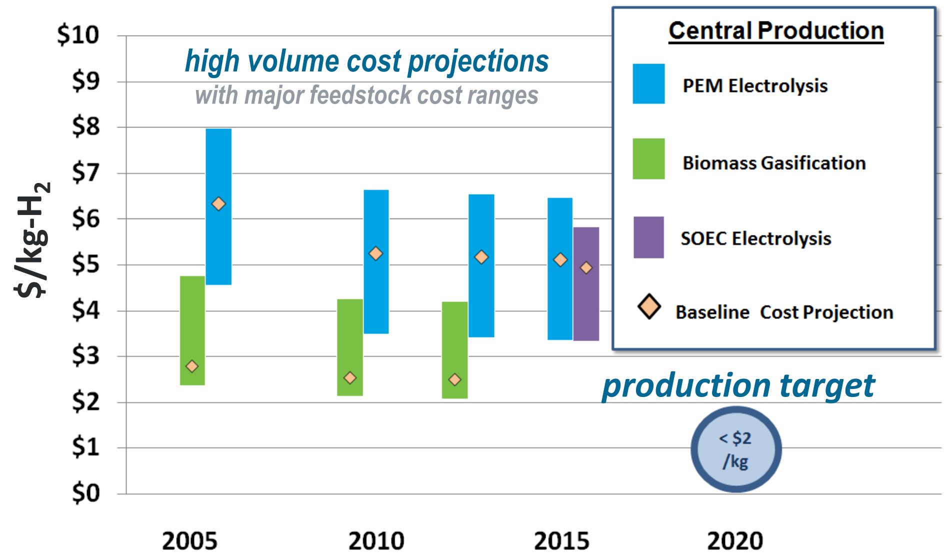
1. City: 1.4M population, 10% market penetration FCEVs
2. Station: 750 kg/day
3. Production: Centralized location, 62 miles from city
4. Manufacturing: All equipment manufactured at economies of scale

In all delivery modes, compression/ pumping, storage, and dispensing accounts for 60-70% of station cost.

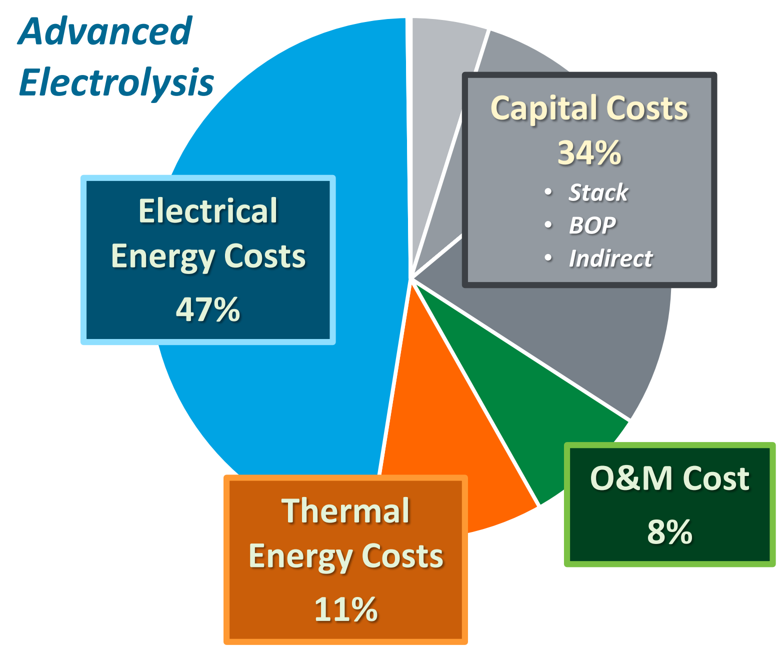
Reducing cost of FCEV refueling stations is an immediate priority

Renewable H_2 Production Cost Trajectories





H2A techno-economic analysis quantifies projected cost status and identifies key levers for reducing costs through RD&D

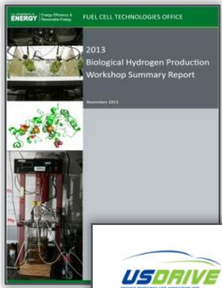


Advanced high-T solid oxide electrolysis offers cost benefits over PEM electrolysis, but energy and capital costs still dominate

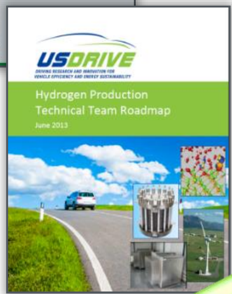
Continued RD&D to reduce cost of renewable pathways is critical

Applied RD&D Portfolio Development

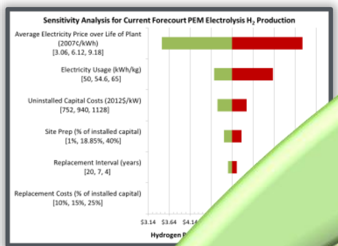
Workshops

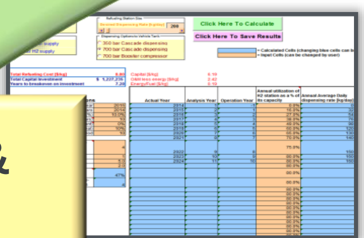


U.S. DRIVE Tech Team Roadmaps



H2A





HDSAM

Analysis & Studies

Stakeholder Input

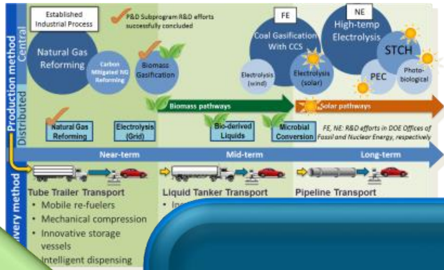
Collaboration & Coordination

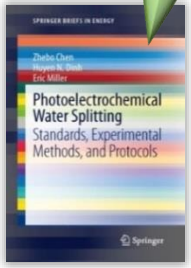
SBIR / STTR
Small Business Innovation Research
Small Business Technology TRansfer

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

H2FIRST
Hydrogen Fueling Infrastructure Research and Station Technology

H_2USA





Pathway Working Groups

RD&D Portfolio
priorities, metrics, targets

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

FCTO MYRD&D Plan for Meeting Cost Goals

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

Applied RD&D Strategies and Framework

Challenge

Reduce the cost of clean, sustainable hydrogen production & delivery while meeting safety and performance requirements

- Feedstock costs
- Capital costs
- O&M costs

Strategies

Near-term

Minimize cost of 700 bar hydrogen at refueling stations

Long-term

Improve performance and durability of materials & systems for production from renewable sources

RD&D Focus

- Techno-economic & life cycle analysis
- Reliability and cost of compression, storage and dispensing
- Renewable integration
- Advanced materials and systems for H_2 delivery
- Innovations in materials, devices and reactors for renewable H_2 production
- Improved balance of plant for P&D systems

Key Areas

Delivery

- Polymers & composites for delivery technologies
- Liquefaction technologies
- Nonmechanical compression
- Novel pressure vessel designs

Production

- Advanced electrolysis
- Biomass conversion
- Hybrid approaches
- Solar water splitting: PEC & STCH

RD&D Support Framework:

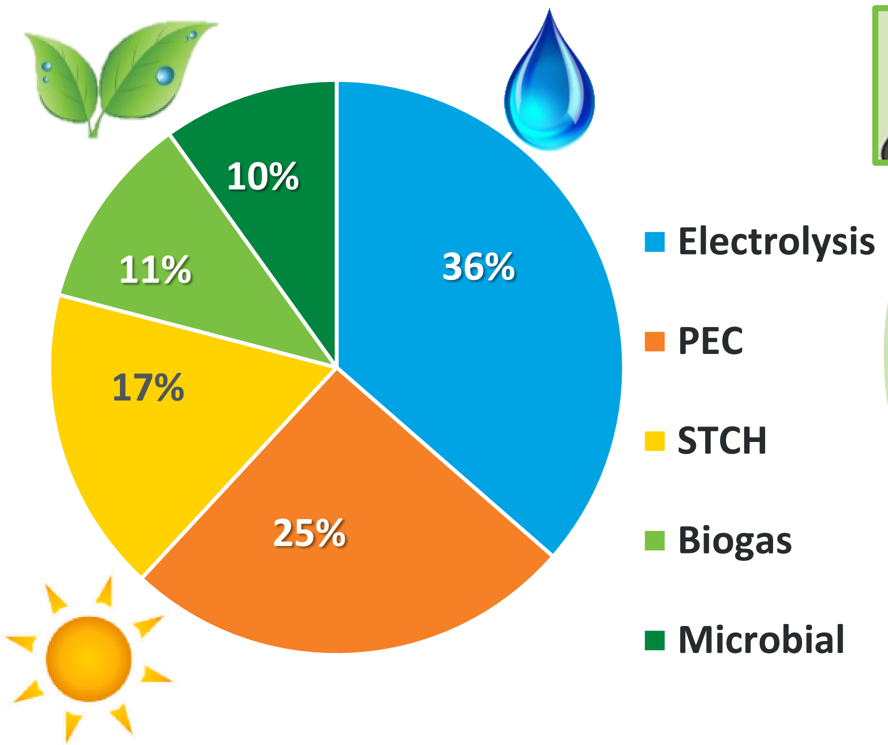
- FCTO FOA & Lab Calls
- SBIR/ STTR
- DOE MOUs: NSF & NIST
- Incubator/ Seedlings
- Crosscuts: Grid, EMN…
- Prizes and Other

Leveraging resources to address near- to longer-term challenges

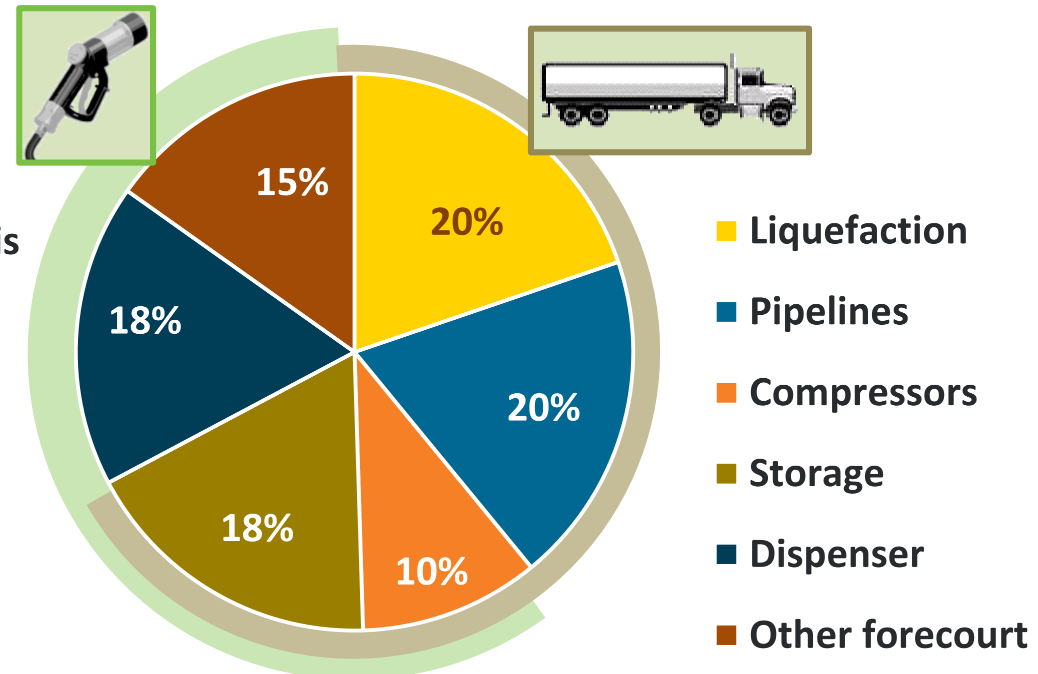
Hydrogen RD&D Portfolio Distribution

FCTO funding distribution in FOA, LAB, SBIR/STTR & joint NSF projects

H_2 Production



H_2 Delivery

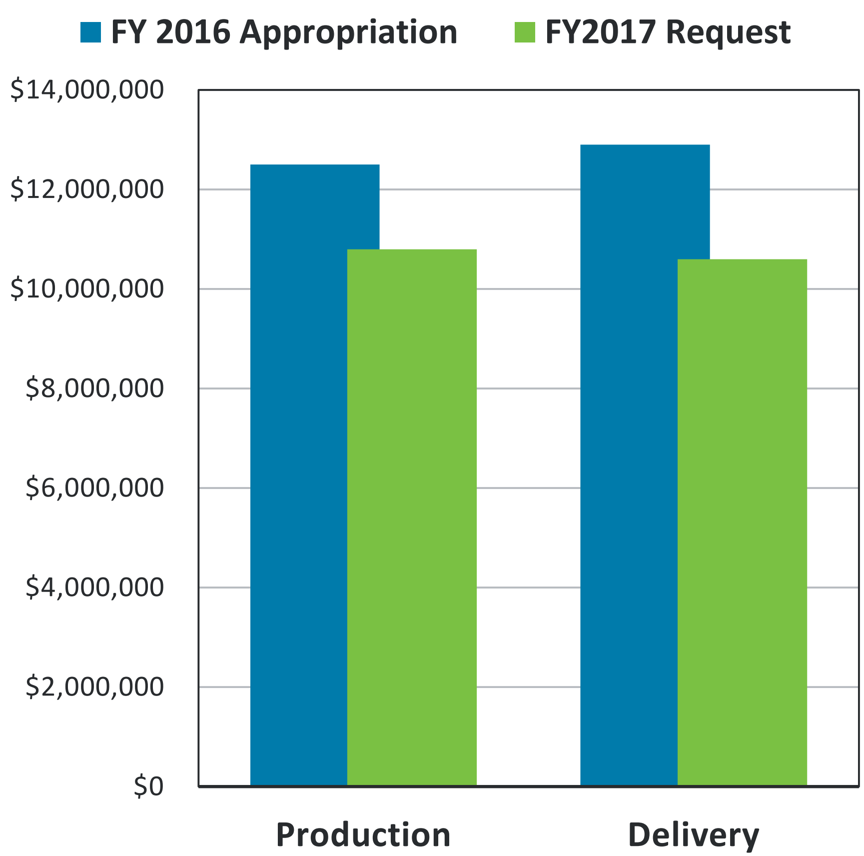


Balanced portfolio addressing near- to longer-term challenges

FCTO H_2 Production & Delivery Budget

FY 2017 Request = $21.4M

FY 2016 Appropriation = $25.4M



EMPHASIS

- **Expand TE & LCA analysis , and refine near- and long-term targets**
- **Expand portfolio of near-, mid- and long-term P&D technologies**
  - ***advanced high-T electrolysis***
  - ***advanced compression***
- **Continue cross-office/agency and international coordination/collaboration**
- **Support H2@Scale Lab Big Idea**
- **Initiate HydroGen Advanced Water Splitting Materials consortium within Energy Materials Network**

Stabilized budgets are needed to sustain critical RD&D; Continued leveraging of broader research resources is needed

H_2 Production & Delivery Collaborations

INTERNATIONAL ACTIVITIES

Examples:

- IEA HIA Tasks
- Infrastructure Workshops
- IPHE

DOE/EERE

FCTO

Hydrogen P&D Applied RD&D

- FOA/Lab projects
- SBIR projects
- Joint NSF projects
- Incubator projects

INDUSTRY

- USDRIVE Tech Teams
  - *H_2 Production*
  - *H_2 Delivery*
  - *Analysis*
- H_2USA – H_2First
- Codes & Standards Organizations

DOE CROSS-CUTS

- Grid cross-cut
- EMN cross-cut

TECHNOLOGY VALIDATION

Grid Integration/ Energy Storage

INTRA- AND INTER-AGENCY COLLABORATIONS

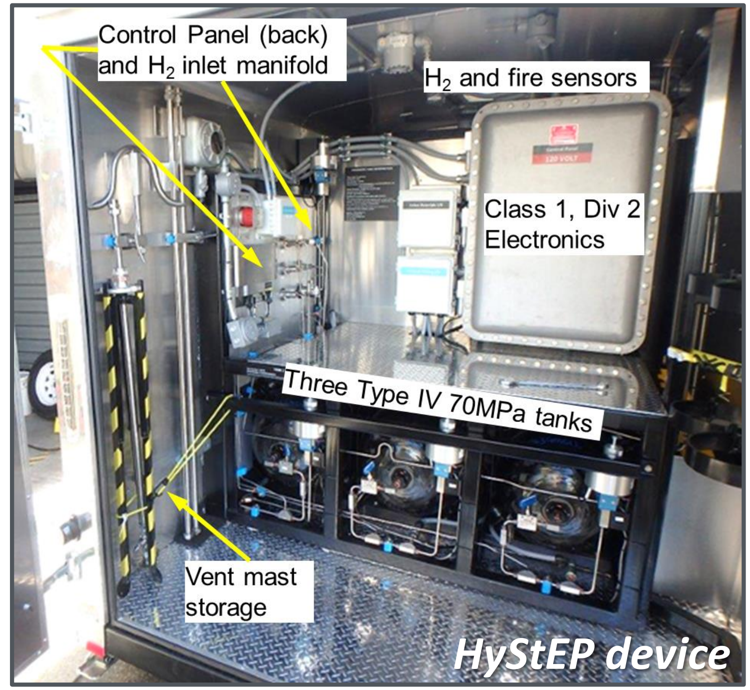
- DOE: BES *Including JCAP*
- DOE: NE and FE
- BETO & SETO
- ARPA-E
- NSF
- NIST
- H2@Scale

H2First Accomplishment– HyStEP

Hydrogen Station Equipment Performance (HyStEP) testing device

- **The mobile HyStEP device:**
  - *Enables rapid hydrogen station commissioning by collecting the data needed to validate station fueling protocols*

TV026



- **The HyStEP has been testing stations in CA since December 2015**

Mercedes, Honda, Hyundai, and Toyota have all tested and validated the device and have accepted it as deployment ready!

H2 Refuel H-Prize Finalist Announced!

Finalist must meet all technical and cost criteria simultaneously to win!

$1 M competition for on-site H_2 fueling

H2 refuel
U.S. Department of Energy

Now	Summer	Fall	
System building	System testing	Data Analysis	$1M?

PD000 Finalist team

PD128 HEF, H-Prize administrator

Finalist team: simple.fuel.™

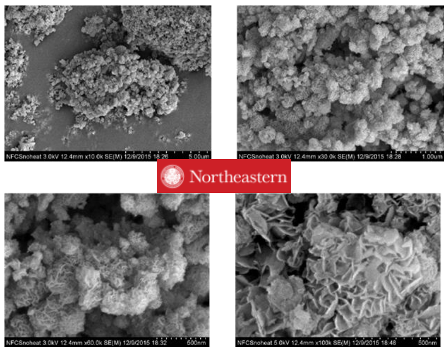
- Innovative packaging for reduced footprint
- H_2 produced by electrolysis, stored at 350 bar
- Boost fill for 700 bar fueling

For more information about the H-Prize, visit http://hydrogenprize.org/

Advanced Electrolysis Accomplishments

Alternative chemistries & operations challenging the state-of-the art

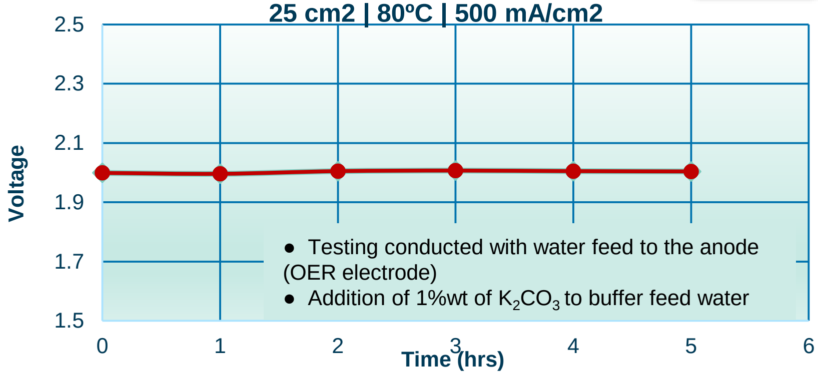
Activity and stability optimized through tuning composition and support of non-PGM catalysts.



PROTON ON SITE

PD123

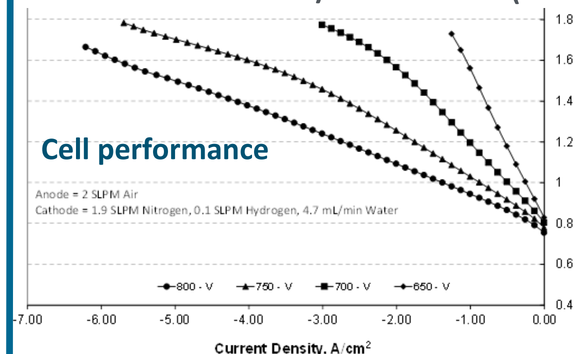
Full non-PGM Operational Test
25 cm2 | 80ºC | 500 mA/cm2



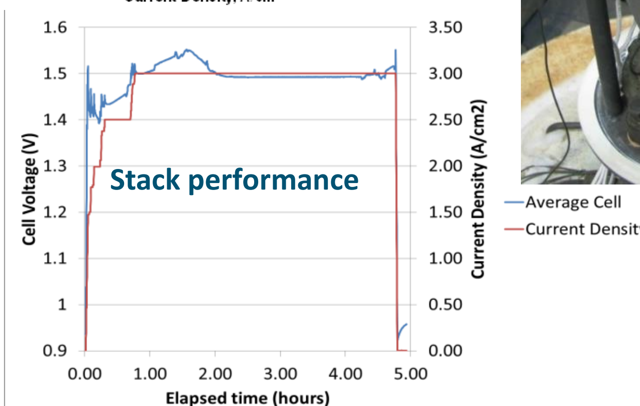
First demonstration of stable, PGM-free AEM electrolysis!

Metrics achieved:

- Cell: 6 A/cm² at ~1.65 V (78% LHV efficiency)
- 20 cell stack: 3 A/cm² at ~1.5 V (84% LHV efficiency)



Versa Power Systems



PD124

First demo of ultra-high current, high-T SOEC cell and stack with potential for reversible operation

Bio-Derived H_2 Accomplishments

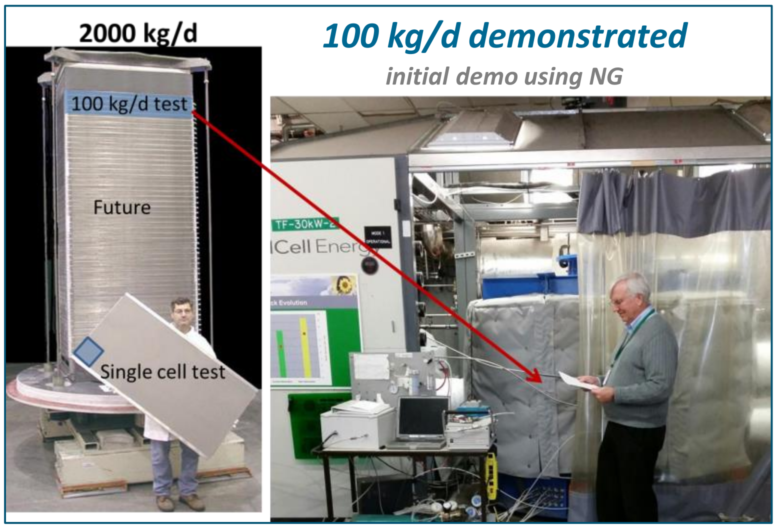
Advances in low carbon H_2 production from bio-feedstocks

Commercial fuel cell technology operated in electrolysis mode for:

- *Higher (~98%) purity H_2*
- *Lower CO_2 emissions*

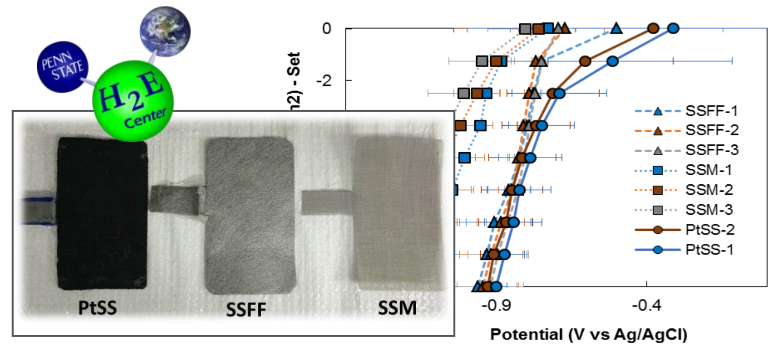
FuelCell Energy

PD112

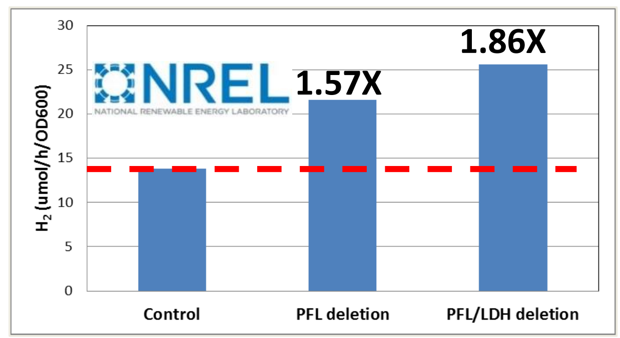


First prototype demo of Reformer/Electrolyzer/Purifier

NREL and Penn State: improved fermentation and MEC production while reducing costs



PD038



Double-mutant's H_2 rate: >85% increase over last year's strains

H_2 Liquefaction Accomplishment

Magnetocalorics could be a game-changer in H_2 liquefaction

New 25 kg/day system with by-pass loop enabled:

- World record breaking 100˚C temperature span, and liquefying a gas from room temperature
- 88% reduction in kilograms of magnetocalorical material used from 184 kg to 22.3 kg
- 87% increase in the figure of merit from 0.4 to >0.75

PD131

Pacific Northwest NATIONAL LABORATORY

THE Ames Laboratory
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

EMERALD ENERGY NW
Solutions with Power and Energy

World's first demonstration of gas liquefaction from room temperature using innovative magnetocaloric materials!

Solar H_2 Applied RD&D Accomplishments

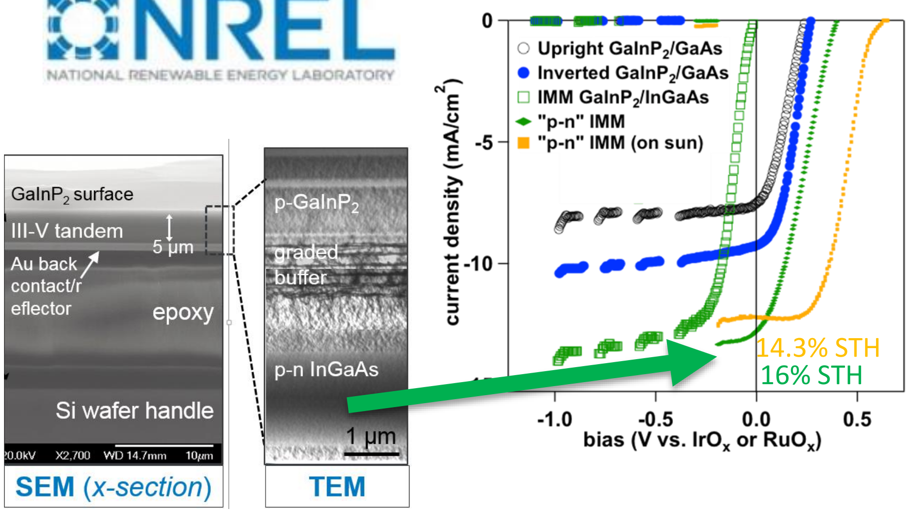
Exciting photoelectrochemical & solar thermochemical progress

Inverted metamorphic multijunctions (IMM)

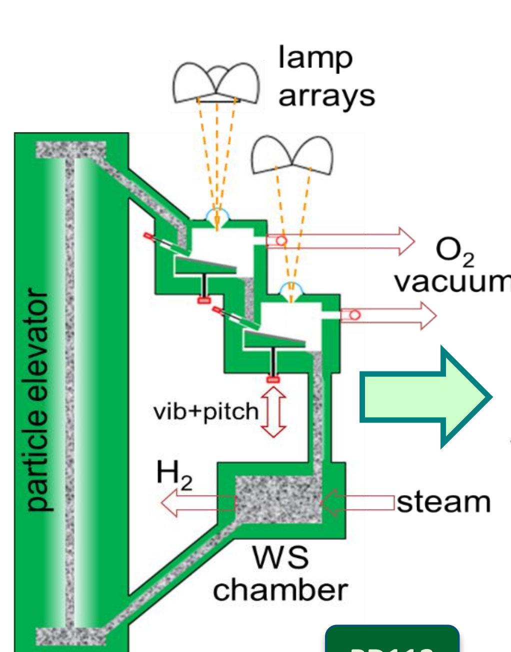
- Grown by organometallic vapor phase epitaxy
- Incorporates buried p/n junction
- Achieved 16% STH using solar simulator
- Achieved 14.3% STH under outdoor testing

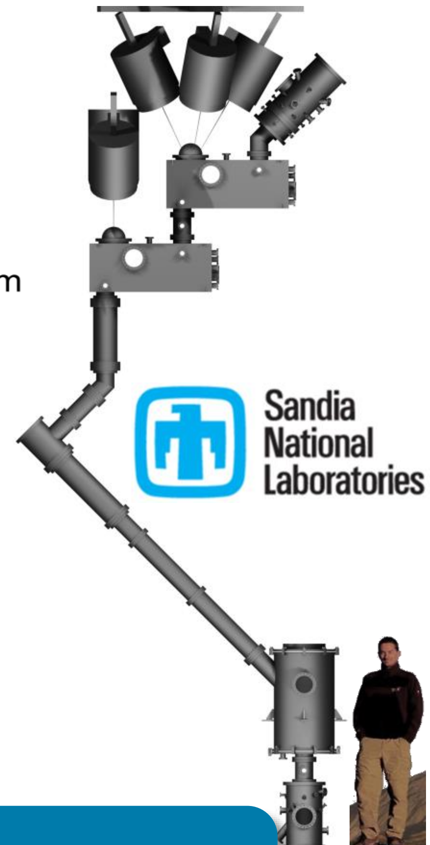
PD115

NREL
NATIONAL RENEWABLE ENERGY LABORATORY



Cascading Pressure Receiver-Reactor (CPR2)





New PEC conversion efficiency world records!

STCH innovative reactor: concept to demo in 1 year!

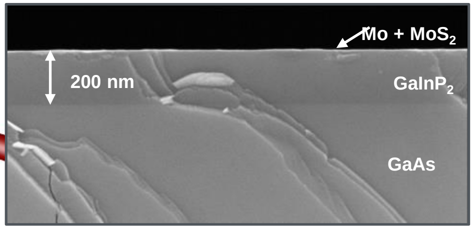
Cross-Cutting NSF/DOE Solar H_2 Joint Projects

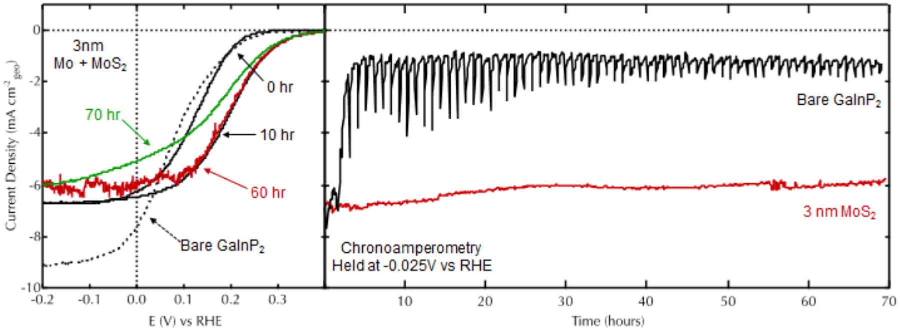
Innovative materials research to advance PEC and STCH pathways

Protecting the surface of $GaInP_2$

- MoS_2 was used to protect $GaInP_2$ in acid
- MoS_2 further functions as a catalyst for the Hydrogen Evolution Reaction improving onset potential

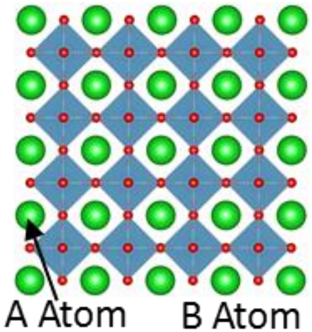
PD119

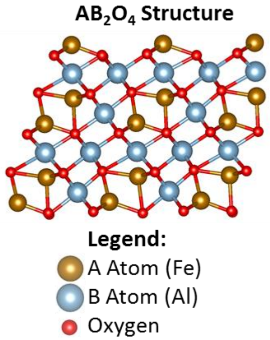


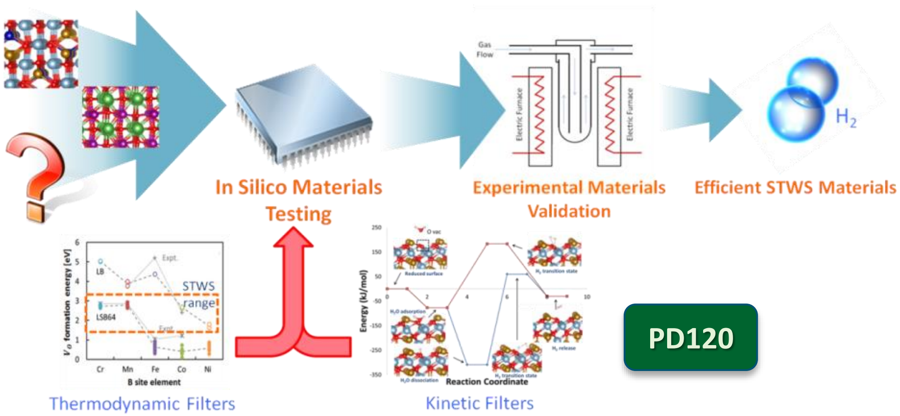


Breaking new ground in PEC surface engineering

Advanced computational materials discovery







PD120

Accelerating discovery of new STCH Redox materials

New Path Forward: HydroGen Consortium

HydroGen
Advanced Water Splitting Materials

New DOE Energy Materials Network consortium to accelerate the discovery and development on innovative materials critical to advanced water splitting technologies for renewable hydrogen:

Advanced Electrolysis	Photoelectrochemical	Solar Thermochemical

Energy Materials Network
U.S. Department of Energy

http://energy.gov/eere/energy-materials-network/about-energy-materials-network

Recent Activities and Upcoming Milestones

- DOE QTR *Hydrogen Fuel Sub-Chapter* and *Technology Assessment* published
- NRC evaluation of Hydrogen Production and Delivery Programs under US Drive Partnership
- New projects in fermentation, liquefaction, advanced electrolysis and advanced compression
- Continued projects under H2First (including HyStEP) in support of the H2USA mission
- Cross-office collaborations with EMN/MGI, CEMI, WBS, Grid Integration, Solar Fuels
- Webinars on topics including *Infrastructure*, *Solar Hydrogen*, and *H-Prize*
- Workshops, including *Advanced Water Splitting Materials* and *International Infrastructure*
- Initiation of the *HydroGen Advanced Water Splitting Materials* EMN consortium

FY 2016 | FY 2017 | FY 2018

- **2Q 2015** FCTO/BETO joint Wastewater Workshop
- **4Q 2015** Successfully negotiated and awarded FY 15 P&D projects
- **1Q 2016** SBIR topic for mangetocaloric materials discovery released
- **2Q 2016** FOA Topics released in Hi-T electrolysis, analysis advanced compression
- **3Q 2016** International Infrastructure Workshop
- **3Q 2016** Advanced Water Splitting Materials Workshop
- **4Q 2016** Anticipated announcement of H2 Refuel Contest outcome
- **4Q 2016** Establish HydroGen EMN Consortium laboratory core
- **1Q 2017** Negotiate and award FY16 Office Wide FOA Selections
- **2Q 2017** FY17 FOA topics released, including HydroGen topics
- **3Q 2017** FCTO/WBS workshop on power electronics for electrolysis
- **4Q 2017** Design a reactor/receiver system for solar-based central production of > 50,000 kgH_2 /day.
- **4Q 2017** Complete ASME certification of wire-wrapped pressure vessel design for hydrogen storage.
- **1Q 2018** Negotiate and award FY17 Office Wide FOA Selections

Hydrogen Production & Delivery Team

Thank you for your kind attention!

Eric L. Miller, Program Manager
(202) 287-5829
eric.miller@ee.doe.gov

Katie Randolph
(720) 356-1759
katie.randolph@ee.doe.gov

David Peterson
(720) 356-1747
david.peterson@ee.doe.gov

Benjamin Klahr
(202) 586-1758
benjamin.klahr@ee.doe.gov

Max Lyubovsky
(202) 586-4031
maxim.lyubovsky@ee.doe.gov

Carlos Gomez (Red Horse)
(202) 586-4786
juan.gomez@ee.doe.gov

Erika Gupta
(202) 586-3152
erika.gupta@ee.doe.gov

Neha Rustagi
(202) 586-8477
neha.rustagi@ee.doe.gov

Sarah Studer
(202) 586-4031
sarah.studer@ee.doe.gov

Kim Cierpik-Gold (CNJV)
(720) 356-1266
kim.Cierpik-gold@ee.doe.gov

Leah Fisher (SRA)
(202) 586-1646
leah.fisher@ee.doe.gov

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