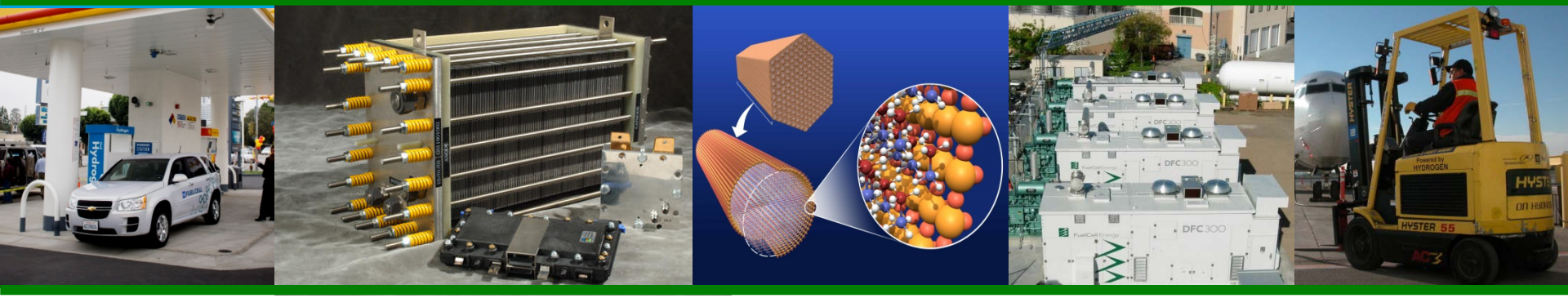
U.S. DEPARTMENT OF ENERGY



Hydrogen Production & Delivery Program

- Plenary Presentation-

Eric L. Miller

2017 Annual Merit Review and Peer Evaluation Meeting

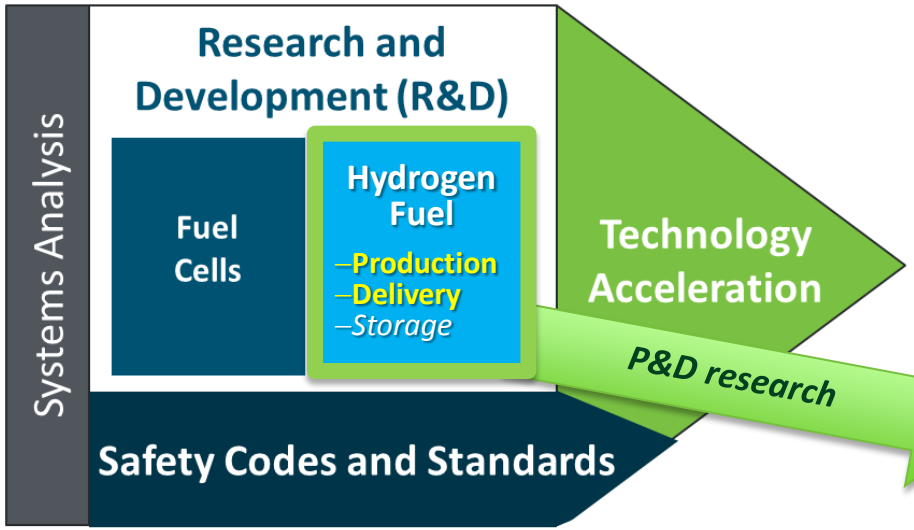
5 June, 2017

DOE Hydrogen and Fuel Cells Program

Program Focus

Applied research, development and innovation of hydrogen and fuel cell technologies that enable **energy security, resiliency, and a strong domestic economy** in emerging markets.

Sub-Programs



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)	

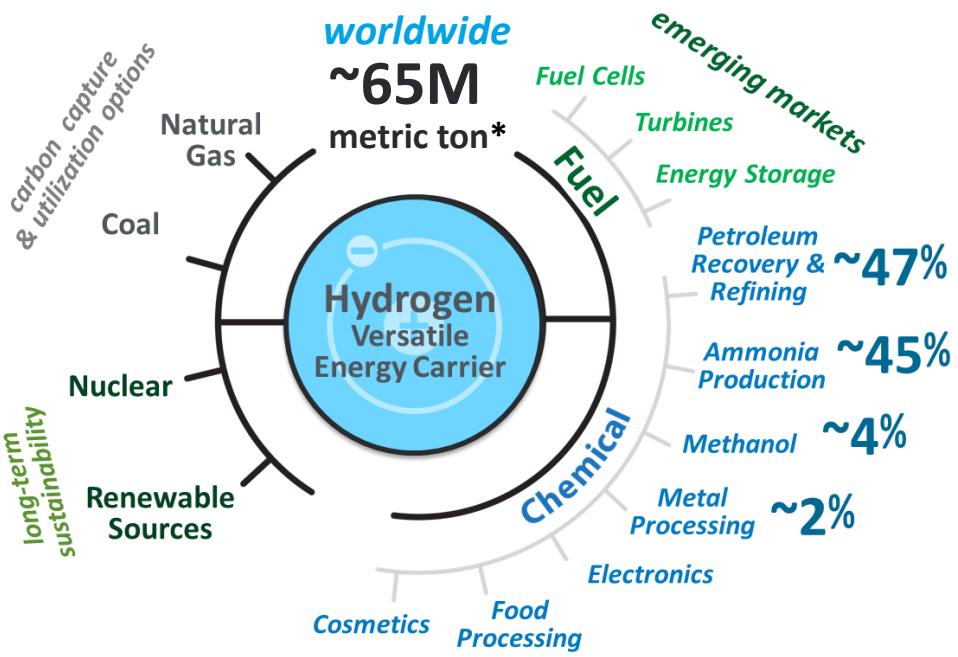
*For Natural Gas **For Biogas

Strengthening U.S. energy security and the economy through R&D on hydrogen & fuel cells

Goal: Widespread H_2 Production & Delivery

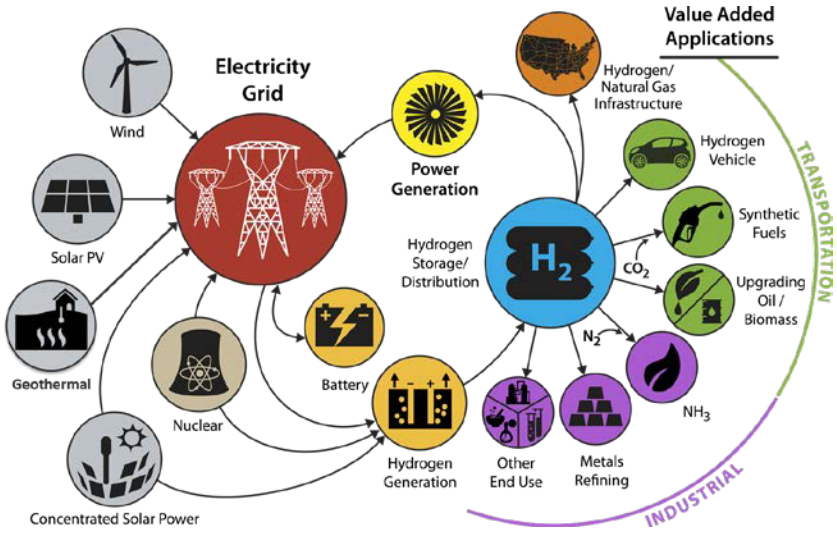
Diverse Sources

Diverse Applications



"H2 @ Scale" Initiative

- Complementing today's electric & natural gas grids with H_2 to enhance flexibility in energy & other major industrial sectors
- Developing diverse low-cost domestic H_2 production & delivery options opens significant market opportunities while offering environmental benefits



Growing industrial demand for H_2

>$100B global market and expanding

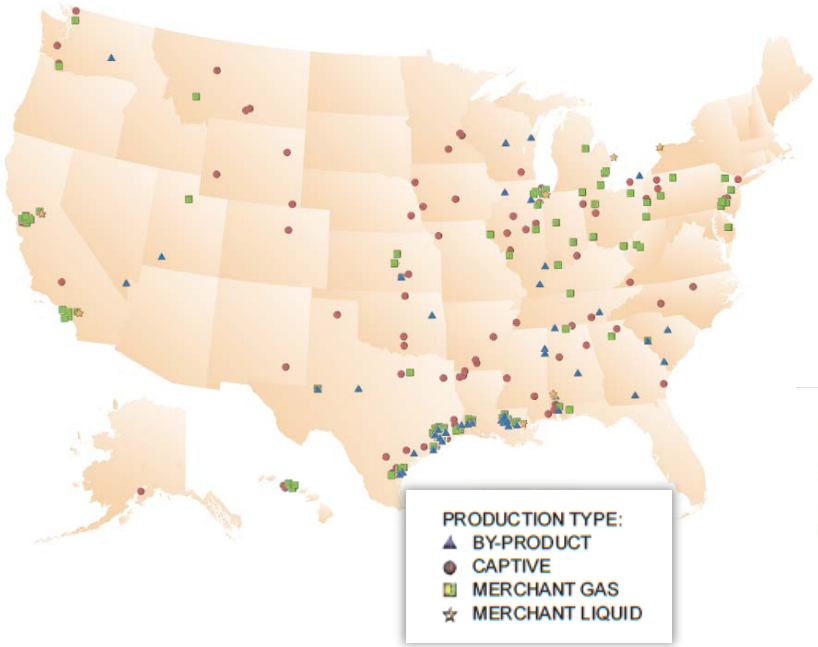
** 10M metric ton domestically*

Hydrogen enables domestic energy & environmental security, with large-scale market potential, job creation and economic growth opportunities

Goal: Sustainable Domestic H_2 Production

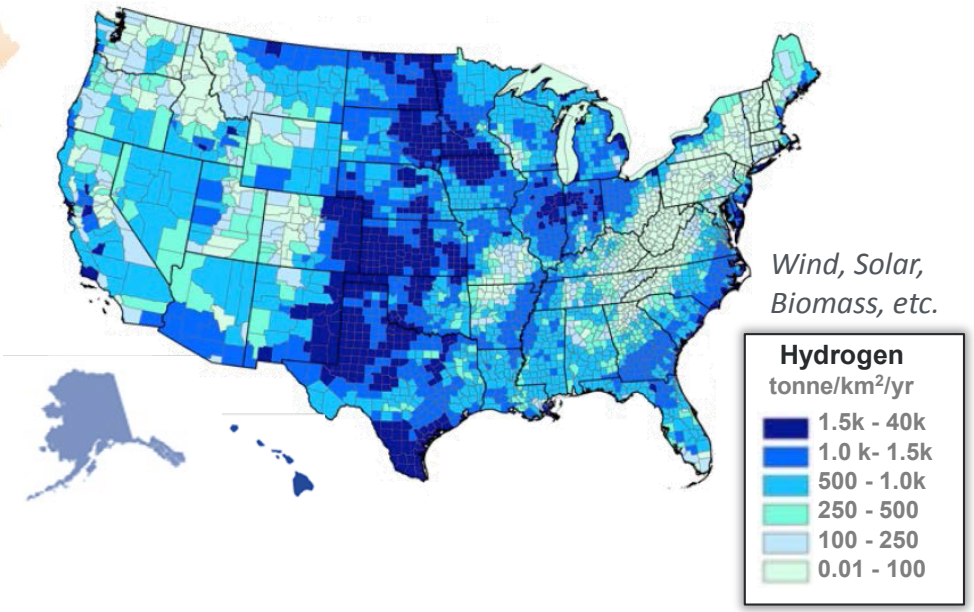
Hydrogen production from domestic fossil resources

Current: ~10 MMT/y
Future: ~10 - 150 MMT/y for 10 -100 y



Hydrogen production from diverse sustainable resources

Current: < 1 MMT/y
Future: >150* MMT/y SUSTAINABLY



Every state has substantial resources to produce hydrogen

**U.S. demand could grow to >50 MMT/y, including 20 MMT/y for 100M FCEV*

The diversity of domestic H_2 options can enable long-term US energy independence with export opportunities & regional job creation

Cost Status and Targets: Dispensed H_2

Targets

Early Market Target

$7/kg

$4/kg

Ultimate Target

Cost Status

(untaxed)

Low-Volume *early markets using NG*: **$16/kg** to **$10/kg**

High-Volume*: **$7.5/kg** to **$5/kg**

*high-volume projections assume economies of scale

LOW-VOLUME

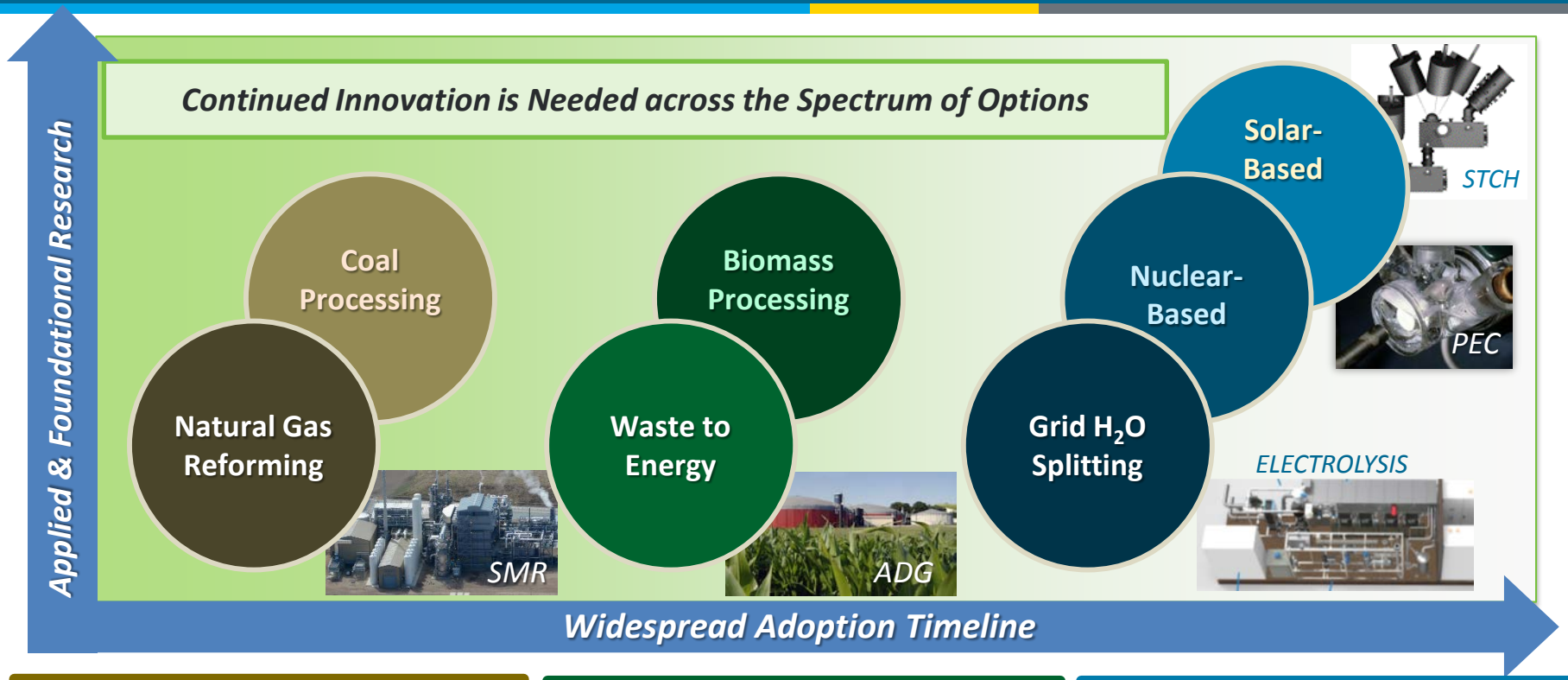
- Early market status based on low-cost H_2 from NG (<$2/kg) plus delivery & dispensing
- R&D innovations are essential to reduce H_2 delivery & dispensing costs

HIGH-VOLUME

- Projected status based on large-scale deployments of a portfolio of H_2 production, delivery & dispensing options
- R&D of diverse, sustainable hydrogen production pathways remains vital

Continued R&D is needed to reduce H_2 production & delivery costs

H_2 Production from Diverse Domestic Resources



FOSSIL RESOURCES

- Low-cost, large scale H_2 production with CCUS options
- New options offer scalability and byproduct benefits (e.g. CHHP)

WASTE/BIOMASS

- Options included biogas reforming & fermentation of waste streams
- Byproduct benefits include clean water, electricity & chemicals

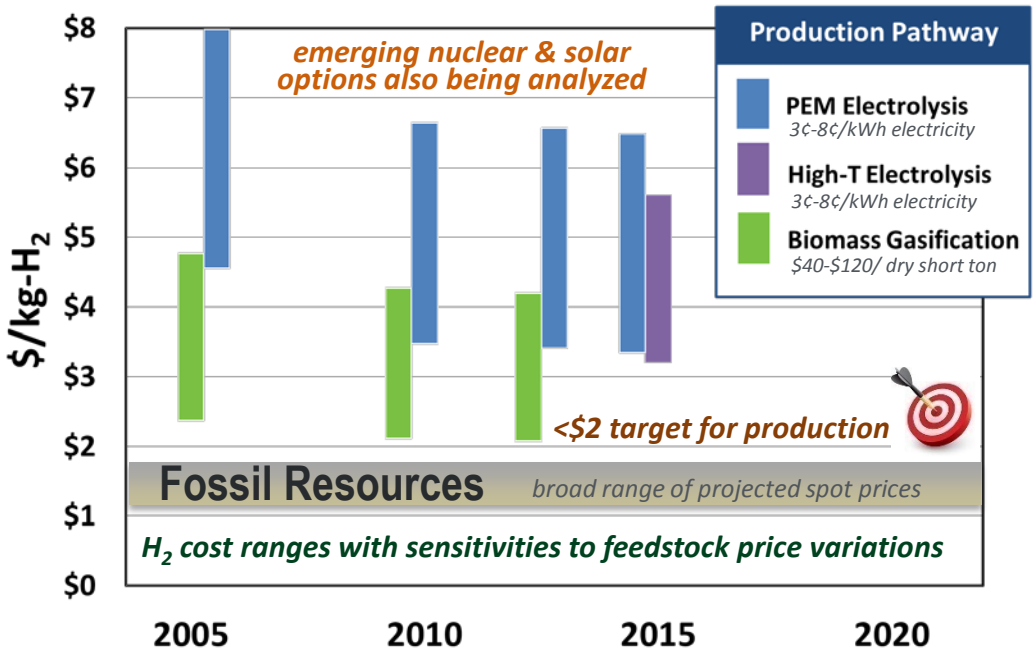
WATER SPLITTING

- Grid electrolysis is proven process being improved with innovation
- Emerging nuclear/solar options offer long-term sustainable H_2

A broad portfolio of near- to longer-term H_2 production technology options is being addressed through early-stage R&D

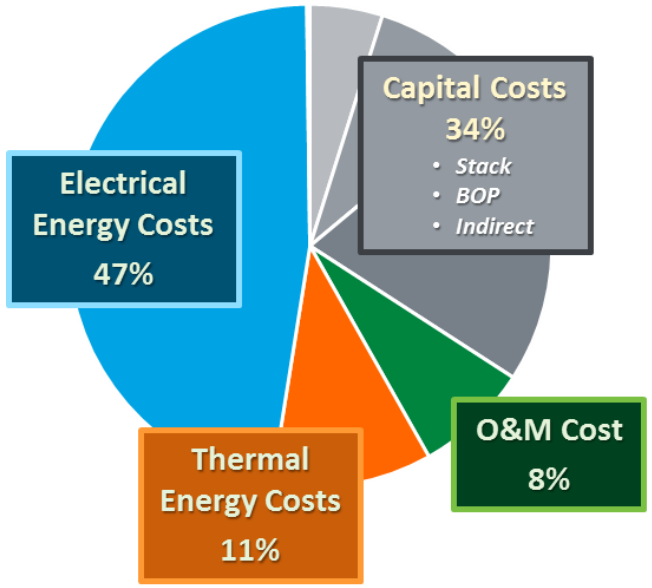
R&D Impact on H_2 Production Costs

Continued R&D needed to enable a broad portfolio of competitive options



Techno-economic analysis identifies key levers for reducing costs

High-T electrolysis example



Early-Stage Applied R&D:

- *Innovative Reactor Concepts*
- *Novel Devices & Components*
- *Materials Compatibility*

Foundational Research:

- *Breakthrough Materials: catalysts, separators, thermal & optical materials…*

Innovative applied & foundational R&D is addressing the cost-competitiveness of H_2 production from diverse, sustainable domestic resources

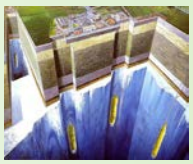
Hydrogen Delivery & Dispensing Options

Delivery from Central Facility

Terminal → Tube Trailer (up to 150 mi)

Liquefier → Terminal → Liquid Tanker (up to 300 mi)

long range → Pipeline → Pipeline



Alternative H_2 delivery approaches (e.g. advanced liquid carriers) are longer-term options

H_2 End Uses

Fueling Station/ Dispenser

Oil Refinery

Fueling Station Dispensing

Liquid Tanker → Liquid Storage → Pump/Evaporator

Pipeline → Low Pressure Storage

Tube Trailer → Compressor

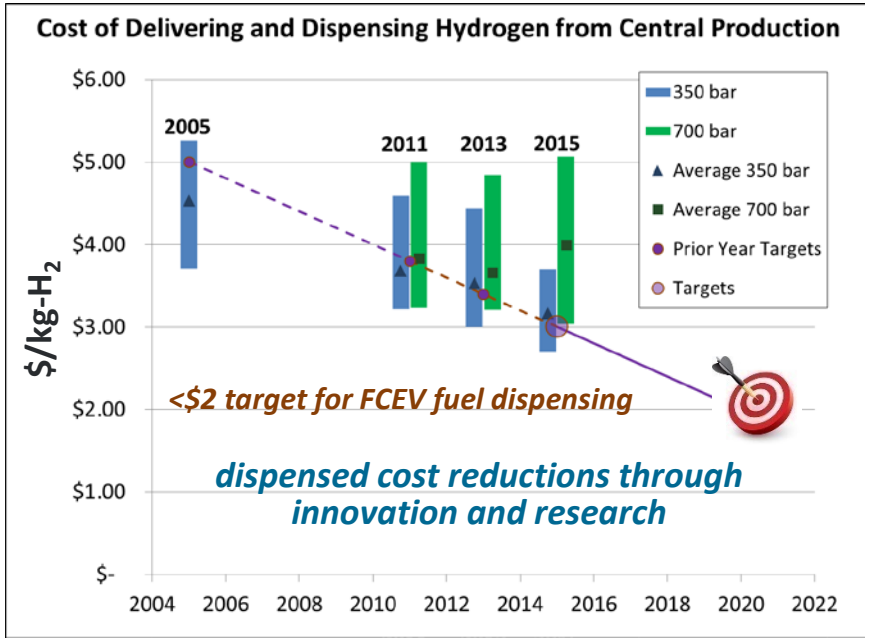
Cascade Storage
- High Pressure
- Med. Pressure
- Low Pressure

Fueling Station/ Dispenser

Continued research and development of affordable delivery & dispensing options are key to enabling large-scale benefits of hydrogen

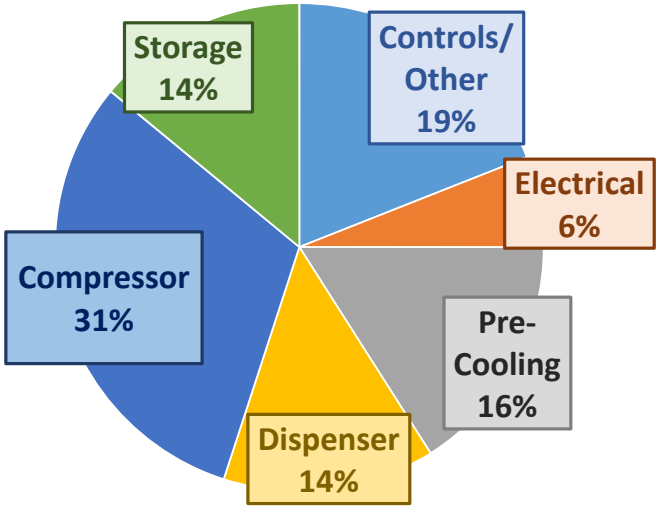
R&D Impact on H_2 Delivery & Dispensing Costs

R&D to enable affordable H_2 delivery and dispensing is a vital need



Techno-economic analysis quantifies delivery/dispensing cost drivers

Tube trailer delivery example



Early-Stage Applied R&D:

- *Gaseous & Liquid Delivery*
- *Compressors, Storage, Dispensers*
- *Materials Compatibility*

Foundational Research:

- *Breakthrough Materials: liquefaction, storage, pipeline & joining materials…*

Cost reductions through R&D are vital to H_2 market growth

R&D Strategies and Framework

Challenge

Sustainable Low-Cost H_2 Production & Delivery

- Materials issues
- Feedstock use
- Capital costs
- O&M costs

Strategies

Foundational and Applied Research

- Foundational R&D to enable broad hydrogen production options
- Applied R&D to enable delivery & dispensing at H_2 refueling stations

R&D Focus

Research Guided by Techno-economics

- Early-stage materials R&D addressing key challenges in energy conversion, catalysis, separations, hydrogen compatibility, etc.
- Leveraging research innovations in hybrid systems & BOP

Key Areas

Hydrogen Production

- Advanced water-splitting
- Waste & bio-conversion
- Nuclear/hybrid approaches

H_2 Delivery & Dispensing

- Non-mechanical compression
- Novel liquefaction concepts
- Liquid hydrogen carriers

R&D Support Framework:

- FCTO FOA & Lab Calls
- H2@Scale Ecosystem
- DOE MOUs: NSF & NIST
- SBIR/STTR
- Crosscuts: EMN/Grid…
- Prizes and Other

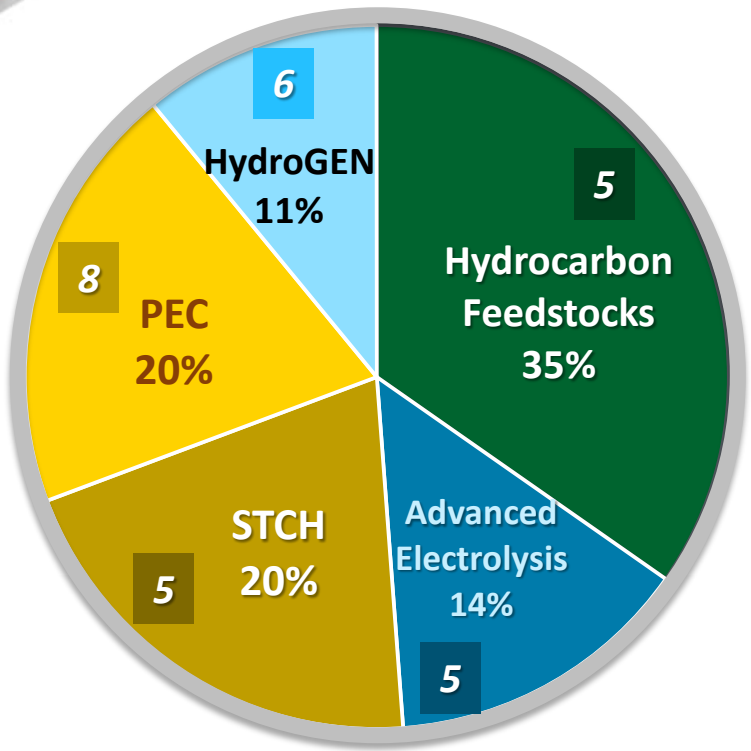
Leveraging resources to optimize research impact

Current R&D Portfolio Distribution

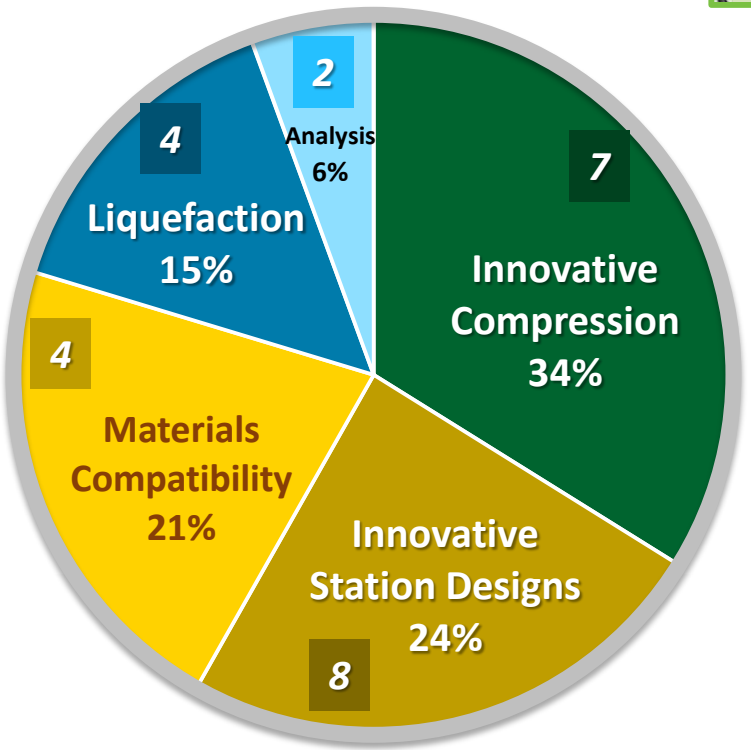
funding distribution in FOA, LAB, SBIR/STTR & joint NSF projects

including number of projects and % of portfolio funding

H_2 Production

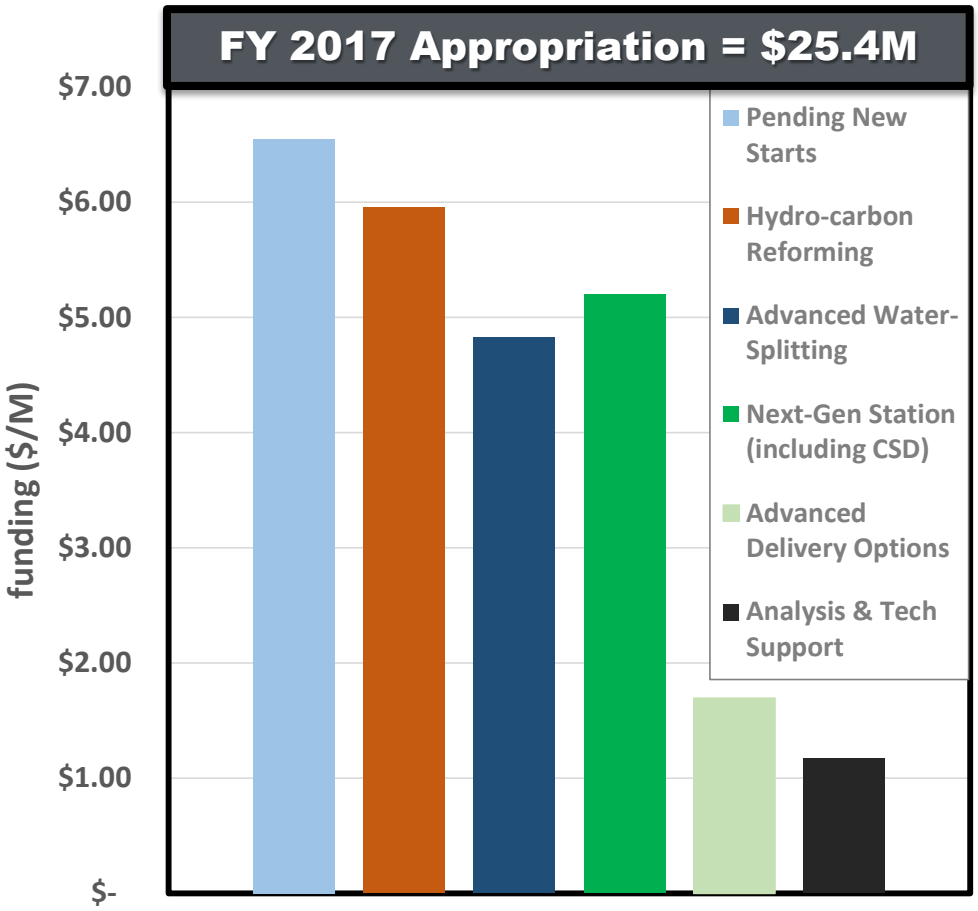


H_2 Delivery



Balanced portfolio addressing early-stage research challenges

H_2 Production & Delivery FY 2017 Budget



CURRENT EMPHASIS

- **Support R&D needs identified through the H2@Scale Initiative:**
  - *Early-stage R&D through the HydroGEN Advanced Water Splitting Materials EMN Consortium*
  - *Early-stage materials R&D essential to viable hydrogen delivery and dispensing technologies, including novel H_2 carrier options*
- **Continue leveraging cross-program, cross-office and cross-agency R&D opportunities and resources**

Continued leveraging of broad research resources is needed to support the diverse H_2 production & delivery portfolio

H_2 Production & Delivery Collaborations

INTERNATIONAL ACTIVITIES

Examples:

- IPHE
- Infrastructure Workshops
- IEA HIA TCPs

DOE/EERE FCTO

Hydrogen P&D Research

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

INDUSTRY

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

DOE CROSS-CUTS

- EMN initiative
- Grid cross-cut
- WBS institute

TECH VALIDATION

- Grid modernization
- Energy storage

INTRA- AND INTER-AGENCY COLLABORATIONS

H2@Scale	DOE EERE: *BETO, AMO, SETO*	DOE-Wide: *SC, NE, FE, ARPA-E*	Inter-Governmental *NSF, NIST, DOD, DOT*

DOE Office of Science H_2 Research

Tailoring Hydrogen Evolution Reaction (HER) Catalysts for Operation at Specific pH Values: **Bianca Ceballos, U. of California, Irvine**

poster *Wed.:1830* | **BESH2020** *Wed.: 1645*

Multiple Approaches to Photocatalytic Hydrogen Production using Photosystem I as a Light Harvesting Module: **Michael Gorka, Pennsylvania State U.**

poster *Wed.:1830* | **BESH2021** *Wed.: 1715*

Hybrid Perovskites and Non-adiabatic Dynamics Simulations: Catching Realistic Aspects of the Charge Recombination Process: **Joanna Jankowska, U. of Southern California**

BESH2022 *Wed.: 1745*

Nano-bio Systems for Light-Driven Hydrogen Production: **Kara Bren, University of Rochester**

BESH2023 *Th.: 1415*

Mechanistic Investigations on Hydrogen Catalysis by [FeFe]-Hydrogenase: **David Mulder, National Renewable Energy Laboratory**

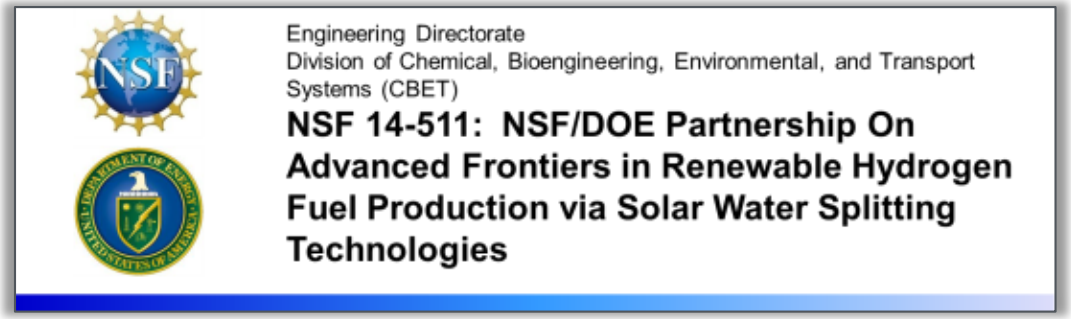
poster *Wed.:1830* | **BESH2024** *Th.: 1445*

Reversible Conversion between CO2/H2 and Formic Acid by Molecular Catalysts: **Etsuko Fujita, Brookhaven National Laboratory**

BESH2025 *Th.: 1515*

Special thanks to our BES guest presenters!

DOE / NSF Joint Projects in Water Splitting



New Metal Oxides for Efficient Hydrogen Production via Solar Water Splitting: **Balcheng Weng, U. of Toledo**

poster *Wed.:1830* **PD 118**

Accelerated Discovery of Advanced RedOx Materials for STWS to Produce Renewable Hydrogen: **Charles Musgrave, U. of Colorado Boulder**

poster *Wed.:1830* **PD120**

Engineering Surfaces, Interfaces, and Bulk Materials for Unassisted Solar Photoelectrochemical (PEC) Water Splitting: **Thomas Jaramillo, Stanford U.**

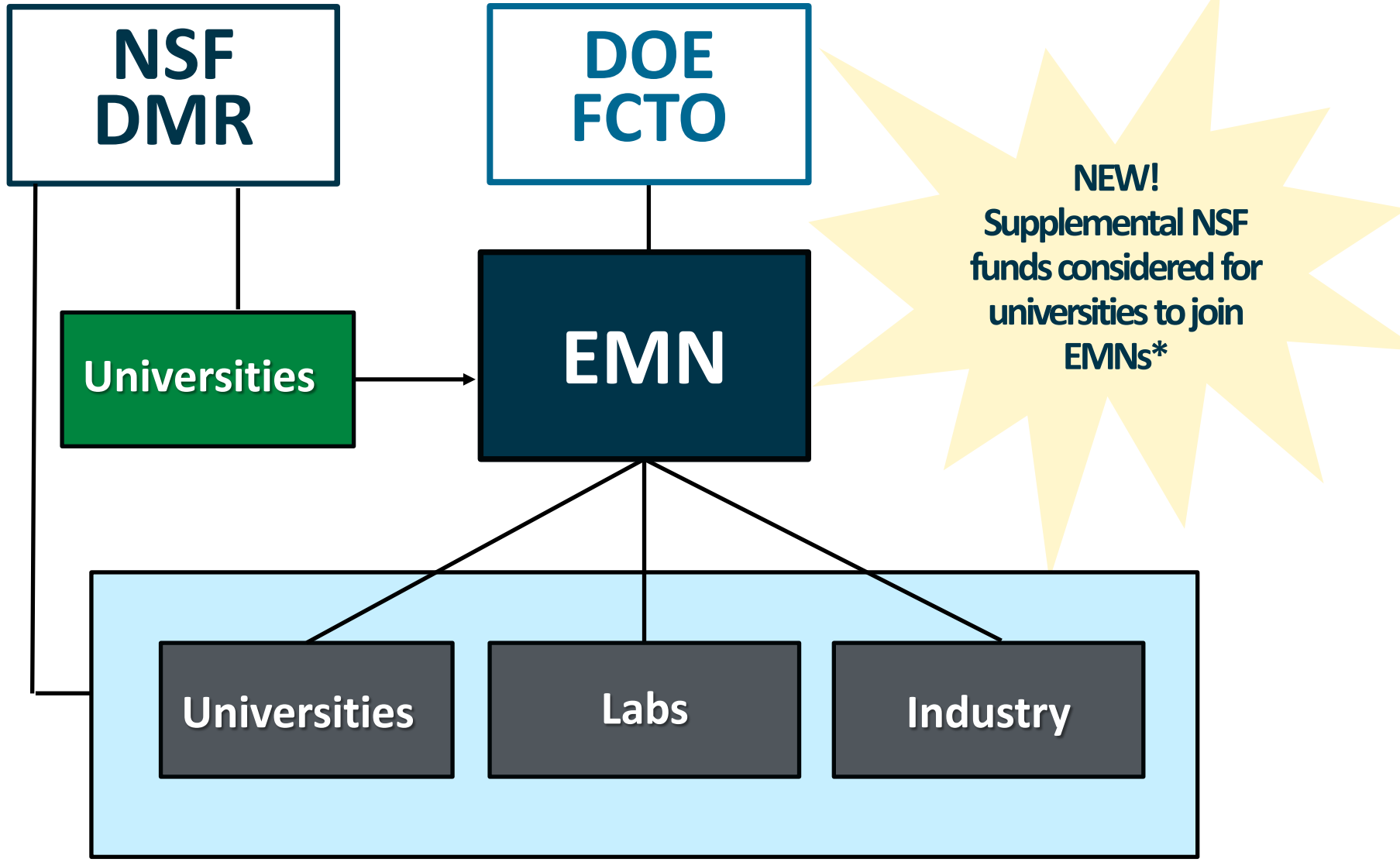
Poster *Wed.:1830* **PD119**

Tunable Photoanode-Photocathode-Catalyst Interface Systems for Efficient Solar Water Splitting: **G. Charles Dismukes, Rutgers U.**

Poster *Wed.:1830* **PD121**

Exploring new avenues of collaboration through EMNs

Leveraging Funding- Example Pilot



DMR- Division of Materials Research, NSF

FCTO- Fuel Cell Technologies Office, EERE, DOE

* Guidance to be provided by NSF DMR in upcoming 'Dear Colleague' communications

Accomplishment: H_2 Refuel H-Prize Award

H2refuel
U.S. Department of Energy

$1M Competition: On-site H_2 fueling

Winner Announced:
More at hydrogenprize.org

simple.fuel.™

H-Prize Authorized in Energy Independence and Security Act

System Details

- Hydrogen produced via **electrolysis**
- Refuels **1 kg H_2 in 15 mins** or less
- Refueling at **700 bar**

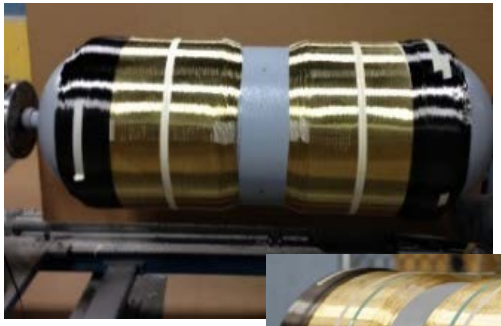
poster
Mon.: 1900

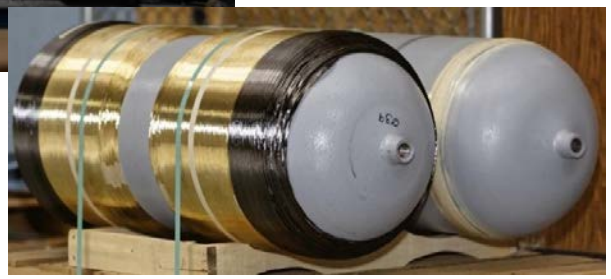
Accomplishment: Stationary Storage Innovation

WireTough develops innovative steel-wrap approach to low-cost 875 bar H_2 storage

Major Benefits

- The 875-bar H_2 storage vessels are expected to cost 30% less than 2011 baseline and *at least 50% less than currently on the market!*
- WireTough's vessel design certified compliant with ASME Boiler and Pressure Vessel (BPV) Code, Division 3 (adopted in all U.S. states)
- Additional benefit through the innovative research in basic science of hydrogen embrittlement





PD110
Tu.: 1100

Continuing Efforts

- Manufacturing a full-size, 34-kg prototype to demonstrate scalability and evaluate viability of approach
- Independent 3rd party verification of projected cost savings (SA Inc.)

High pressure stationary H_2 storage vessel with 50% cost savings

Accomplishment: Novel Pipeline Materials Enabled

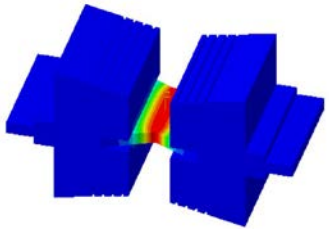
Cost Savings with FRP Pipelines

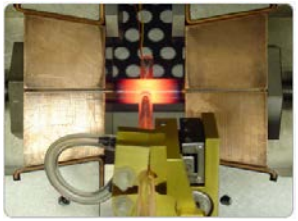
- Fiber reinforced polymer (FRP) pipelines projected to cost >25% less to install than steel
- Evaluation of mechanical properties concluded that FRP can be used for high-pressure hydrogen transmission. (SRNL, ORNL)
- ASME accepted FRP into B31.12 Hydrogen Piping and Pipelines Code
- *Ongoing work: Development of a durable joint (i.e. electrofusion coupler)*

MN015
Tu.: 0215

Reduced-Thickness Steel Pipelines

- Cost reduction estimated for X70 steel over X65 is ~20% for a 12” pipe
- Impact of steel strength on risk of embrittlement evaluated (SNL, NIST, ORNL)
- ASME B31.12 removed thickness penalties on X70 steels
- *Ongoing Work:*
  - *Evaluation of welds in modern steels*
  - *Development of strain-based, mechanistic models of H_2 embrittlement for specific steel microstructures*





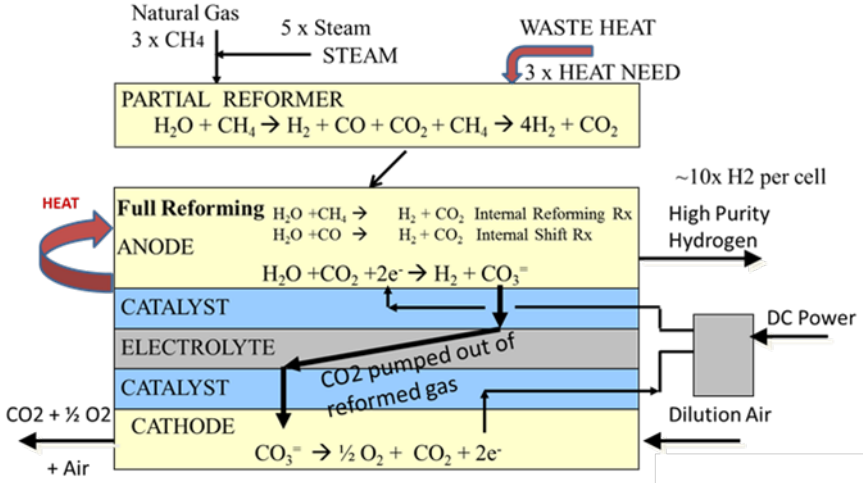
PD025
Tu.: 1130

Lab-led materials evaluation resulted in acceptance of FRP and high-strength steels by industry code committees.

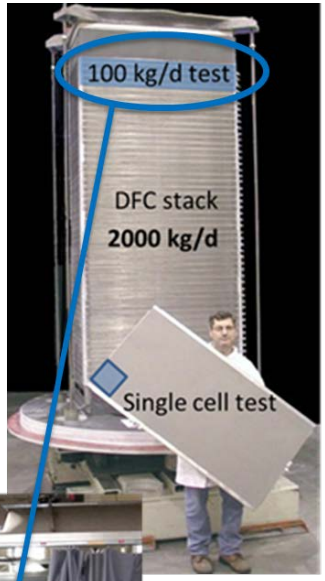
Accomplishment: Reformer-Electrolyzer-Purifier

Successful operation of molten-carbonate stack in reformer-electrolyzer-purifier (REP) mode

REP operational mode



	Target	Design	Test Results
Amps		1040	950 ✓
Volts/cell	<1.35	1.21	1.22 ✓
H2 Purity	>95%	97.4	97.5 ✓
Kwh/kg	<8	7.4	7.6 ✓
Kg/day	~100	123	110 ✓



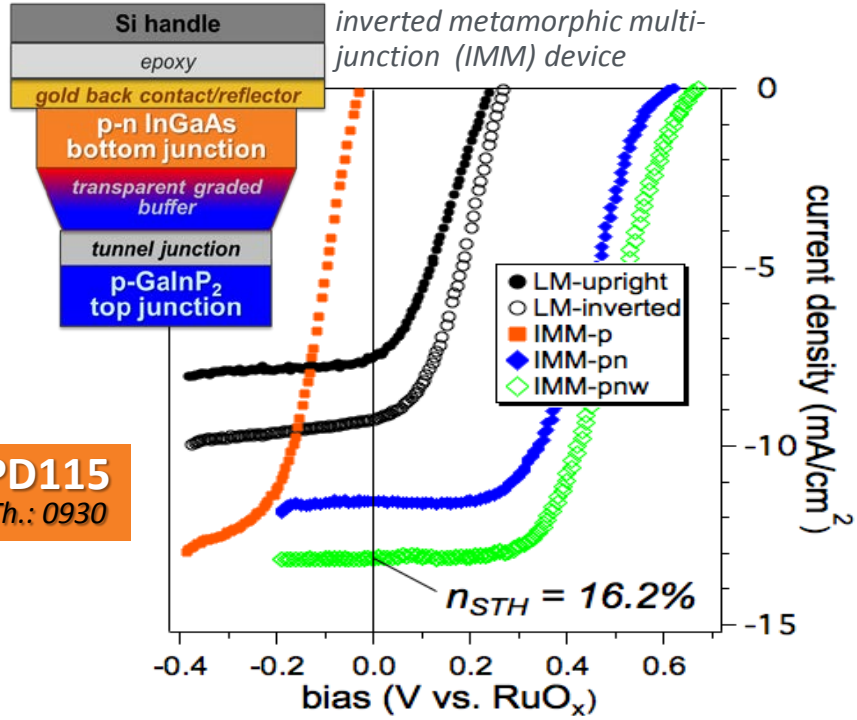
Achieved robust, cost-effective H_2 production from NG and electricity at 100 kg/ day

Potential for full scale system integration @ 2000 kg/day based on 100 kg/day results

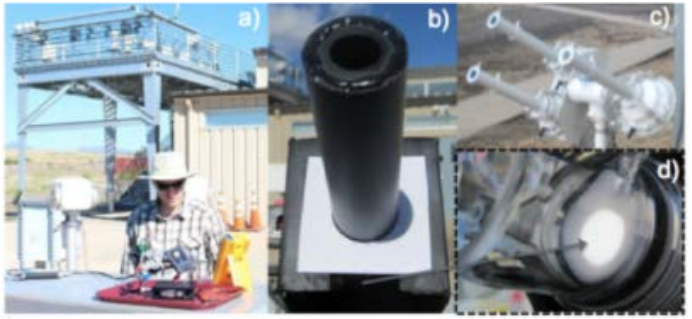
Innovative scalable reforming technology that could enable distributed/on-site hydrogen production for FCEV fueling stations

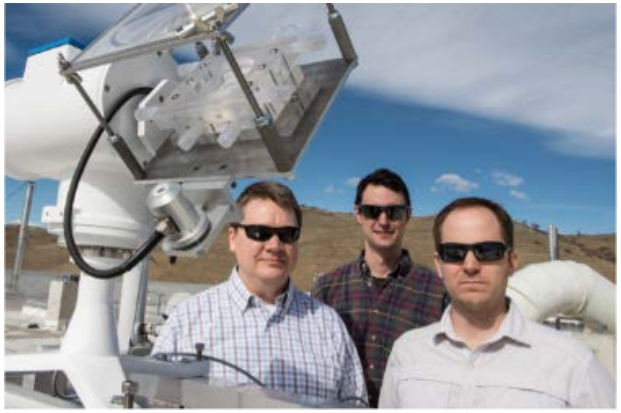
Accomplishment: New PEC World Record!

NREL surpasses its own old record using a novel tandem device configuration



PD115
Th.: 0930





Nature Energy 2, 17028 (2017)

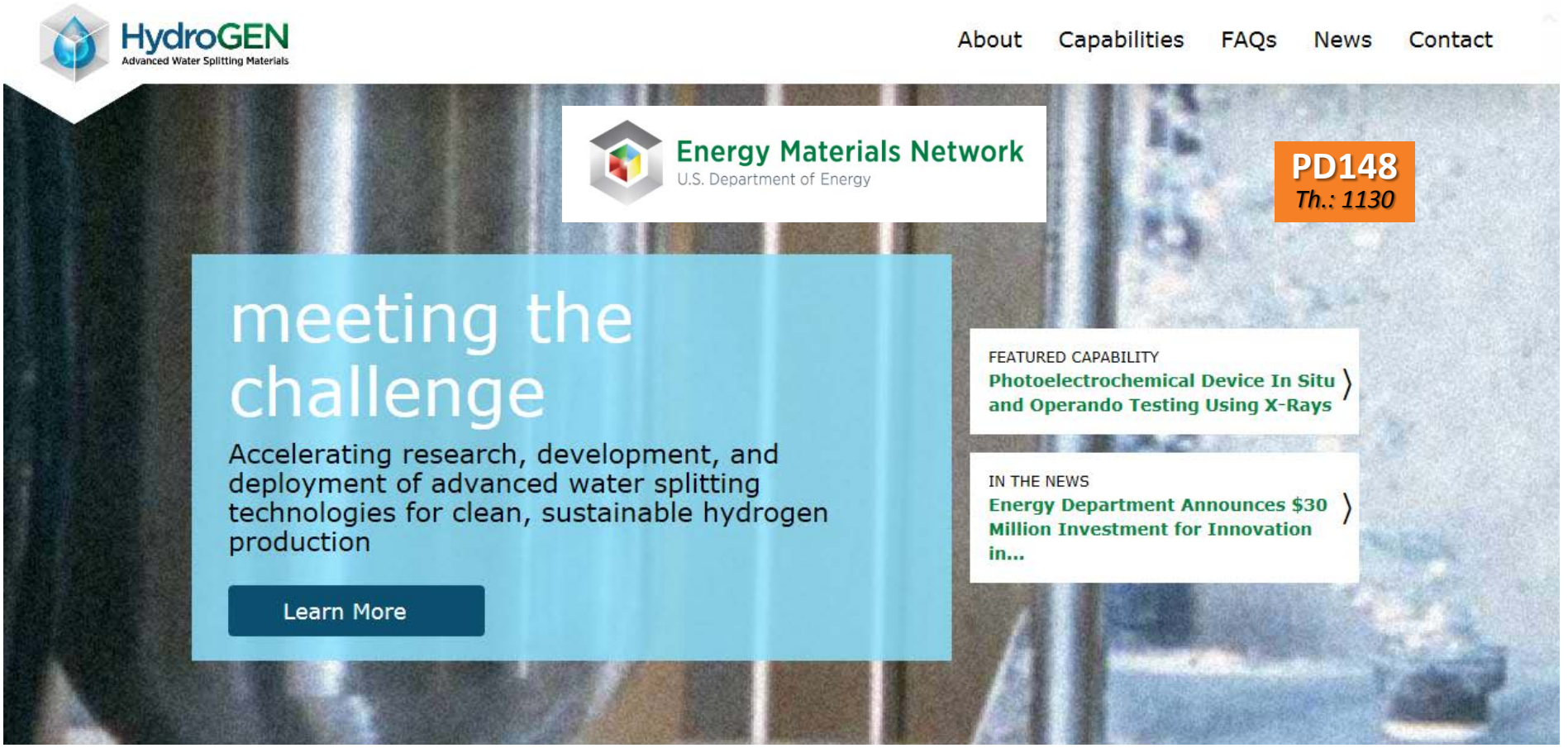
Direct solar-to-hydrogen conversion via inverted metamorphic multi-junction semiconductor architectures, J. L. Young, M. A. Steiner, H. Döscher, R. M. France, J. A. Turner, and T. G. Deutsch

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Innovations in materials synthesis & characterization led NREL researchers to a new record solar-to-hydrogen conversion efficiency of 16.2%

Accomplishment: HydroGEN Consortium Launch

From drawing-board to full consortium deployment in 6 months!



Visit the HydroGEN website at https://www.h2awsm.org

HydroGEN: Advanced Water-Splitting Materials

HydroGEN
Advanced Water Splitting Materials
Core Labs

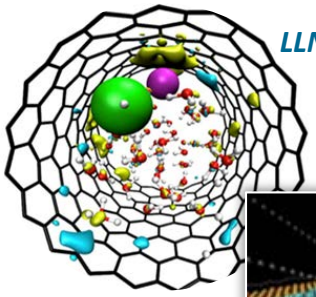
NREL · Berkeley Lab · Sandia National Laboratories · INL Idaho National Laboratory · Lawrence Livermore National Laboratory · SRNL

Accelerating the discovery & development of innovative materials critical to advanced technologies for sustainable H_2 production, including:

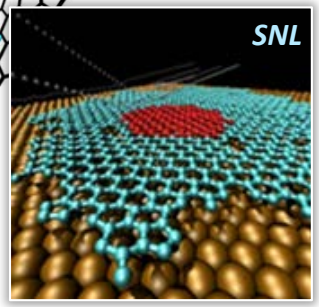
- ***Advanced high- and low-temperature electrochemical conversion***
- ***Direct photoelectrochemical solar water splitting***
- ***Direct solar thermochemical water splitting***

➢ **Comprising more that 80 unique, world-class capabilities/expertise in materials theory/computation, synthesis, characterization & analysis:**

Materials Theory/Computation

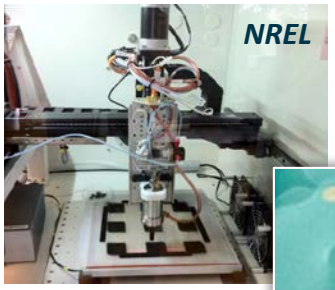


Bulk & interfacial models of aqueous electrolytes

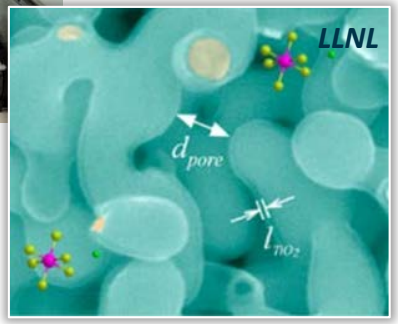


LAMMPS classic molecular dynamics modeling relevant to H_2O splitting

Advanced Materials Synthesis



High-throughput spray pyrolysis system for electrode fabrication



Conformal ultrathin TiO_2 ALD coating on bulk nanoporous gold

Characterization & Analytics

Stagnation flow reactor to evaluate kinetics of redox material at high-T

TAP reactor for extracting quantitative kinetic data

HydroGEN fosters cross-cutting innovation using theory-guided applied materials R&D to advance all emerging water-splitting pathways for hydrogen production

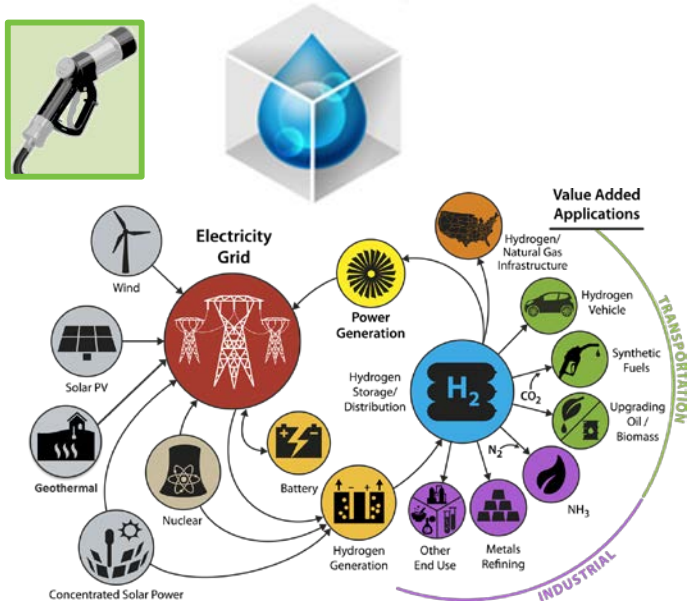
H_2 Production & Delivery Summary

Recent Activities and Milestones

- HydroGen Advanced Water Splitting Materials consortium established, supporting H2@Scale
- Demonstration of 100 kg/d H_2 production in novel, scalable reforming technology
- New world record established for photoelectrochemical hydrogen production
- New projects in high-temperature electrolysis and advanced compression
- Cross-office collaborations with *EMN, PowerAmerica, Grid Integration, Solar Fuels*
- Webinars on topics including *Grid Integration of Fuel Cell and Electrolyzer Technologies*
- Workshops, including *Power Electronics for Fuel Cells and Electrolyzer Technologies*

Ongoing Focus Areas

- Foundational R&D supporting H2@Scale needs
- Early-stage R&D through the HydroGEN Advanced Water Splitting Materials Consortium
- Early-stage materials R&D essential to viable hydrogen delivery and dispensing technologies
- Continue leveraging cross-office and cross-agency R&D opportunities and resources



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

James Vickers
(202) 586-1758
james.Vickers@ee.doe.gov

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

Neha Rustagi
(202) 586-8424
neha.rustagi@ee.doe.gov

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

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

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

thanks also to Richard Farmer for his support of the Team