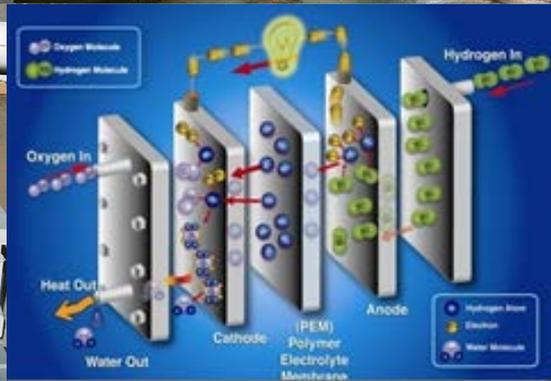


U.S. Department of Energy Fuel Cell Technologies Office Program Overview

U.S. DEPARTMENT OF
ENERGY | Energy Efficiency &
Renewable Energy



Hydrogen and Fuel Cell Technical
Advisory Committee
Washington, DC

November 18, 2014

Dr. Sunita Satyapal

U.S. Department of Energy
Fuel Cell Technologies Office
Program Director

- **HTAC Charter & Membership**
- **Program Overview**
 - **Budget & Organization**
- **HTAC Recommendations**
 - **Key Accomplishments & Program Responses**
- **National Lab Impact Initiative and Next Steps**

Academia

- Anthony Eggert, UC-Davis
- Dr. Timothy Lipman, UC-Berkeley
- Dr. Joan Ogden, UC-Davis
- Dr. Levi Thompson, U. of Michigan

Associations/Non-Profits

- **Catherine Dunwoody, California Fuel Cell Partnership → CARB**
- **Dr. Kathryn Clay, American Gas Association**
- Robert Rose, Fuel Cell and Hydrogen Energy Association → BTI

Environmental

- **Margo Oge, Environmental Protection Agency (ret'd)**

Fuels Production

- John Hofmeister, Shell Oil Company (ret'd)

Government

- Dr. Peter Bond, Brookhaven National Laboratory
- Dr. Richard Carlin, Office of Naval Research
- Maurice Kaya, State of Hawaii (ret'd)
- **Commisioner Janea Scott, California Energy Commission**

Stationary Power

- Harol Koyama, H2 PowerTech

Transportation

- Charles Freese, GM
- Dr. Alan Lloyd, ICCT (ret'd)

Utilities (Electricity & Natural Gas)

- Frank Novachek, Xcel Energy

Venture Capital

- **Paul Leggett, Morgan Stanley → Mithril Capital**
- Robert Shaw, Aretê Corporation

To advise the Secretary of Energy on:

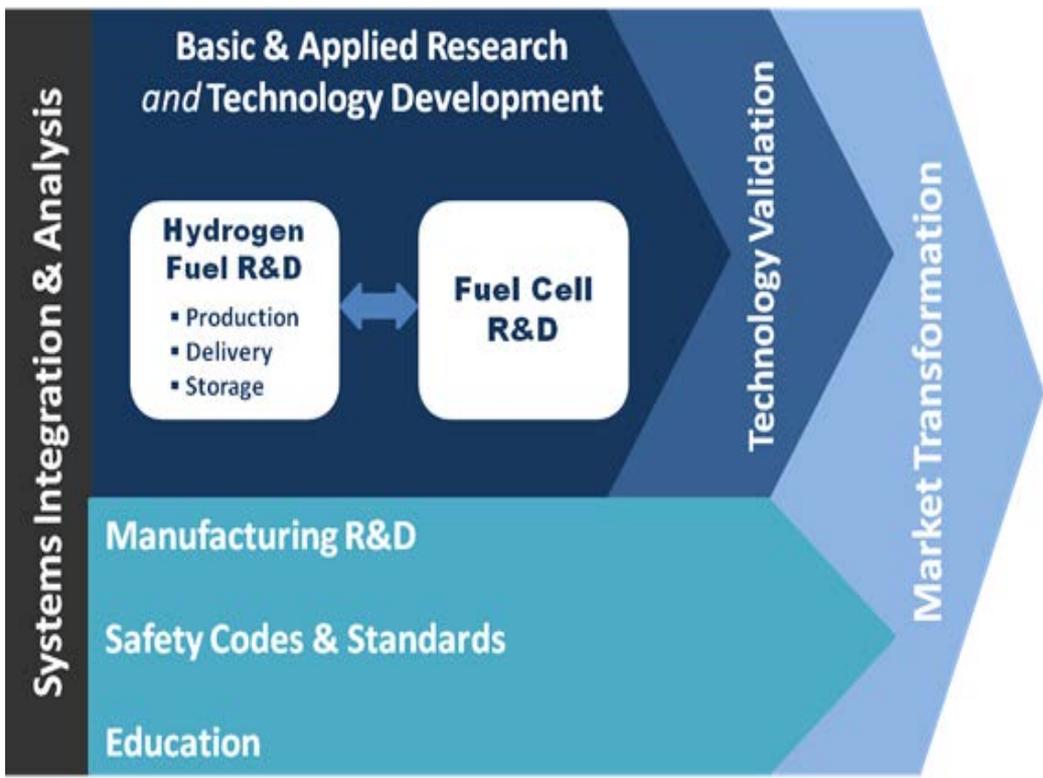
- 1. The implementation of programs and activities under Title VIII of EPACK**
- 2. The safety, economical, and environmental consequences of technologies to produce, distribute, deliver, store or use hydrogen energy and fuel cells**
- 3. The DOE Hydrogen & Fuel Cells Program Plan**

“The purposes of this title are—

- 1) to enable and promote comprehensive development, demonstration, and commercialization of hydrogen and fuel cell technology in partnership with industry;**
- 2) to make critical public investments in building strong links to private industry, institutions of higher education, National Laboratories, and research institutions to expand innovation and industrial growth;**
- 3) to build a mature hydrogen economy that creates fuel diversity in the massive transportation sector of the United States;**
- 4) to sharply decrease the dependency of the United States on imported oil, eliminate most emissions from the transportation sector, and greatly enhance our energy security; and**
- 5) to create, strengthen, and protect a sustainable national energy economy. ”**

DOE Hydrogen and Fuel Cells Program Areas and Targets

Mission: Enable widespread commercialization of a portfolio of H₂ and fuel cell technologies through basic and applied research, technology development and demonstration.

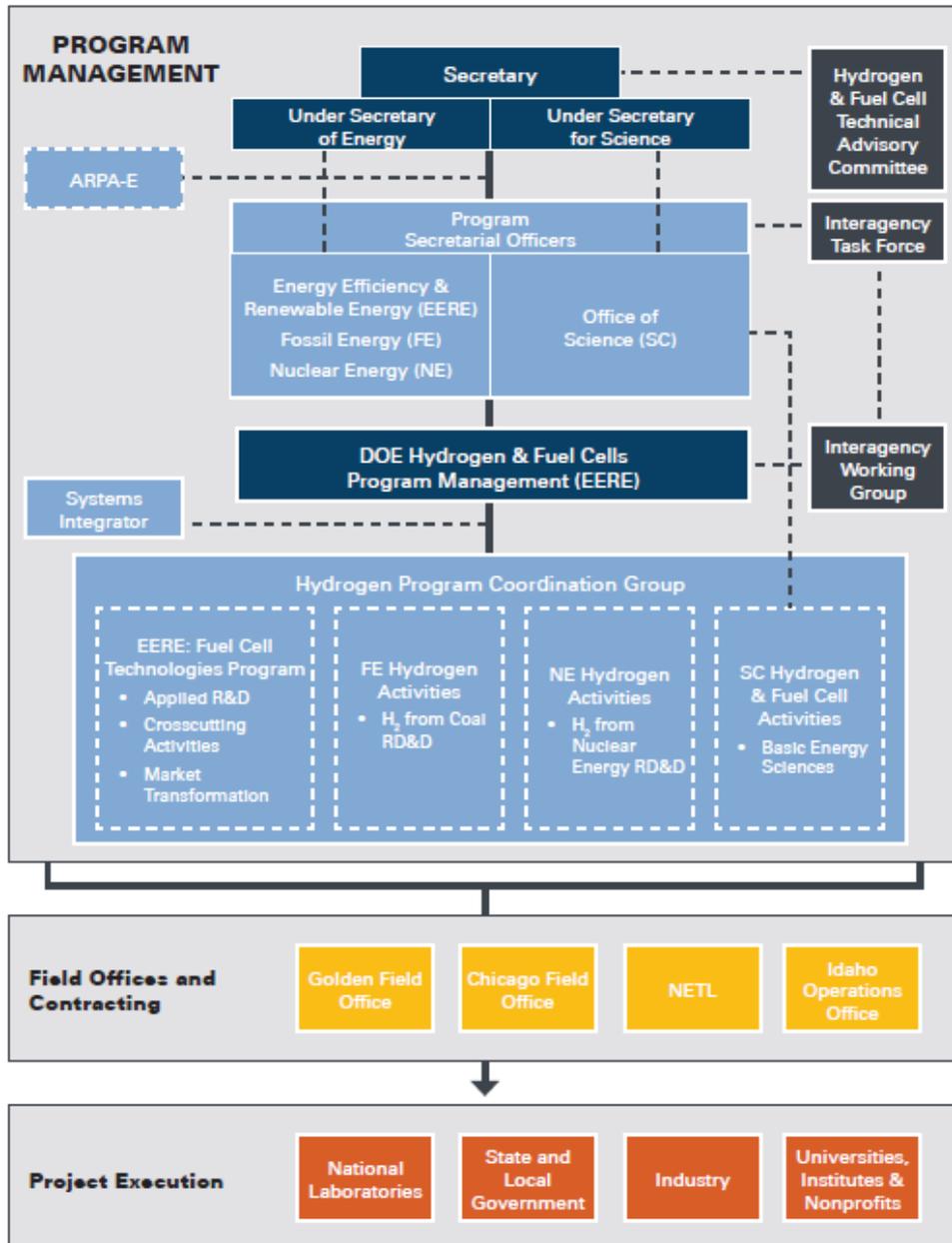


Fuel Cell Cost	\$40/kW	\$1,000/kW* \$1,500/kW**
Durability	5,000 hrs	80,000 hrs
H ₂ Storage Cost (On-Board)	\$10/kWh	
H ₂ Cost at pump	<\$4/gge	

*For Natural Gas
 **For Biogas

The Program includes a comprehensive portfolio of activities to address the purposes in EPACT 2005 Title VIII.

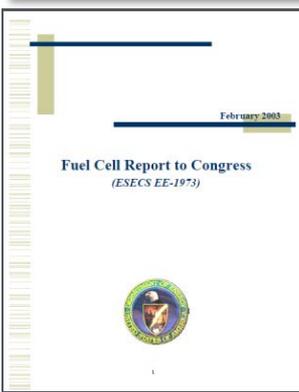
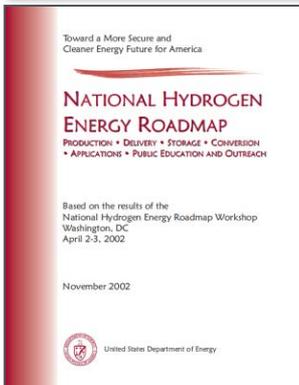
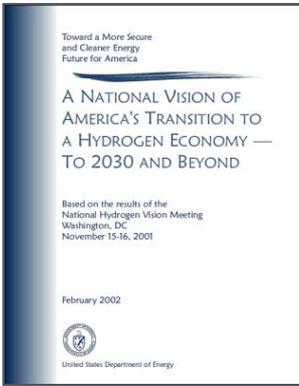
Overall Hydrogen and Fuel Cells Program Organization



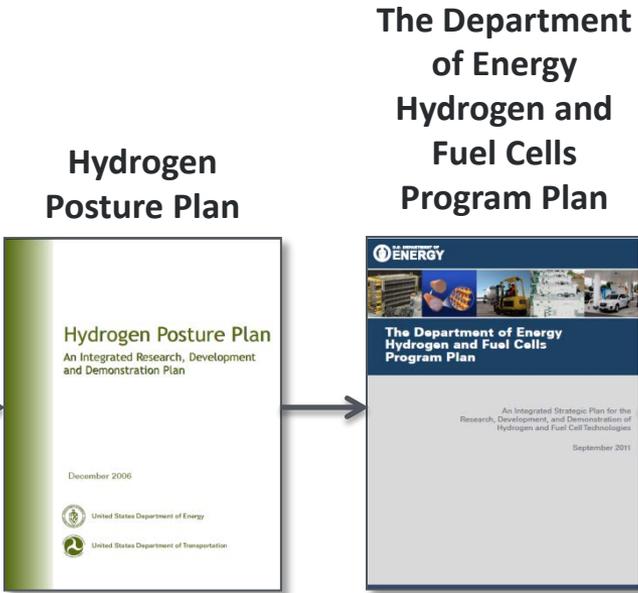
History:

- Hydrogen Program (renamed Hydrogen and Fuel Cells Program in FY10) includes EERE, FE, NE and SC
- EERE is lead for overall Program (since 2004)
- Program conducts monthly coordination working group meetings across EERE, FE, NE, and SC, and has an integrated strategic plan (Program Plan)
- Each office has its own multiyear RD&D plan

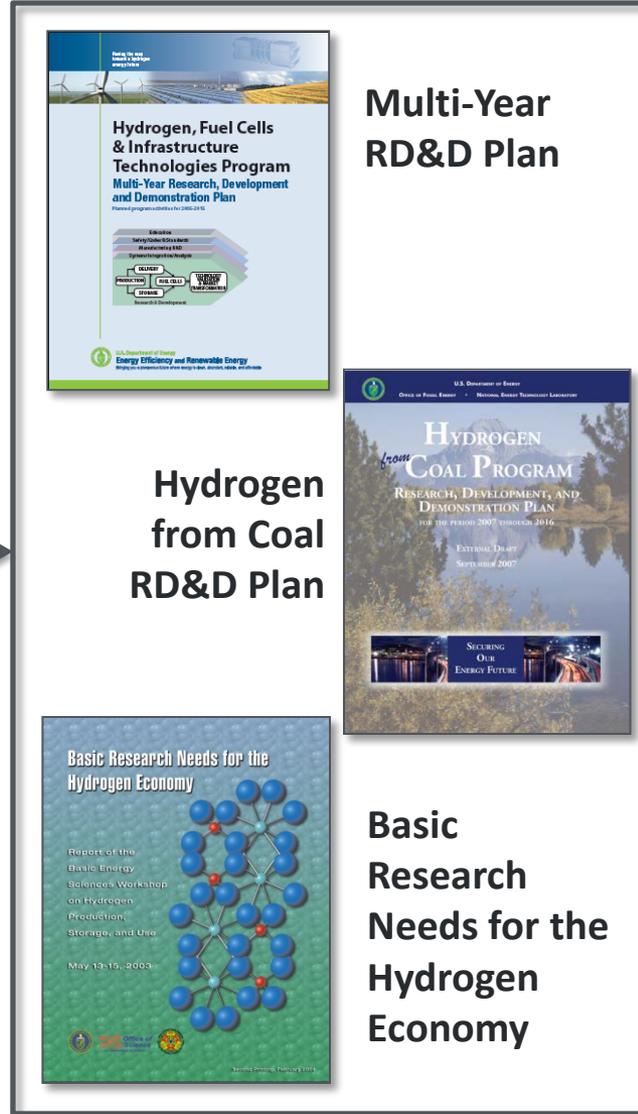
Stakeholder input



Strategy



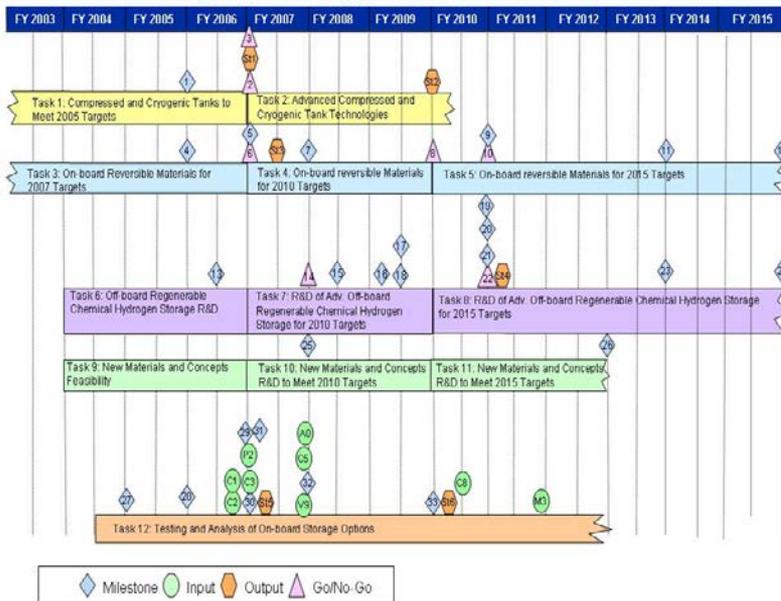
Planning



Subprogram Milestones and Targets - Examples

Each subprogram has detailed milestones, inputs, outputs, go-no go decision points and technical targets

Hydrogen Storage R&D Milestone Chart



Update of Multiyear RD&D Plan in process

Example- Target Table for Electrocatalysts

Electrocatalysts for Transportation Applications	Status ^a	Targets ^b
	2011	2017
Platinum group metal (PGM) total content (both electrodes)	0.19 g/kW	0.125 g/kW
PGM Total Loading	0.15 mg/cm ²	0.125 mg/cm ²
Loss in catalytic (mass) activity ^c	<40%	<40% loss of initial
Catalyst support loss ^d	<10% mass loss	< 10% mass loss
Mass activity ^e	0.24 A/mg Pt in MEA >0.44 A/mg Pt new alloy in RDE	0.44 A/mg PGM
Activity per volume of supported catalyst (non-PGM) ^f	60 A/cm ³ (measured) 160 A/cm ³ (extrapolated)	>300 A/cm ³

^a single cell status – will require scale-up

^b preliminary targets – approval pending

^c after 30,000 cycles from 0.6 – 1.0 V;

^d after 400 hours at 1.2 V

^e baseline @ 900mV_{IR-free}

^f baseline @ 800mV_{IR-free}

H = High (significant challenge)	M = Medium
M/H = Medium/High	L = Low (minimal challenge)

Collaborations and Partnerships

R&D

Demonstration & Deployment

Accelerated Commercialization



- Pre-Competitive R&D
- USCAR, energy companies, EPRI and utilities



- State Partnership and Collaboration



- International Government Coordination
- 17 countries and European Commission



- Implementing Agreements
- 25 countries



- National lab (SNL & NREL) led activities with industry



- Public-Private Partnership
- ~30 partners

In addition to above partnerships, advice & peer review provided by Federal Advisory Committee (HTAC), NAS, GAO, IG, AMR

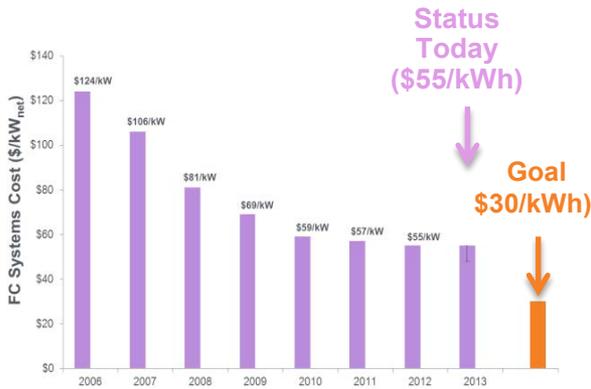
- **Stronger commitment to R&D to ensure U.S. technology leadership.**
- **Direct investment in hydrogen infrastructure as part of a integrated strategy or comprehensive National Energy Policy to accelerate deployment and attract private investment.**
- **Collaboration with infrastructure initiatives in Germany, Japan, Korea, and the UK on technical and regulatory issues to reduce cost and accelerate deployment.**
- **Emphatic public support for FCEV deployment to inspire confidence and increase public awareness.**

DOE Activities Span from R&D to Deployment

Research & Development

- **50% reduction since 2006**
- **80% electrolyzer cost reduction since 2002**

Fuel Cell System Cost*



*At 500,000-unit production

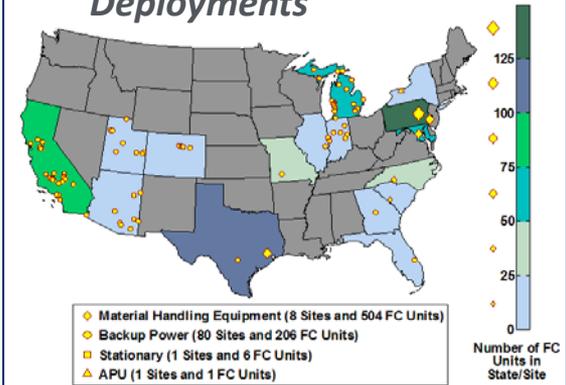
Demonstration

- **>180 FCEVs**
- **25 stations**
- **3.6 million miles traveled**
- **World's first tri-gen station**
 (250 kW on biogas,
 100 kg/d H₂ produced)



Deployment

- **Government Early Adoption**
 (DoD, FAA, California, etc.)
- **Tax Credits: 1603, 48C**
- **~1,600 fuel cells deployed**
- **DOE Recovery Act & Market Transformation Deployments**



DOE's RDD&D activities are enabling commercialization of fuel cells

Key Activity	FY 2014 (\$ in thousands)		FY 2015 (\$ in thousands)
	Request	Approp.	Request
Fuel Cell R&D	37,500	32,422	33,000
Hydrogen Fuel R&D	38,500	34,467	36,283
Manufacturing R&D	4,000	2,879	3,000
Systems Analysis	3,000	3,000	3,000
Technology Validation	6,000	6,000	6,000
Safety, Codes and Standards	7,000	6,909	7,000
Market Transformation	3,000	2,841	3,000
NREL Site-wide Facilities Support	1,000	1,000	1,700
SBIR/STTR	-----	3,410	TBD
Total	\$100,000	\$92,928	\$92,983

Office	FY 2014
EERE	\$93M
Basic Science ²	\$20M to \$25M
Fossil Energy, SECA	\$25M
ARPA-E ³	\$33M

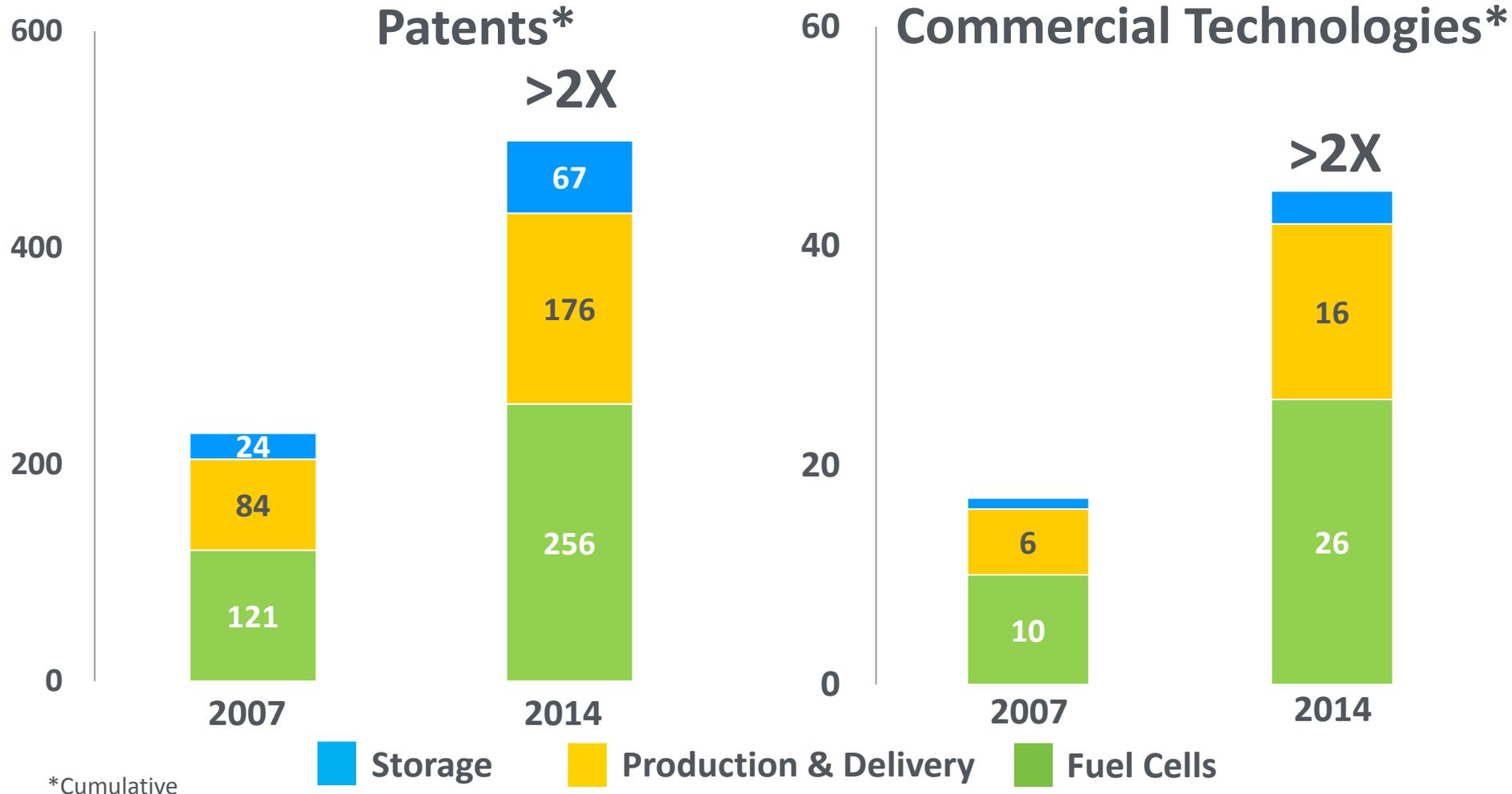
FY14 DOE Total: ~\$175M

Consistent R&D funding request and appropriations in recent years

Hydrogen and Fuel Cell Summary

FY15 Senate and House Language

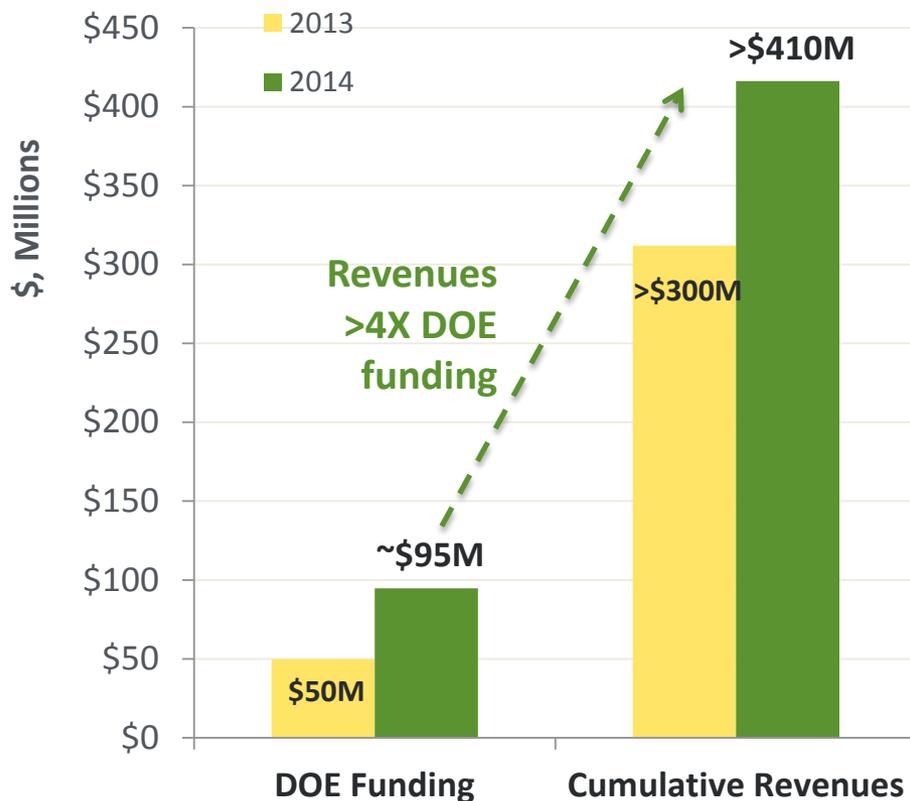
SENATE	HOUSE
Total recommendation: \$93,000,000	Total recommendation: \$100,000,000
<ul style="list-style-type: none"> • DOE should analyze, research and make suitable investments in order to transform the size, cost, scalability (including modular stations), and interoperability of new retail hydrogen stations. • DOE should focus on consumer acceptance and strategic locations. 	<p>Technology Validation:</p> <ul style="list-style-type: none"> • \$5,000,000 of funding above the request is for testing and analysis of fuel cells as industrial-scale energy storage devices, with validation and testing using full-scale testing and demonstration capabilities. • Recommends that DOE leverage national laboratory, university, and regional stakeholder partnerships and capabilities, including at-scale grid infrastructure, modeling expertise, extreme environment testing capabilities, and public-private partnerships.
<p>No specific direction on allocation of \$93M (consistent with request).</p>	<p>Advanced demonstration and deployment:</p> <ul style="list-style-type: none"> • \$2,017,000 above the request is for demonstration and deployment activities that validate commercial viability, including material handling equipment, ground support equipment, refrigerated trucks, auxiliary power units, and associated hydrogen infrastructure.
<p>H2USA: Committee is encouraged by the collaborative approach reflected in H2USA.</p>	<p>No direction.</p>



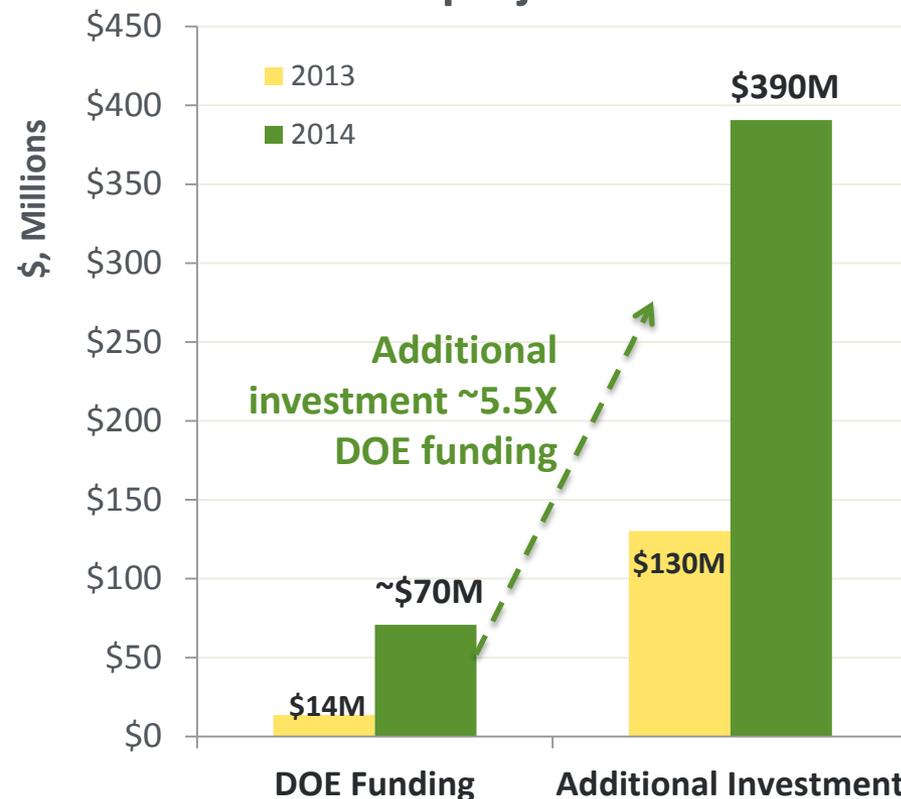
DOE funding has led to ~500 patents and 45 commercial technologies

“Tech to Market” Assessing the Impact of DOE Funding

Example: Revenues resulting from DOE funded projects*



Example: Private investment resulting from DOE funded projects*

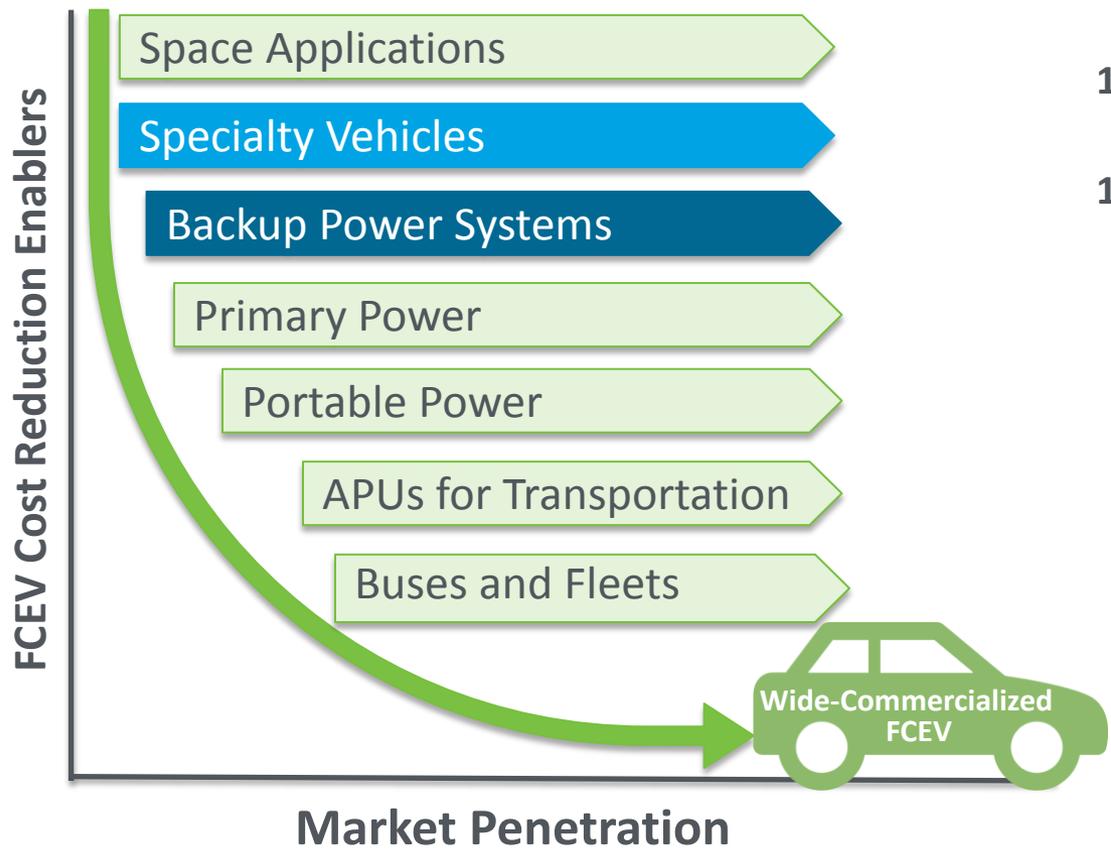


Revenues include estimates based off number of units sold.

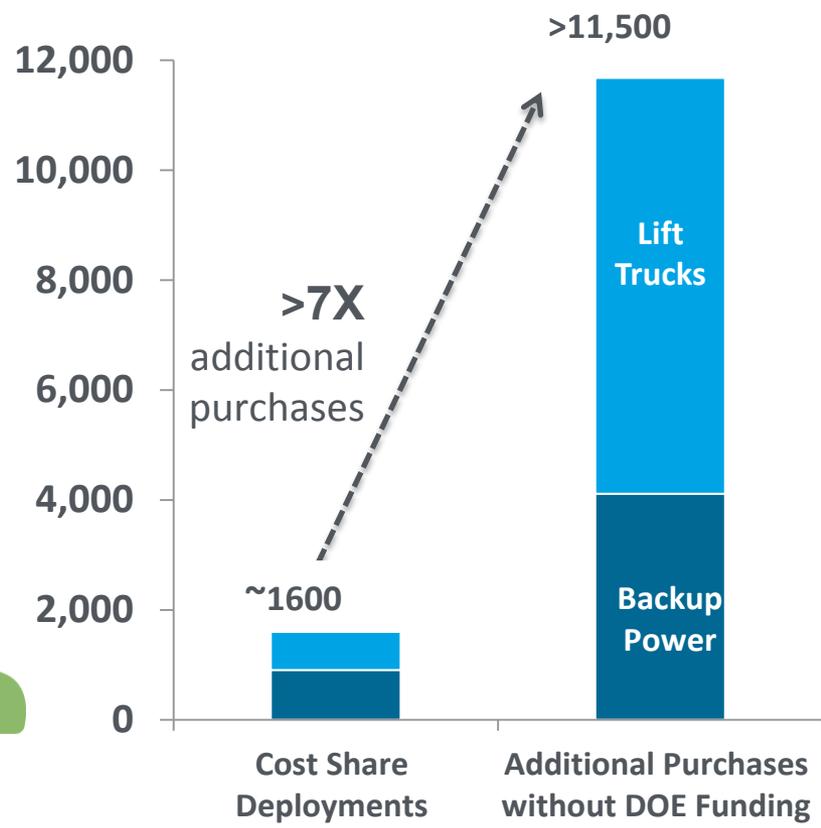
*July 2014 rev.

Revenues and additional investment valued at >4X and >5X the DOE investment.

FCEV Commercialization Strategy



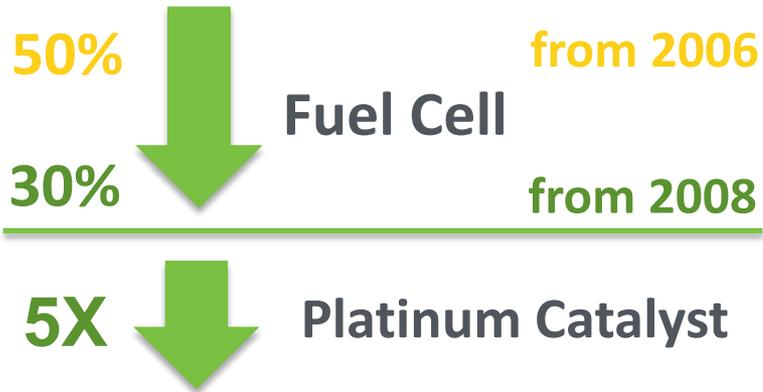
DOE Cost-Shared Deployments and Additional Purchases



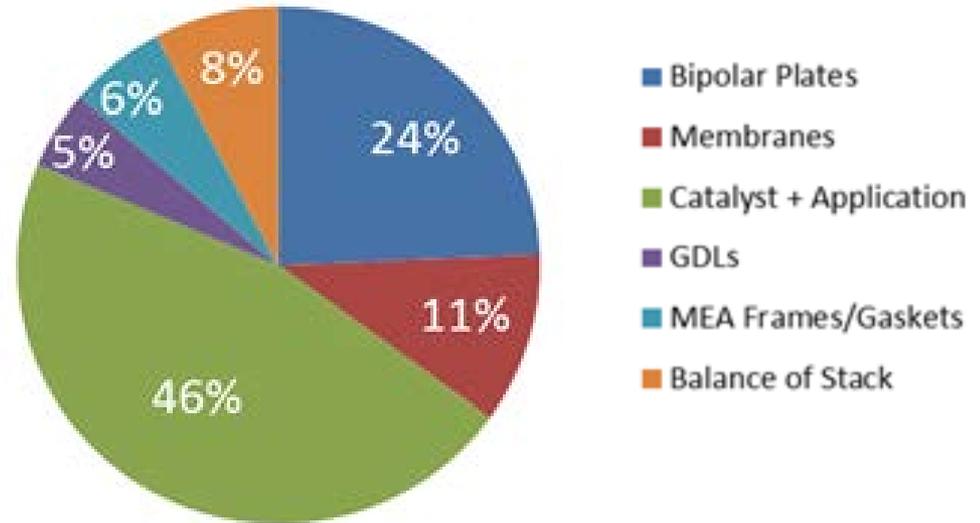
Catalyzing early markets enables broader commercialization of FCEVs

Fuel Cell Cost Reductions Enabled by R&D

Fuel Cell Cost Reductions



Fuel Cell System Cost* Cost Breakdown



Catalyst accounts for **>45%** of total system cost

Fuel Cell Cost Status and Goal

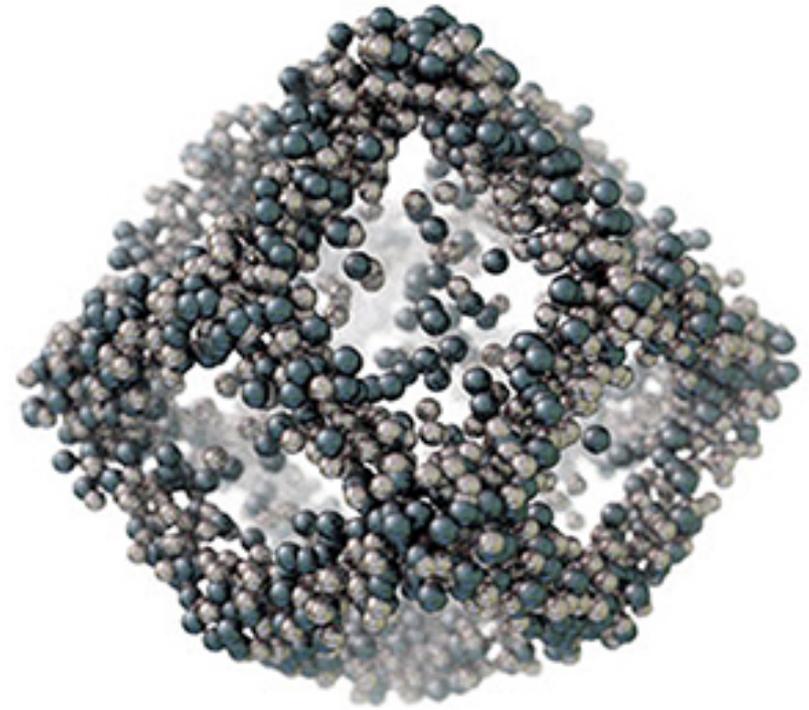
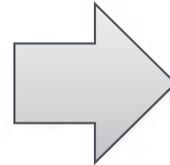
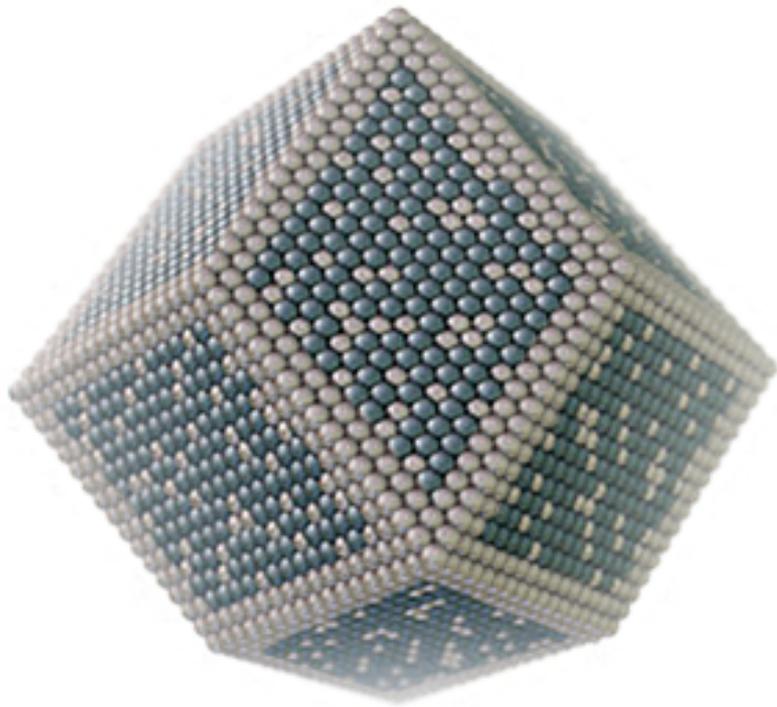
- **\$55/kW*** for high volume
- **~\$280/kW[†]** for low volume
- **\$40/kW** by **2020** is the goal

*For PEMFC Stack cost, 500,000 units per yr.
 Cost is shown as \$/kW-net.

[†]SA, bottom-up analysis of model system manufacturing cost, 500,000 sys/year with next-gen lab technology.
[†]ORNL, top-down analysis based on OEM input, 20,000 sys/yr. with current technology.

Catalyst remains key challenge and opportunity to lower cost

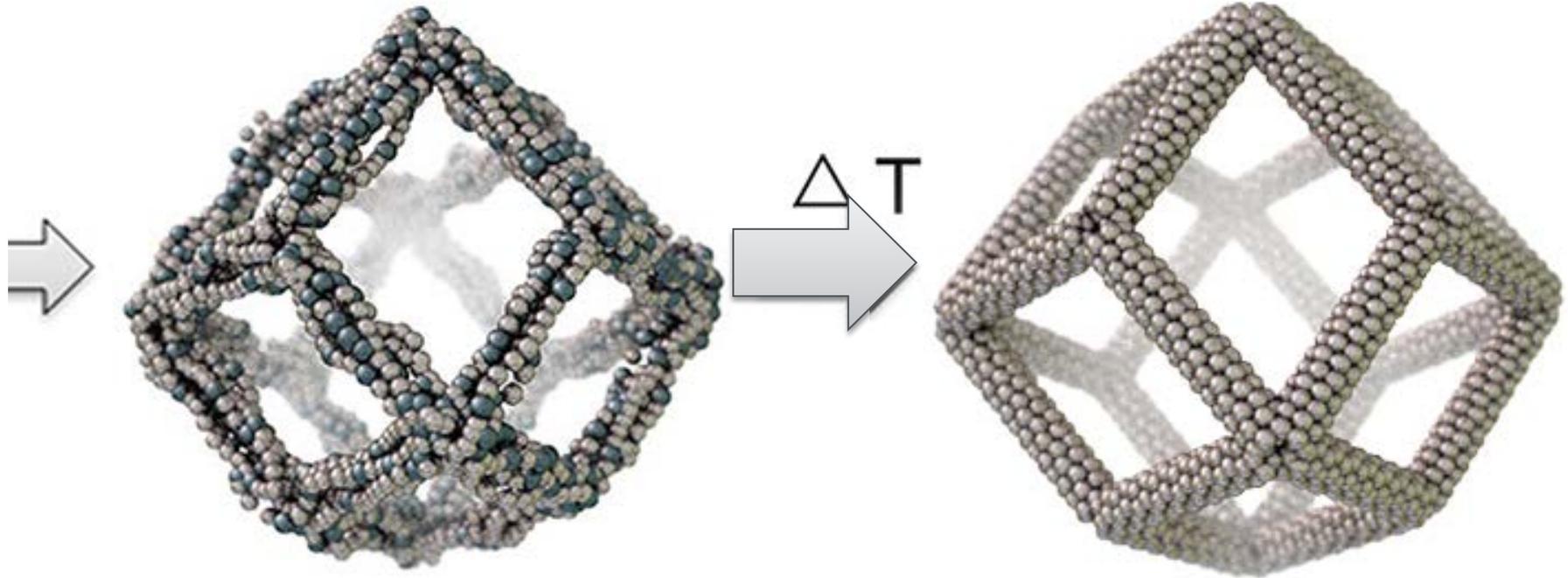
A PtNi₃ Polyhedra **B** PtNi Intermediates



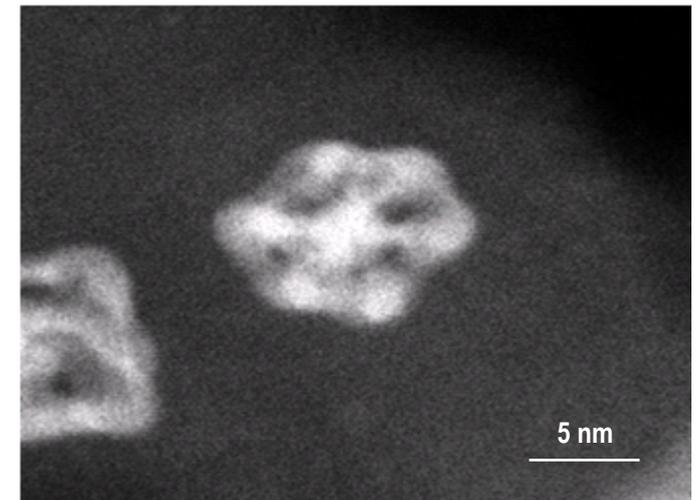
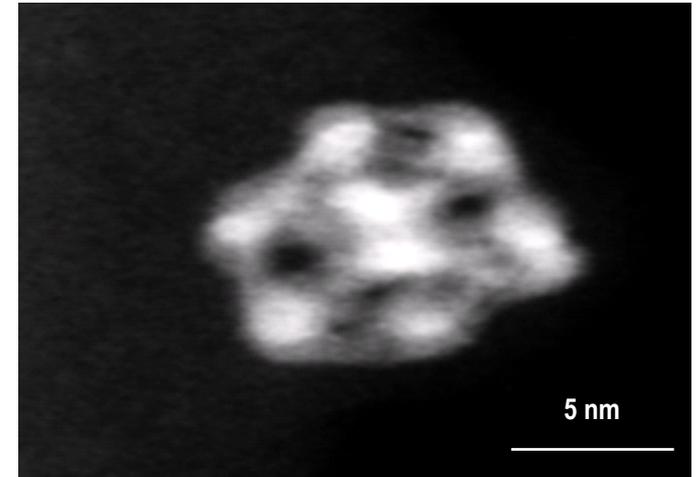
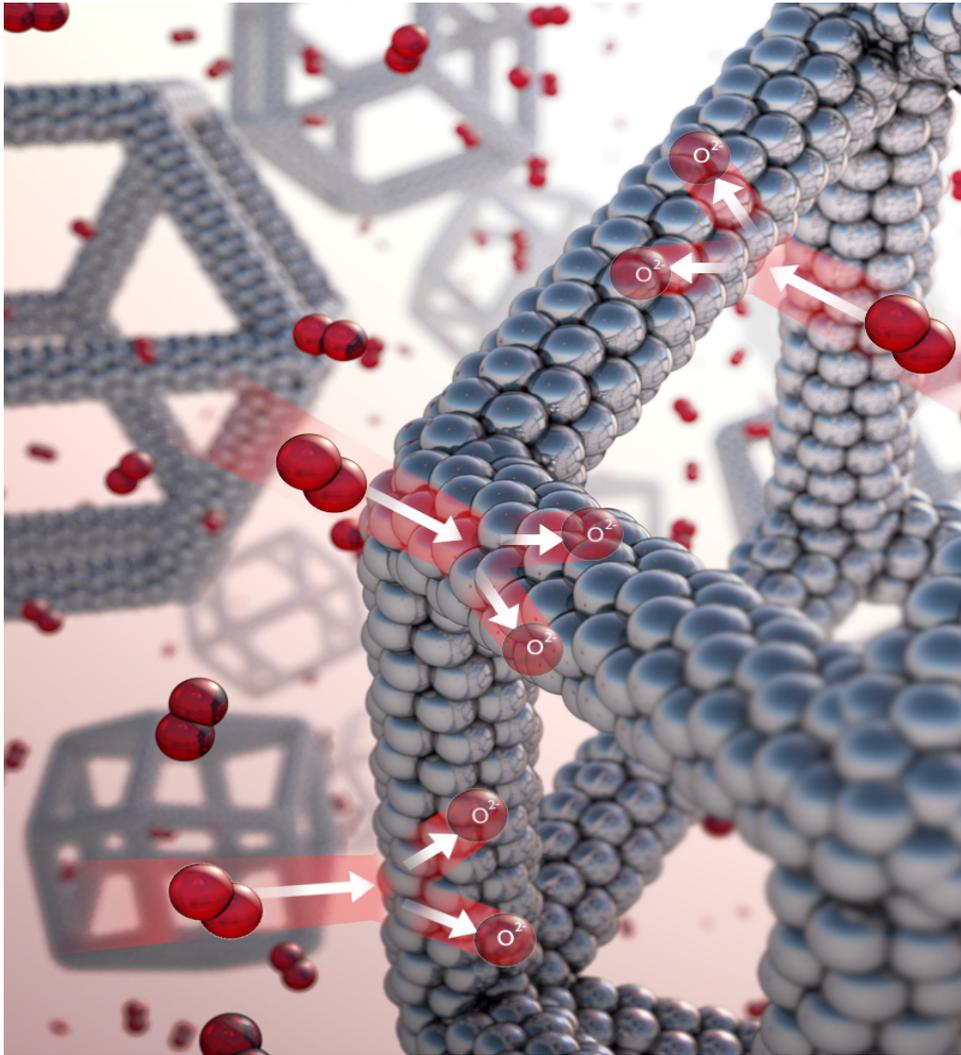
ANL and UC Berkeley scientists develop a high-mass activity nanoframe

C Pt₃Ni Nanoframes

D Pt₃Ni nanoframes/C
with Pt-skin surfaces

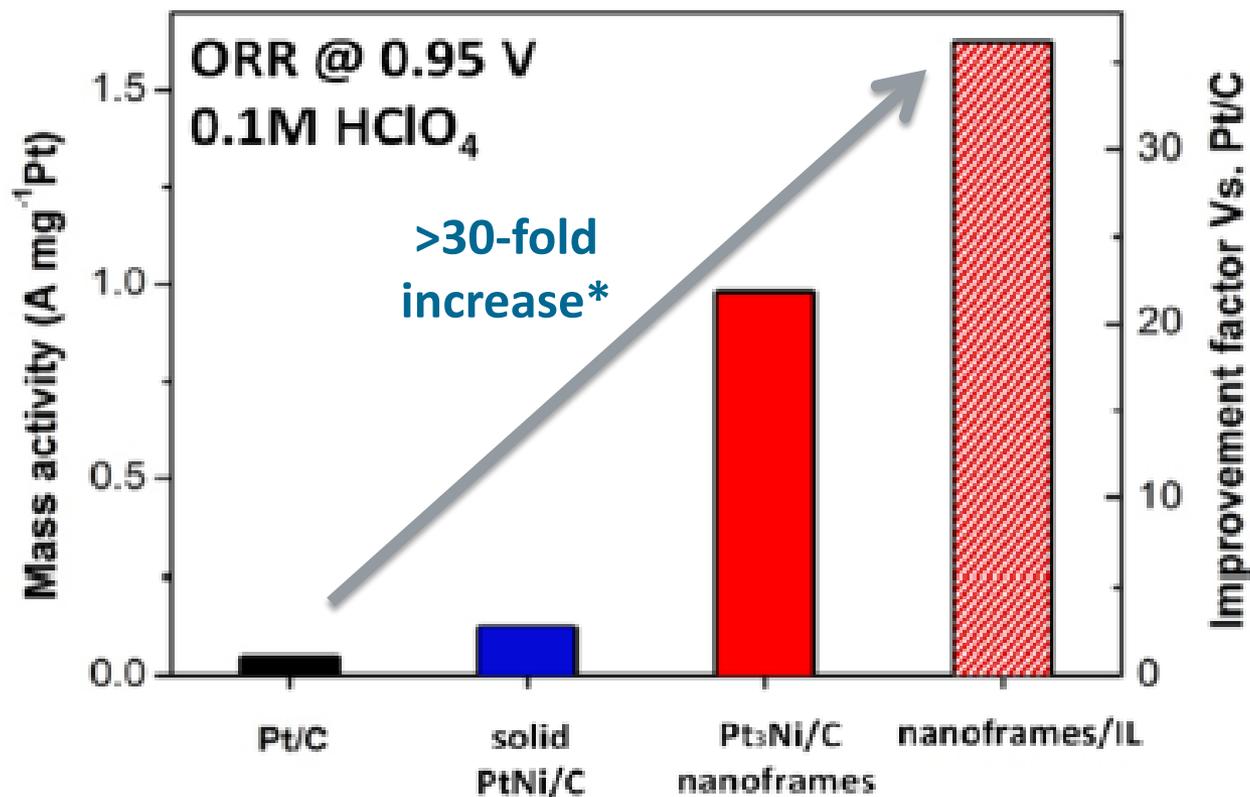


Dispersible cathode catalyst with extended thin film catalyst properties



TEM- Karen Morre, ORNL

Microscopy demonstrates nanoframe hollow structure



*Catalyst only in RDE tests
Future plans:
Demonstrate MEAs

Reference:

"Highly Crystalline Multimetallic Nanoframes with Three-Dimensional Electrocatalytic Surfaces"

Vojislav Stamenkovic (ANL) & Peidong Yang (LBNL/UCB)

Science, 343 (2014) 1339

Catalyst mass activity >30X higher than conventional Pt/C

H₂ Infrastructure Development and Status

Nationwide

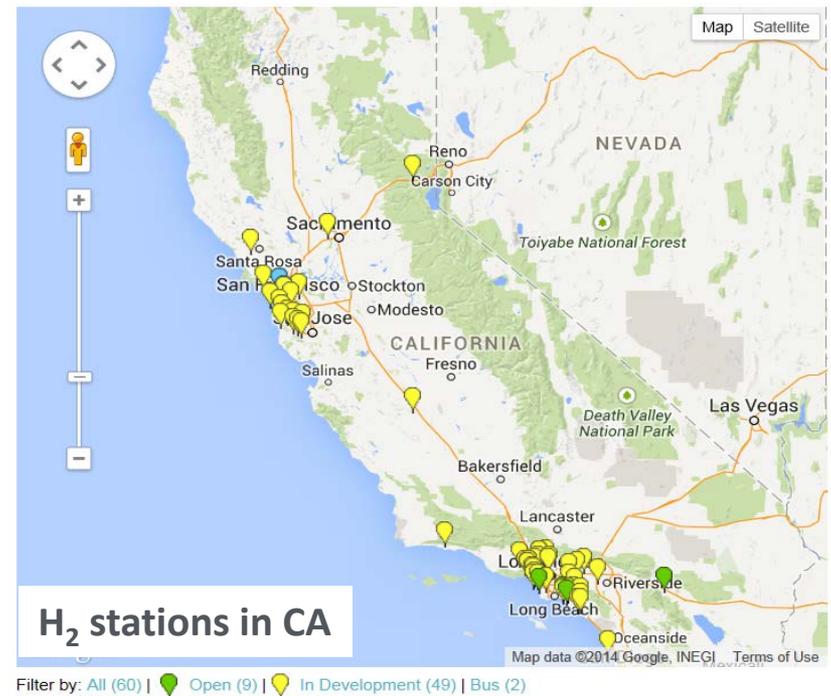
- **1500 mi.** of H₂ pipeline
- **>9M** metric tons produced/yr
- **~50 stations** (~10 public)

Other States

- **8-State MOU Members:** CA, CT, NY, MA, MD, OR, RI and VT
- **MA, NY, CT:** Preliminary plans for H₂ infrastructure and FCEVs deployment in metro centers in NE states.
- **Hawaii:** Public access refueling infrastructure on Oahu by 2020

California

- **100 stations** - Goal
- **>~\$70M** awarded
- **~\$100M** planned through **2023**



California, NE States and Hawaii have H₂ infrastructure efforts underway

H₂ USA Public-Private Partnership to address H₂ Infrastructure Challenges

H₂ USA



3X increase in partners and growing since 2013

\$1.4M DOE Funding
Leveraging Expertise of National Labs



In Support of

H₂USA and tasked to deliver

Reference Station Design

Fuel Contaminant Detection

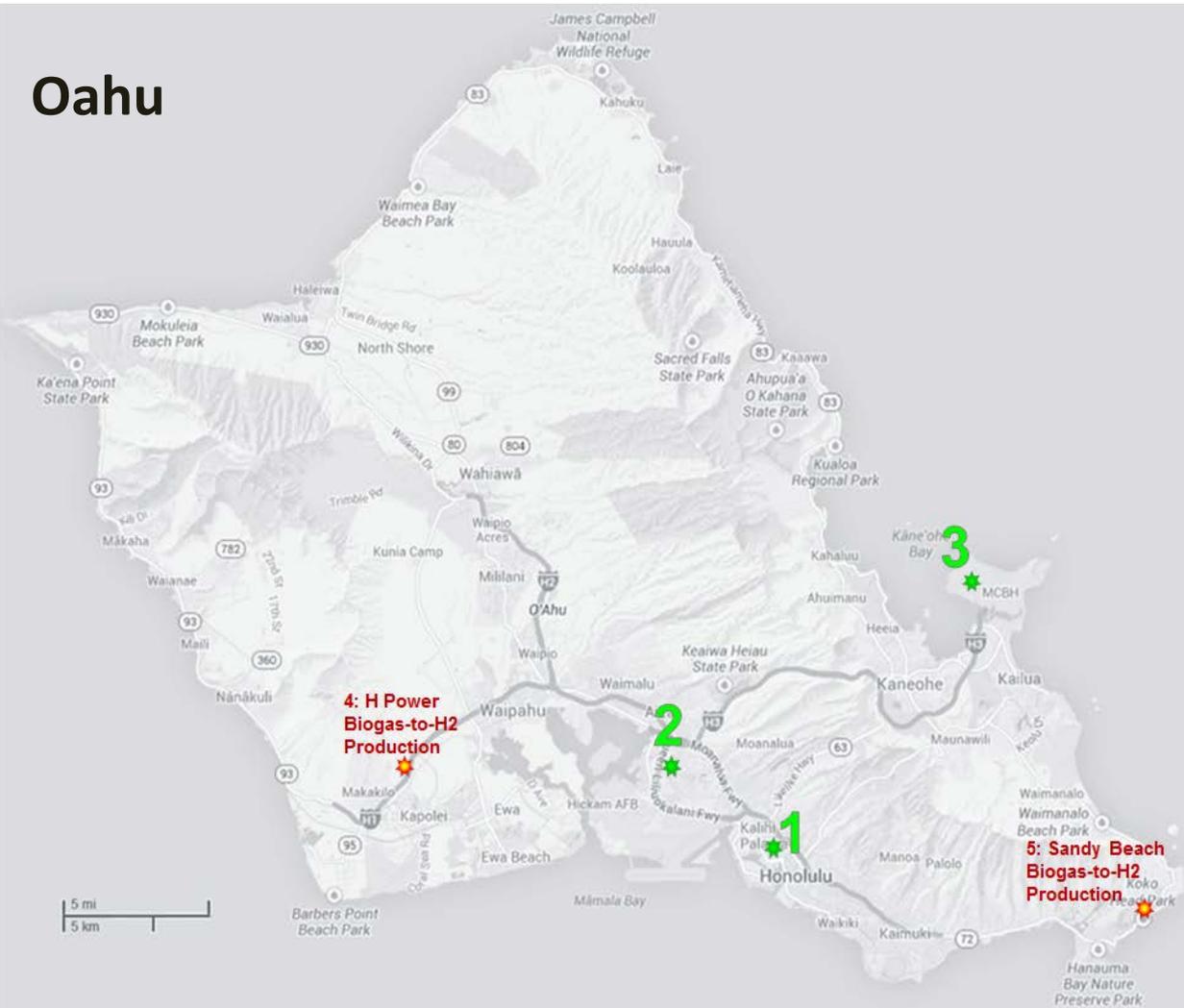
HyStEP Device

- H₂ Station Equipment Performance Device
- H₂First Inaugural Task
- HyStEP will help reduce time required to place H₂ stations in service

DOE's H₂FIRST project supports H2USA goals to address infrastructure

Infrastructure Options at Government Sites

Oahu



1. GSA Fort Armstrong (65 kg/day):

- New greenfield site using 1.45 acre fed parcel

2. Hickam AFB (65 kg/day):

- Electrolyzer behind fence, mobile refueler source only

3. K-Bay USMC:

- Hookup Capacity

4. H-Power:

- Government owned with excess power, possibly electrolysis (LFG power)

5. Sandy Beach:

- WWTP with potential for SMR – H₂ plant

DOE is assessing H₂ infrastructure options in Hawaii



**\$1 million competition
for on-site home and
community-scale H₂
fueling systems.**

1st Year

**Teams form
and submit
designs**

2nd Year

**Selection of
finalists and
testing**

Late 2016

**Technical and
cost analysis to
select winner**

Award

\$1M

*Promoting H₂ fueling system development in the community
Visit <http://hydrogenprize.org/>*



International Partnership for Hydrogen and Fuel Cells in the Economy

- Representatives from 17 member countries & the European Commission
- Facilitates international collaboration and a forum for advancing policies education
- Recent Activities:
 - Infrastructure workshops, data-sharing, tank testing



International Energy Agency

- Implementing Agreements
 - Advanced Fuel Cells Implementing Agreement: 13 member countries currently implementing seven annexes
 - Hydrogen Implementing Agreement: 18 member countries, plus the European Commission currently implementing nine tasks
 - New Task on Hydrogen Safety being defined

Strong International Collaboration on Safety



6th International Conference on Hydrogen Safety
October 19-21, 2015 in Kawasaki/Yokohama, Japan (Hosted by Technova)



IA HySafe Research Priorities Workshop
Facilitate knowledge sharing among international research activities in the field of hydrogen safety

The workshop, held in Torrance, CA in May 2014, was organized by NEDO, NOW, CaFCP, and DOE and included ~70 participants from Japan, the United States, Germany, Scandinavia, and the EU. Toyota and Honda were hosts and sponsors.

Objective: To continue international collaboration from the workshop held in 2013 on infrastructure challenges in four key areas: Refueling, Hydrogen Quality, Metering, and Hardware Reliability.



Key outcomes:

- **Refueling:** Need for internationally standardized methods and devices to validate fueling station performance. Regional initiatives are underway.
- **H2 Quality:** Need for low-cost inline test devices to supplement spot-checks. Fuel quality certification guidelines, best practices for hydrogen production and supply, and a risk-based approach to selection of chemical species that must be analyzed were particular concerns.
- **Metering:** Metering guidelines must be standardized internationally with the Weights and Measures community. Standards should be developed regionally and then proposed to the international community through the OIML¹ and NIST.
- **Station Hardware:** Key concerns included the reliability of compressors, cost of storage, understanding of storage reliability, along with the user-friendliness and durability of hoses.

1. International Organization of Legal Metrology

Examples of Key Activities

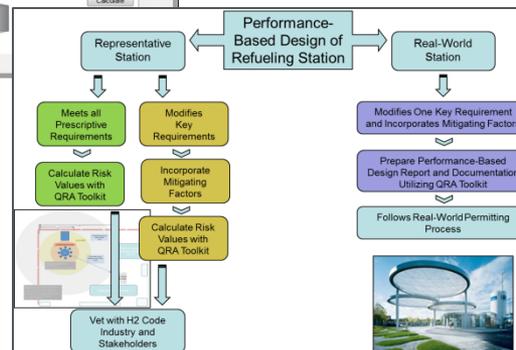
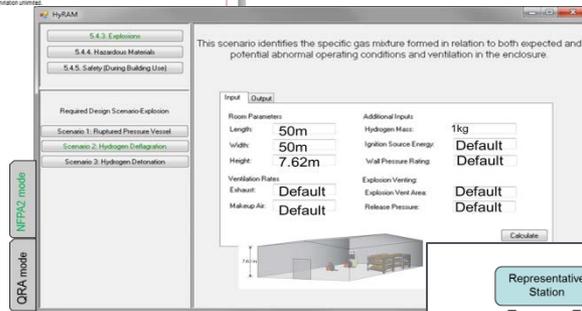
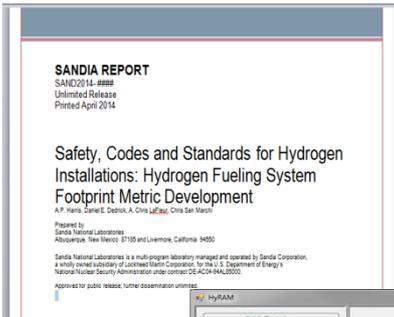
Station Footprint Reduction – Reduced critical separation distances by ~50% for GH2 due to supported SCS R&D efforts and direct participation in code development of NFPA 2 Hydrogen Technologies Code.

New Effort in FY14: Initiating LH2 release behavior experiments to address separation distances in partnership with NFPA 2/55 committees.

Develop tools for stakeholders to understand Risk – HyRAM (Hydrogen Risk Assessment Models) is being developed to enable an integrated approach of probabilistic and deterministic modeling including all relevant hazards and H2 phenomena.

Accelerate deployment of Hydrogen infrastructure by informing local AHJs –

- Develop a performance-based approach for the design of a hydrogen fueling station to increase the number available sites. (NFPA 2, Chapter 5)
- Develop a national permitting template in support of H2USA.



R&D supports development of codes & standards and facilitates domestic and international harmonization



- Trained **> 30,000** first-responders and code officials on hydrogen safety and permitting through on-line and in-classroom courses
- Developed H2Tools portal

**Hydrogen Tools
APP for
iPad/iPhone
(1,130 downloads
as of 11/2014)**

www.eere.energy.gov/hydrogenandfuelcells/codes/

Implementing safety practices and procedures to ensure the safe operation, handling, and use of hydrogen and fuel cell technology

Available for Public Purchase soon....



Toyota Fuel Cell Electric Vehicle

Now Leasing...



Hyundai Tucson Fuel Cell SUV

In Auto Shows...



Honda Fuel Cell Electric Vehicle

OEMs bringing fuel cells to showrooms and driveways

- **Publications - ~80/yr.**
 - Monthly Newsletter
 - Success Stories
 - News Alerts
 - Blogs
- **Investor Days**
 - NYC and CA
- **House Senate Caucus Events**
- **Annual Merit Review & Peer Evaluation**
 - June 2014- 1,800 attendees

- **Ride-n-Drives**



Deputy Secretary of Energy,
Daniel B. Poneman
test driving Hyundai Fuel Cell Tucson

Increasing public awareness and understanding about fuel cells and H₂

“As part of the President's all-of-the-above energy strategy, the Department funds research, development and demonstration activities that are helping to put fuel cell electric vehicles like the Tucson on the road....

...The efforts of the Office of Energy Efficiency and Renewable Energy have helped cut fuel cell costs in half and double durability in the last several years, supporting the emerging domestic fuel cell electric vehicle industry and enabling the development of technologies that will reduce greenhouse gas emissions.”

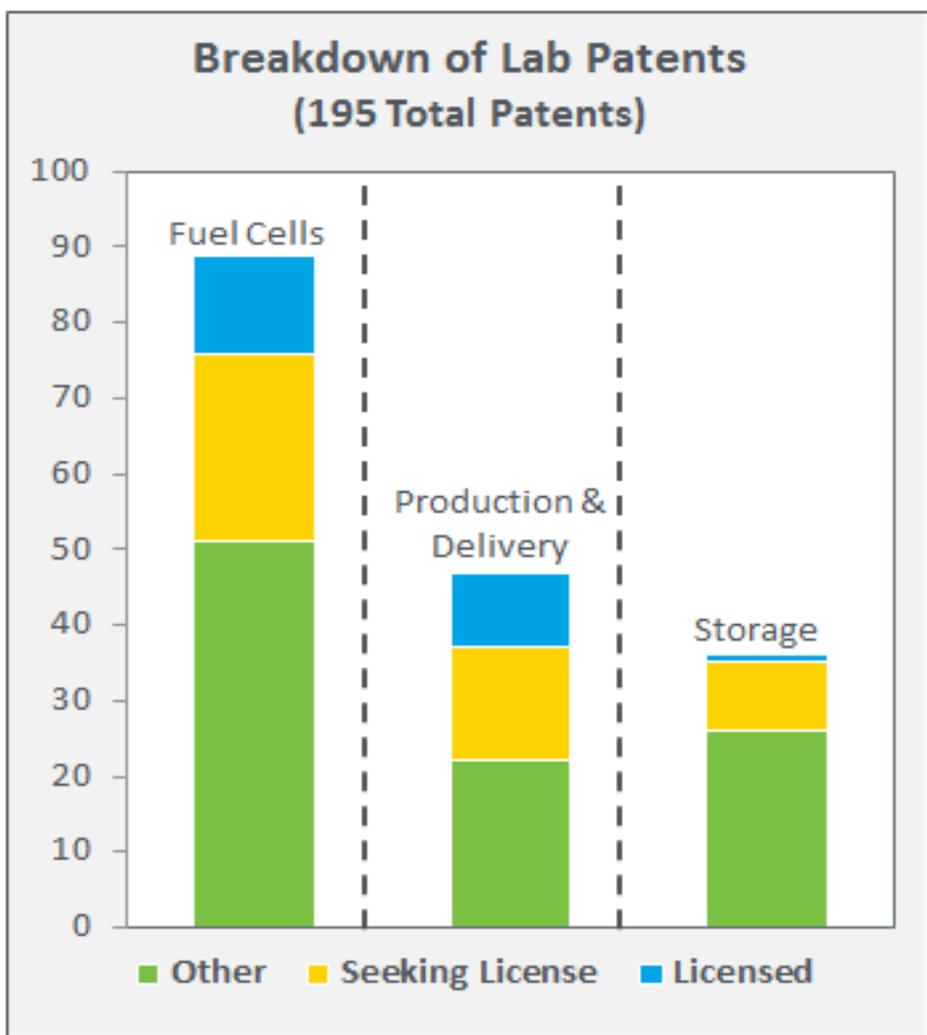
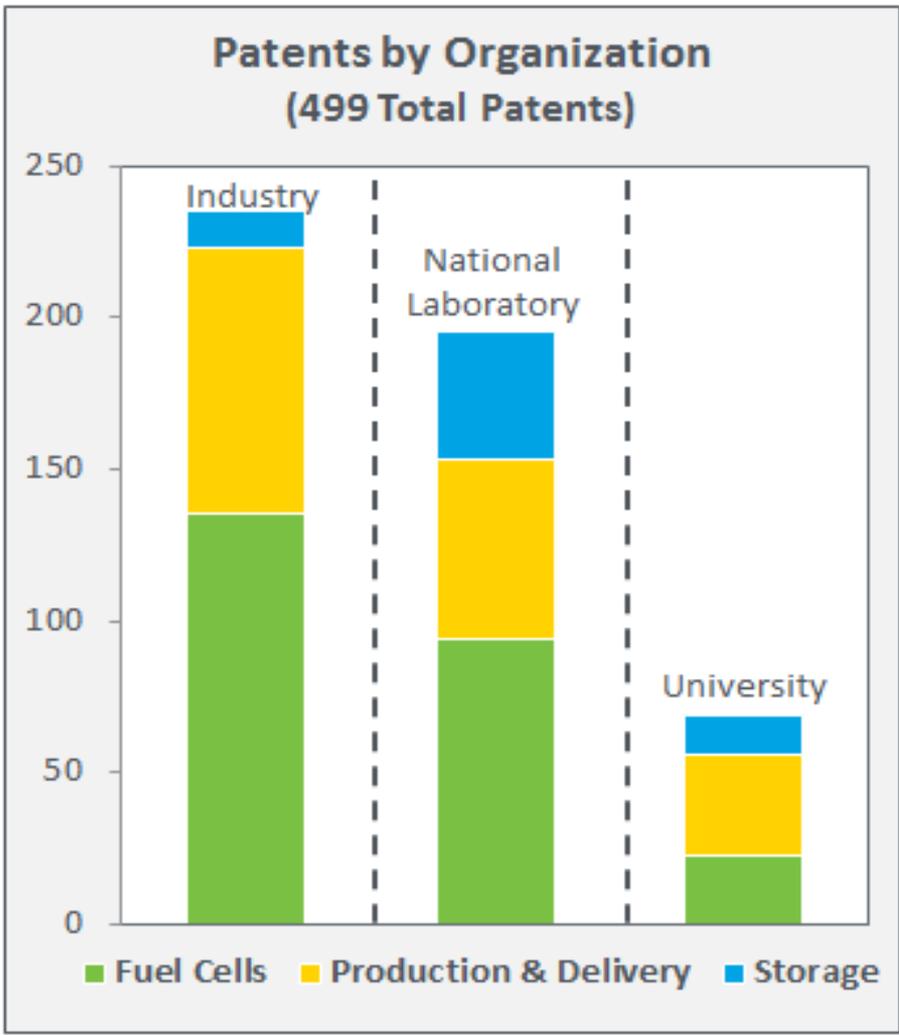
**- Deputy Secretary of Energy,
Daniel B. Poneman during Hyundai Fuel Cell
Tucson Ride-n-Drive at DOE Headquarters**

Committed to...

- EERE-National Lab Guiding Principles
- Long-term and committed relationship with National Labs
- Impact on industry
- Lab brand and identity



EERE Assistant Secretary David Danielson launches one of EERE Lab Impact Initiative key component– *The Tech-To-Market (T2M) Approach*

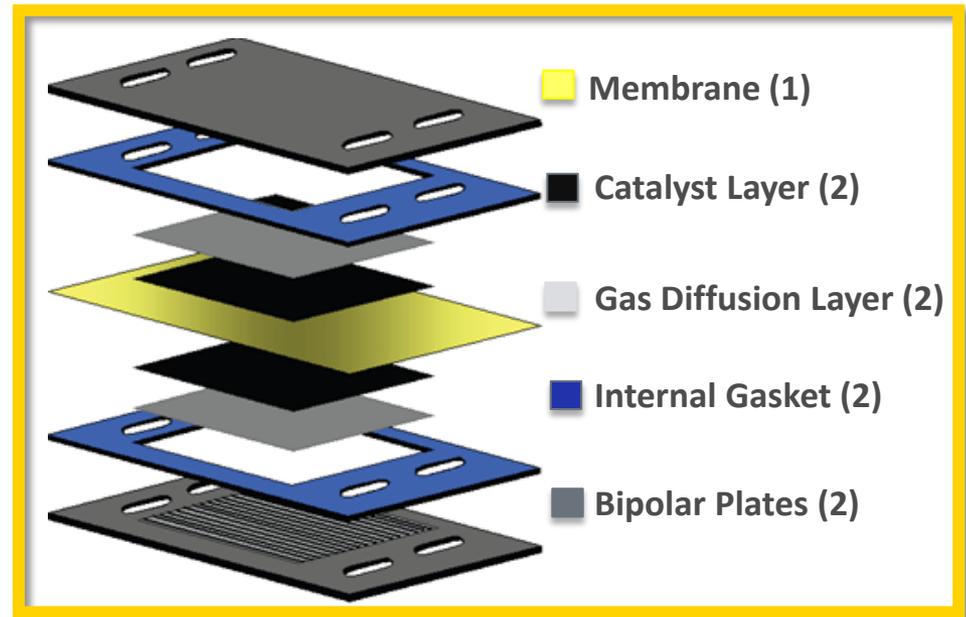


DOE has enabled nearly 500 patents, ~200 from labs

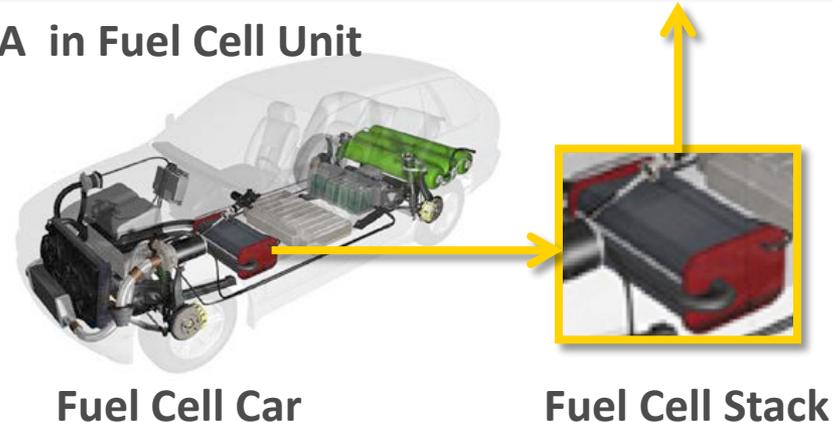
DOE-Led Innovation in Fuel Cells

Examples of DOE-Led Fuel Cell Technology Breakthroughs

- **Ionomer-Impregnated Catalyzed Gas Diffusion Electrodes-** *US Pat 4,876,115 (1989)*
“ELAT” – Electrode, Los Alamos Type
- **Catalyst-Coated Membranes-**
US Pats 5,211,984 and 5,234,777 (1993)
- **Microporous Film on Gas Diffusion Layers-** *US Pat 5,641,586 (1997)*
- **Thermoset Composite Bipolar Plates-**
US Pat 6,248,467 (2001)



MEA in Fuel Cell Unit



Fuel Cell Car

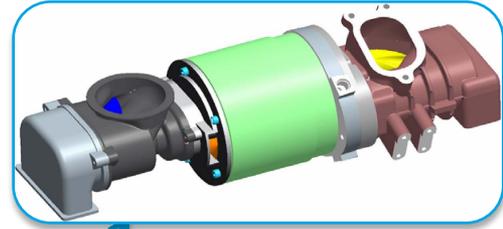
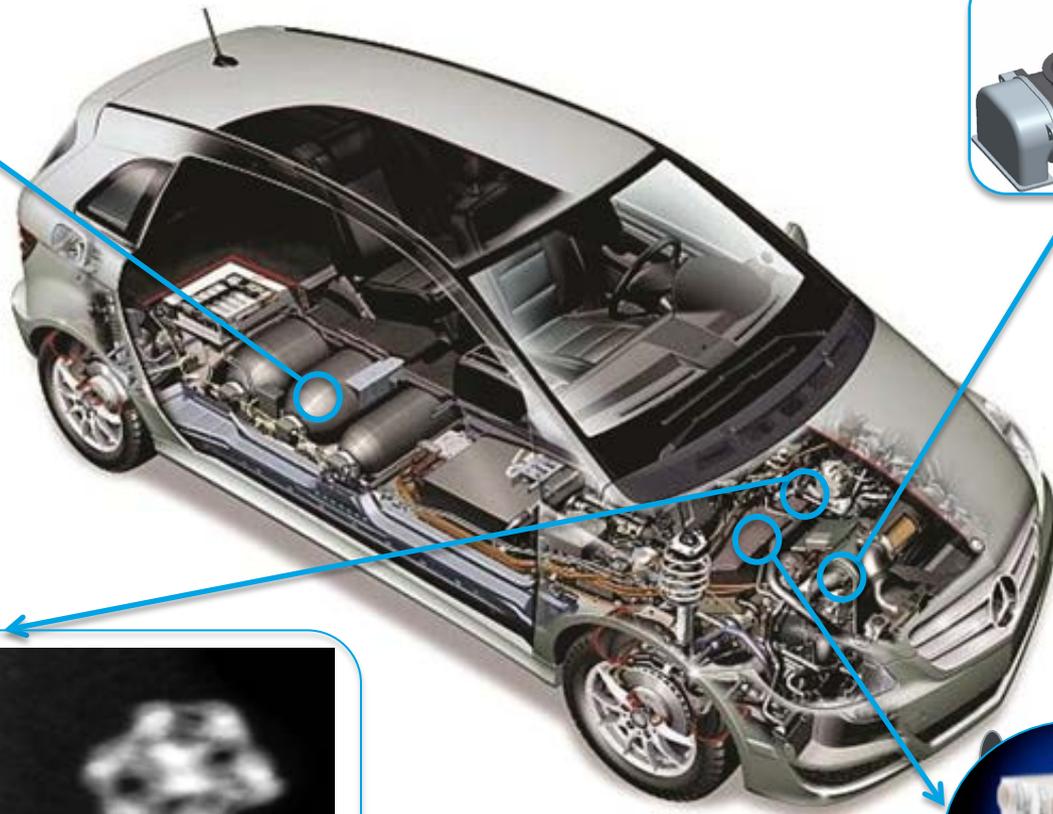
Fuel Cell Stack

Innovation from LANL can be found in most fuel cells today

FCEV Technology Advancements

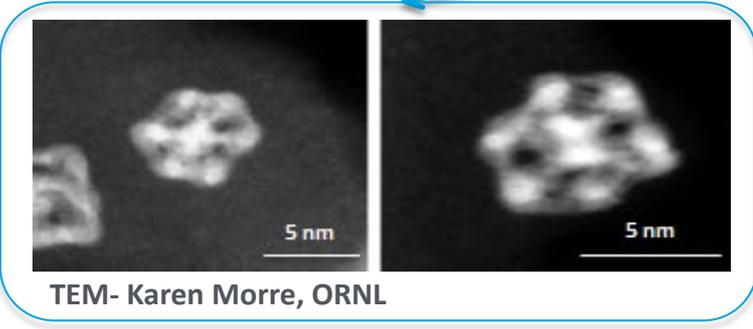


700 bar composite overwrapped pressure vessels



Compressor Expander Motor Module for Air Compression System

ORNL microscopy imaging



TEM- Karen Morre, ORNL

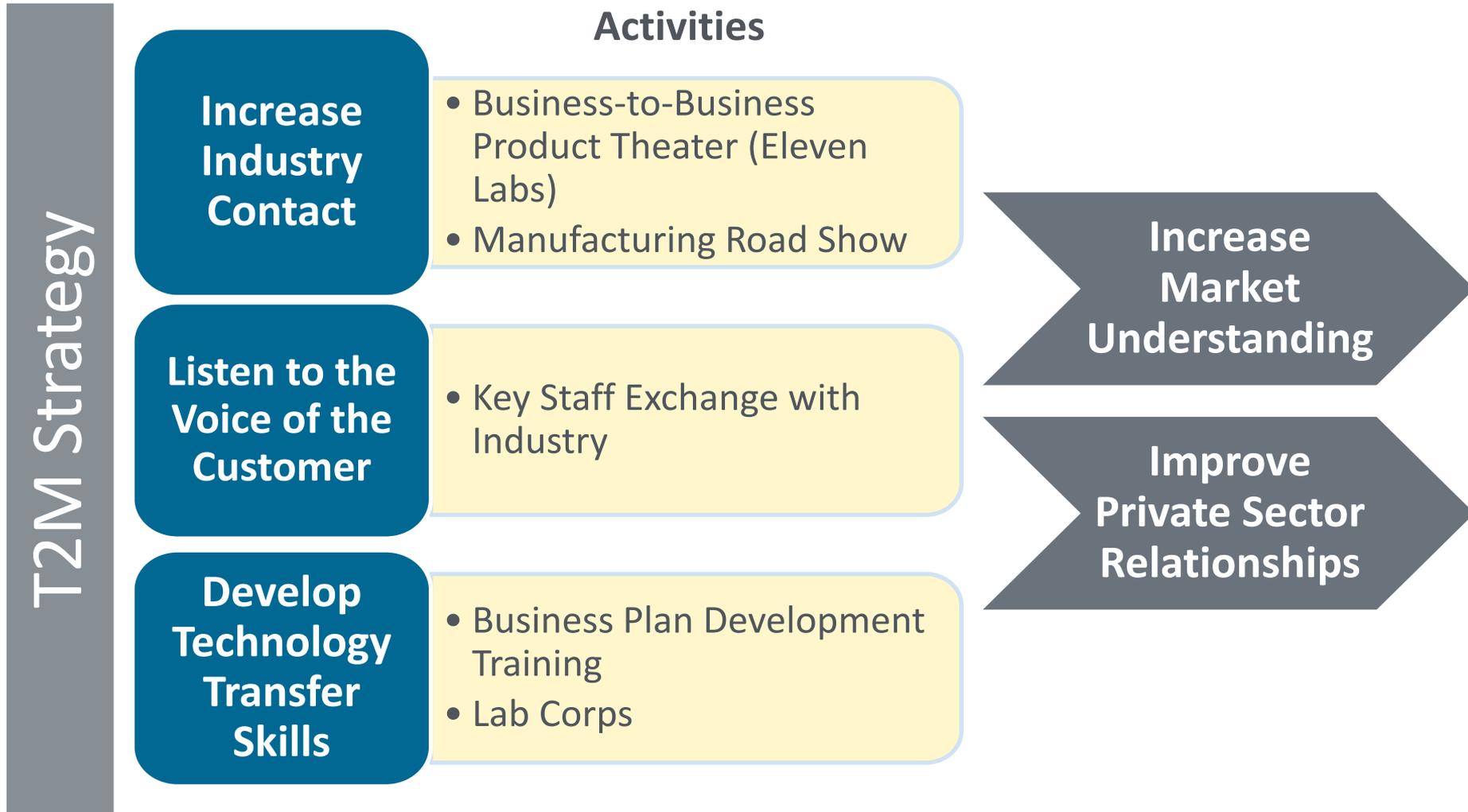


Module for Humidifier

5 nm

DOE funded R&D has advanced the state of technology for FCEV systems

Fuel Cells Tech-to-Market (T2M) Strategy



Improving technology transfer and targeted impact from lab to market

- **Tools**
 - Workshop sessions
 - Business-to-business product theaters
- **Key Questions**
 - How do I work with the National Labs?
 - Why should I work with the National Labs?
- **Objective**
 - Collaboration and understanding between national labs and industry

Fuel Cell Seminar & Energy Exposition

Featuring Hydrogen Fuel Sponsored by the Fuel Cell Technologies Office

KEYNOTE SPEAKER

Tuesday, November 11, 2014 at 9:00 am
Reuben Sarkar
Deputy Assistant Secretary for Transportation
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy



DOE EERE LAB TECH TO MARKET SHOWCASE LEVERAGING NATIONAL LAB CAPABILITIES TO SOLVE INDUSTRY PROBLEMS

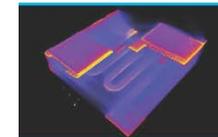
TUESDAY, NOVEMBER 11 | On Tuesday, November 11, join us at these two **one-day-only events** to increase collaboration between national labs and industry:

3-5 PM | LEVERAGING THE LABS

The first session will demystify the process of working with national labs and discuss the mechanisms put in place to put labs to work on industry problems.

5-6 PM | LAB SHOWCASE

The second session, during the Business-to-Business Product Theater, will highlight technologies developed at the national labs, their unique capabilities, and opportunities for collaboration.



3-D X-ray Tomography of a mixed-potential hydrogen sensor at LANL. Sensor response is controlled by the kinetics of the electrode reactions occurring at the gas-electrode-electrolyte interface.



NREL has received four Fuel Cell Hybrid Vehicles--Advanced (FCHV-adv) on loan from Toyota, enhancing their research capabilities related to hydrogen fueling infrastructure.



Xiaoping Wang of Argonne National Laboratory prepares a cell for testing the activity of fuel cell catalysts.

U.S. DEPARTMENT OF
ENERGY

Energy Efficiency & Renewable Energy

EERE-funded research has:

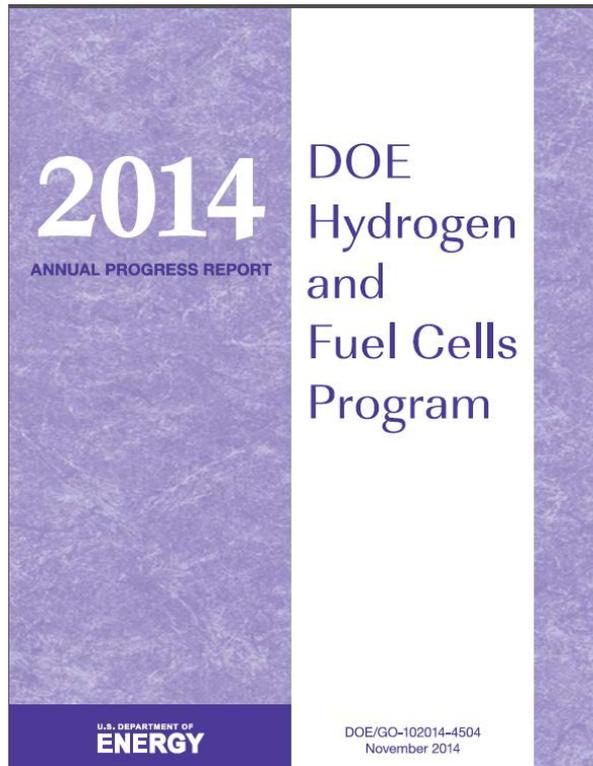
- Reduced cost of fuel cells by more than 50% since 2006 and 30% since 2008
- Achieved a more than five-fold reduction in the platinum content of fuel cells
- Led to more than 450 patents, 40 commercial technologies, and 65 emerging technologies that will be commercialized in the next 3-5 years
- <http://energy.gov/eere/fuelcells/downloads/2013-pathways-commercial-success-technologies-and-products-supported-fuel>

www.energy.gov/eere/fuelcells

FCO's ad on T2M Showcase Activities for the FCS

DOE sponsored several T2M events during FCS&E- Nov 11th, 2014

2014 DOE Hydrogen and Fuel Cells Program Annual Progress Report (APR)



- ~**1,000** pages documenting DOE progress

2013 Fuel Cell Technologies Market Report



- ~ **\$1.3** billion industry
- >**35,000** units shipped worldwide

APR documents DOE progress and Market Report provides update on fuel cell industry

- **Continue to promote and strengthen R&D activities**
 - H₂, fuel cells, safety, manufacturing, etc.
 - Cost, performance, durability need to be addressed
- **Conduct strategic, selective demonstrations of innovative technologies**
 - Industry cost share and potential to accelerate market transformation
- **Continue to conduct key analyses to guide RD&D and path forward**
 - Life cycle cost; infrastructure, economic & environmental analyses, etc.
- **Leverage activities to maximize impact**
 - U.S. and global partnerships
 - H2USA: Public-Private partnership to enable widespread commercialization of H₂ vehicles in the United States

- **Feedback on Goals (Draft) for H2USA Working Groups**
- **Location Roadmap**
 - **Determine number of vehicles planned for 2015-2020 launch and the number, location and capacity requirements for station rollout for at least two states by Q4 2015.**
- **Financing/Investment**
 - **Develop and disseminate refueling station business case studies, identify at least 3 (X) optimal payback scenarios and strategies for risk mitigation, and secure financing or investment by Q4 2016.**

- **Station Technology**

- **Develop and demonstrate critical enabling technologies for station rollout including station performance validation device and validate fueling protocols for at least 5 stations by 4Q 2016.**

- **Communication and Outreach**

- **Increase H2USA partnership by factor of 5 since launch, develop communication and outreach materials and disseminate to at least 10,000 by 4Q 2015.**

Subgoals (examples)

- **Hold H2USA infrastructure financing and investment workshop.**
- **Develop online tool to calculate station payback and disseminate through webinar and conferences to key retail station owners and investors.**

Thank You

Dr. Sunita Satyapal

Director

Fuel Cell Technologies Office

Sunita.Satyapal@ee.doe.gov

hydrogenandfuelcells.energy.gov

Additional Information

- **Wide Bandgap Semiconductor Power Electronics for Hydrogen and Fuel Cell Applications** (Oct 21, 2014)
- **SAE Hydrogen Fueling Standardization** (Sep 11, 2014)
- **Hydrogen Energy Storage for Renewables** (Aug 19, 2014)
- **Hawaii Hydrogen Activities** (Jul 29, 2014)
- **Overview of Hydrogen Fueling for FCEVs** (Jun 24, 2014)
- **NREL's Fuel Cell Contaminant Database** (May 27, 2014)
- **Fuel Cells at NASCAR** (Apr 17, 2014)
- **National Fuel Cell Technology Evaluation Center (NFCTEC)** (Mar 11, 2014)
- **Additive Manufacturing for Fuel Cells** (Feb 11, 2014)
- **Energy 101: Fuel Cells Discussion** (Jan 16, 2014)
- **Hydrogen Student Design Contest** (Nov 6, 2014)
- **H2FIRST Overview** (Nov 18, 2014)

- **Contaminant Detection at the Forecourt** (June 12th, 2014)
- **Energy Storage Workshop** (May 2014)
- **2nd International Workshop on Hydrogen Infrastructure** (May 8-9th, 2014)
- **Hydrogen Safety Resource Tools** (April 2014)
- **Infrastructure Financing Workshop** (April 2014)
- **Electrolytic Hydrogen Production** (February 27-28th, 2014)
- **Hydrogen Transmission and Distribution Workshop** (February 25-26th, 2014)

Hydrogen Production Strategies

Current Technology

- Natural Gas (D/C)
- Electrolysis (D)

Near to Mid-Term:

- Electrolysis- Wind and Solar Powered (D/C)
- Bio-derived Liquids (D/C)
- Fermentation (D/C)

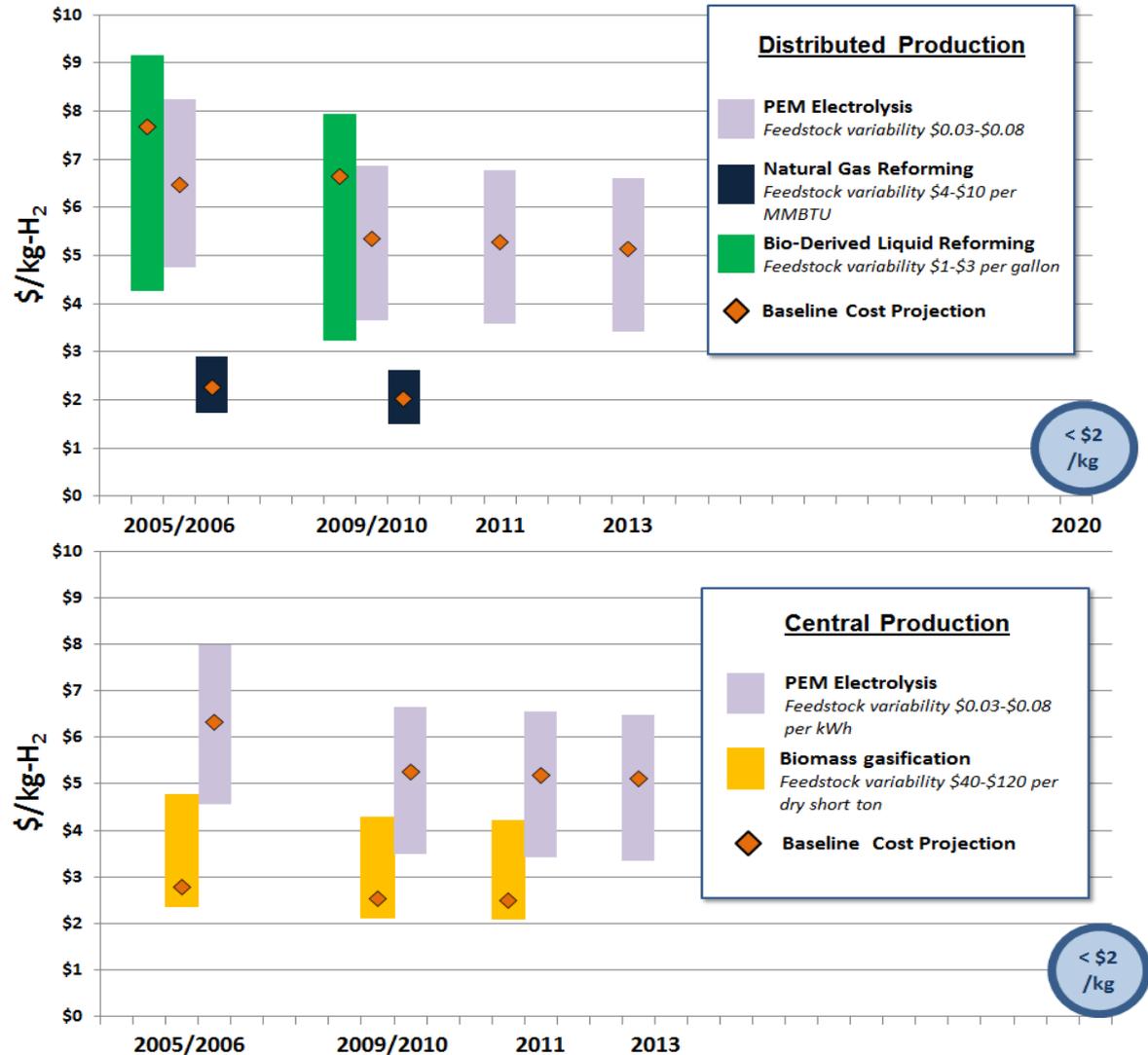
Long-Term (not shown):

Central Renewable H₂

- Solar-based water splitting
- Photolytic Bio-hydrogen

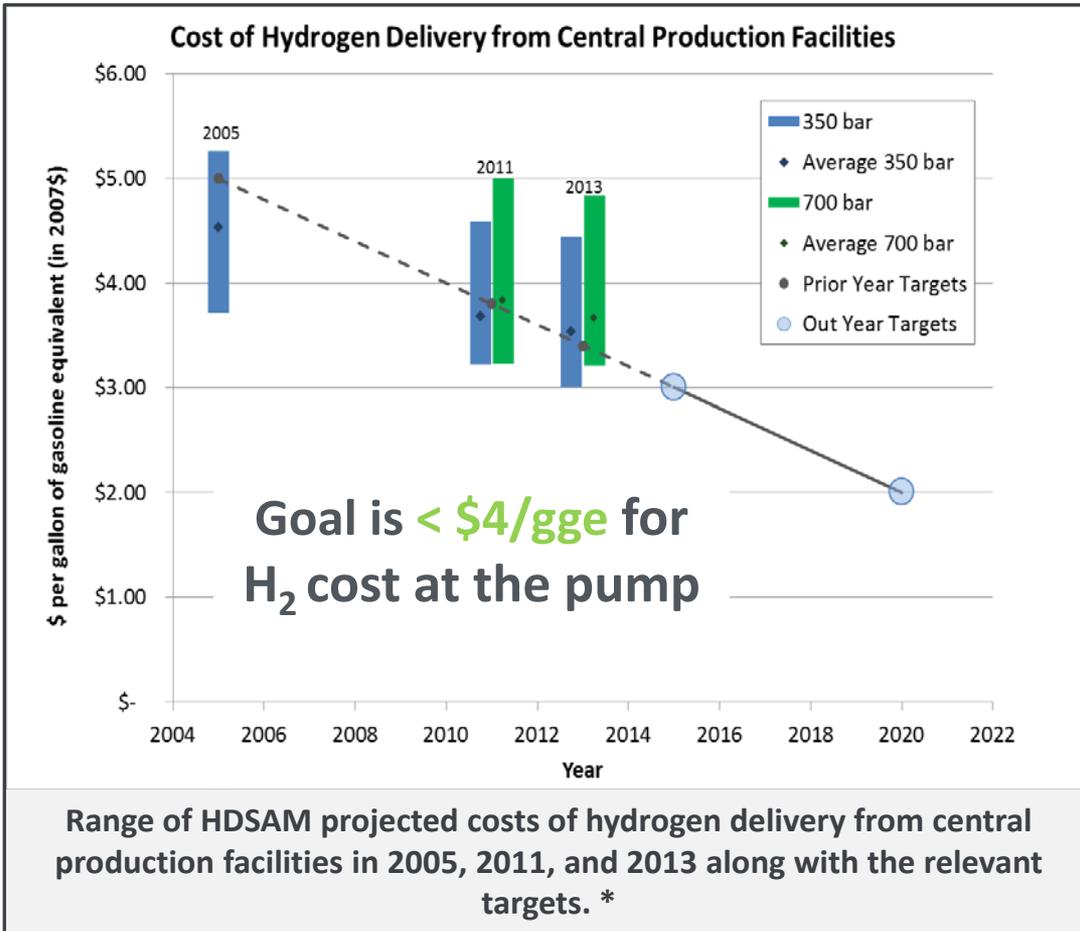
D- Distributed

C- Central

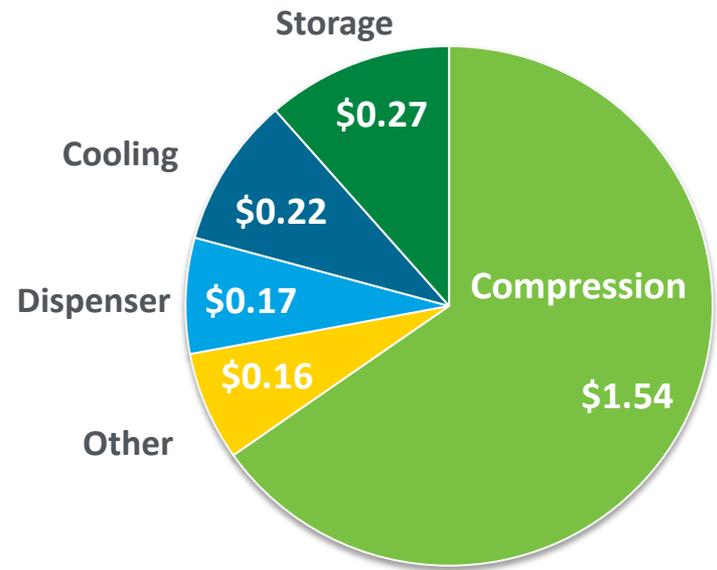


H₂ from natural gas is available now while H₂ from renewables is a longer-term focus.

Hydrogen Delivery Cost Reductions



CSD Cost Breakdown for the Pipeline Scenario (\$2.40/kg total)**



- Compression and Storage comprise approximately **75%** of CSD costs

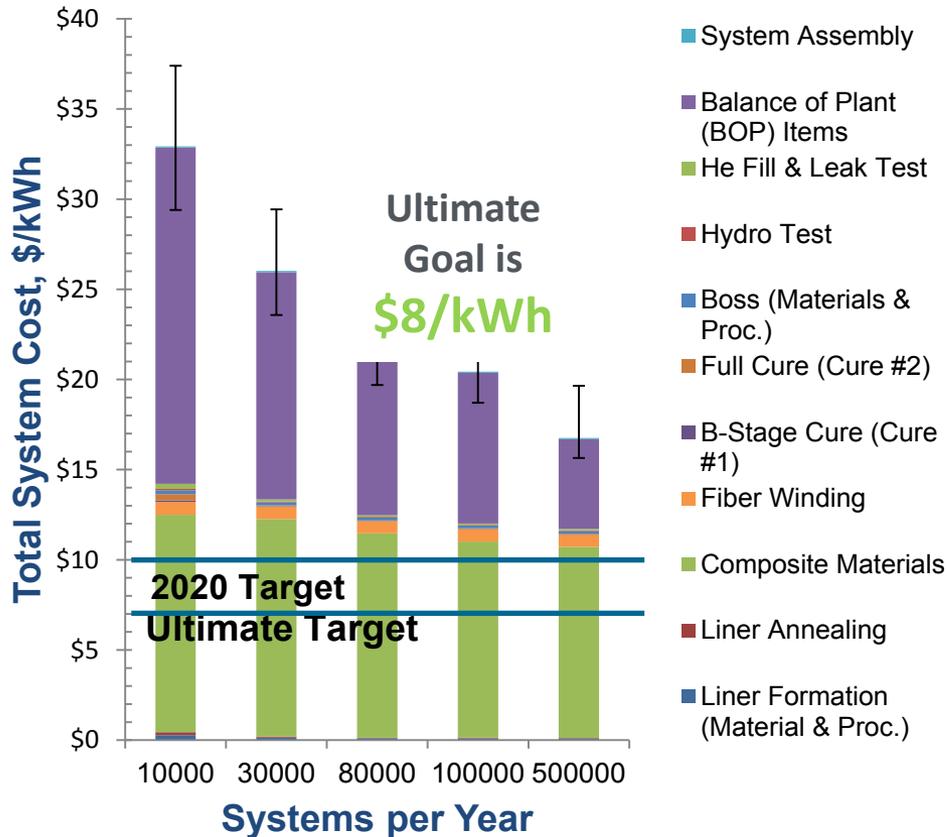
* Details for the high volume cost projection assumptions can be found in Record 13013

**Hydrogen Station Compression, Storage, and Dispensing Technical Status and Costs Record

R&D has enabled H_2 delivery reduction costs but compression is still a key challenge.

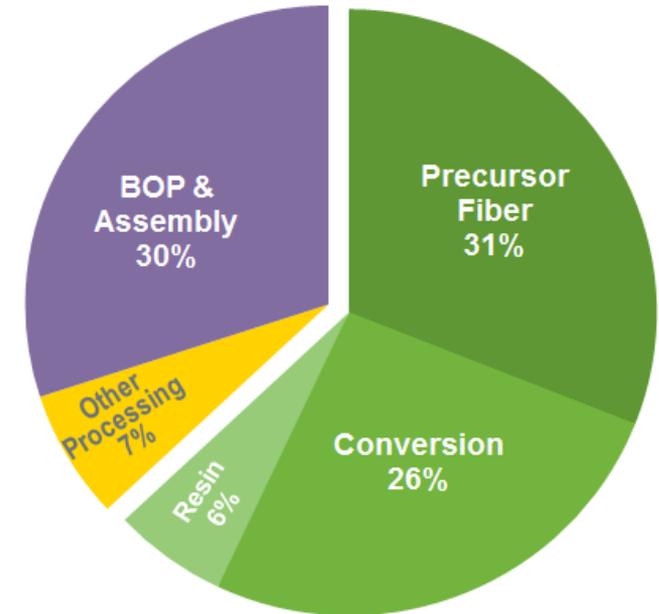
H₂ Storage System Critical Costs

700 bar Compressed Gas Storage System Cost* and Targets



*Single tank holding 5.6kg H₂ total, cost in 2007\$

700 bar system cost breakdown at 500,000 systems/year



- Composite materials account for **>60%** of total storage tank system cost
- Carbon fiber precursor is the **largest** single cost contributor.

700 bar compressed H₂ is the immediate strategy for FCEV rollout, however cost reductions are needed and carbon Fiber is the key.

New Selections for Hydrogen Production RD&D

6 selections, \$13.3 M in federal funds

FuelCell Energy Inc.

(\$900k), Danbury, CT

- Novel reformer-electrolyzer-purifier (REP) system

Pacific Northwest National Laboratory (\$2.2M)

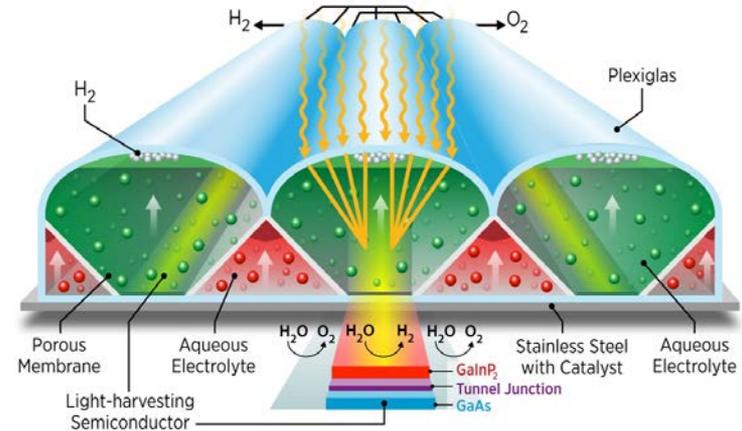
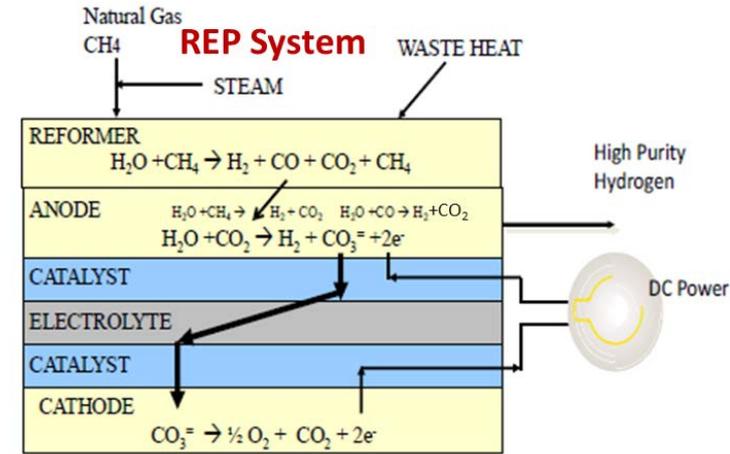
Richland, WA

- Scalable, compact piston-type reactor for H₂ production from bio-derived liquids.

National Renewable Energy Laboratory (\$3M),

Golden, CO

- High-efficiency tandem absorbers based on novel semiconductor materials
- Economical solar hydrogen production from water.



Novel approaches to hybrid reforming, bio-derived liquids and solar water splitting

New Selections for Hydrogen Production RD&D

6 selections, \$13.3 M in federal funds

University of Hawaii (\$3M), Honolulu, HI

- Photoelectrodes based on novel wide-bandgap thin-films for direct solar water splitting.

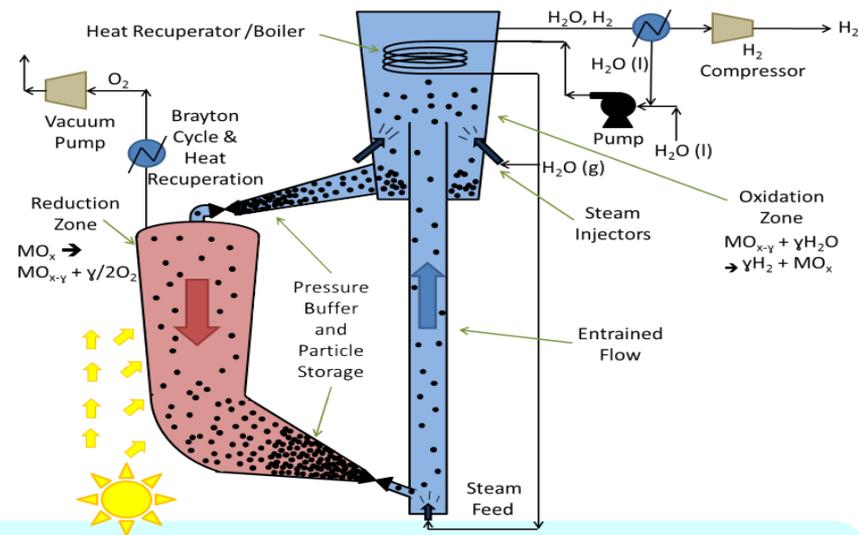
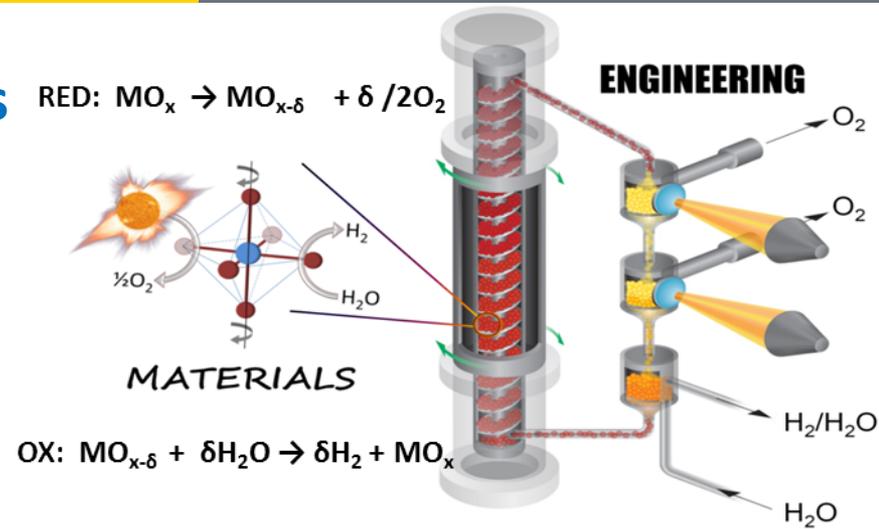
Sandia National Laboratories (\$2.2M)

Livermore, CA

- Innovative high-efficiency solar thermochemical reactor for H₂ production.

University of Colorado, Boulder (\$2M), Boulder, CO

- Novel flowing particle bed solar-thermal reactor to split water with concentrated sunlight.



Novel approaches to hybrid reforming, bio-derived liquids and solar water splitting

New Selections for Hydrogen Delivery RD&D

3 Awards, \$6.8 M in federal funds

Southwest Research Institute (\$1.8M), San Antonio, TX

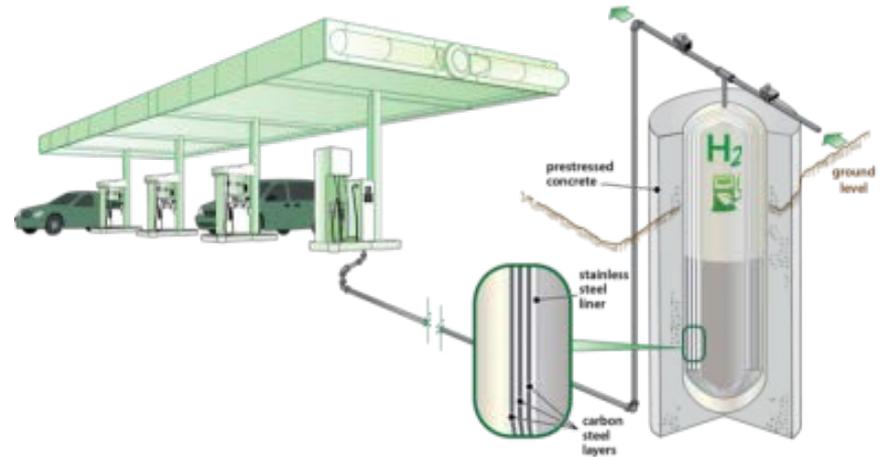
- Linear motor reciprocating compressor for forecourt H₂ compression

Oak Ridge National Laboratory (\$2.0M), Oak Ridge, TN

- Low cost steel concrete composite vessel for high pressure forecourt H₂ storage.

Wiretough Cylinders LLC (\$2.0M), of Bristol, VA

- Low cost 875 bar H₂ storage vessel using a steel wire overwrap.



Innovative technologies for forecourt compression, storage and dispensing

6 Selections, \$8M in federal funds

- **Materia (\$2M), Pasadena, CA**
 - Demonstrate novel resin system and vacuum assisted resin transfer manufacturing process to reduce the cost of high pressure storage tanks.
- **PPG Industries (\$1.2M), Greensboro, NC**
 - Demonstrate novel high strength glass fiber with tensile strengths equal or greater than the carbon fibers used today at half of the cost.
- **Sandia National Laboratories (\$1.2M), Livermore, CA**
 - Systematically screen low-cost alternative steel alloys for use in balance of plant components for hydrogen storage systems.
- **Ardica (\$1.2M), San Francisco, CA**
 - Develop and scale-up a low-cost process for the commercial production of aluminum hydride (alane), a high-capacity hydrogen storage material.
- **HRL Laboratories (\$1M) Malibu, CA**
 - Develop high-capacity reversible hydrogen storage materials that have properties needed for practical hydrogen storage applications.
- **Lawrence Livermore National Laboratory (\$1.2M) Livermore, CA**
 - Use a combined computational/experimental approach to improve the kinetics and properties of magnesium borohydride for practical hydrogen storage

Examples of Activities Supporting ZEV Action Plan

ACTION

RESEARCH

PARTNERSHIPS

M-S ZEV Action Plan
1. Vehicle Markets
2. Incentives
3. Lead-by-Example
4. Fleets
5. Workplace Charging
6. Infrastructure
7. Signage
8. Local Barriers
9. Interoperability
10. Fuel Markets
11. Data
Research
Partnerships

“Collaboration for Success”

DOE/EERE/FCTO
Fuel Cell Cost
H ₂ Production
H ₂ Delivery
Tanks and Storage
Safety Codes and Standards
Tech Validation (NFCTEC)
Market Transformation
H2FIRST
H2USA
CaFCP
IPHE

Online cost calculator (NREL)

- H2FAST (Financial Advisor Scenario Tool)
- Developed by NREL with inputs from ANL's HRSAM (H2 refueling station analysis model)
- Beta testing coming soon

Draft

Hydrogen Station Financing Advisor

Station Inputs

Station Utilization [%]: ▬

Maximum hydrogen price [\$ / kg H₂]: ▬

Total Capacity [kg/day]: ▬

Total Capital Cost [\$]: ▬

Total Installation Cost [\$]: ▬

Scenario Inputs

Capital Incentive [\$ / station]: ▬

Duration of Capital Incentive [years]: ▬

Initial Production Incentive [\$ / station]: ▬

Annual Decrement of Production Incentive [\$ / station]: ▬

Duration of Production Incentive [years]: ▬

Financing Inputs

Debt Interest Rate [%]: ▬

Maximum Return on Equity [%]: ▬

Minimum Debt to Equity Ratio: ▬

Minimum Debt Coverage Service Ratio: ▬

- [Download hydrogen station finance calculator](#)
- [Download results](#)

[Printable Version](#)

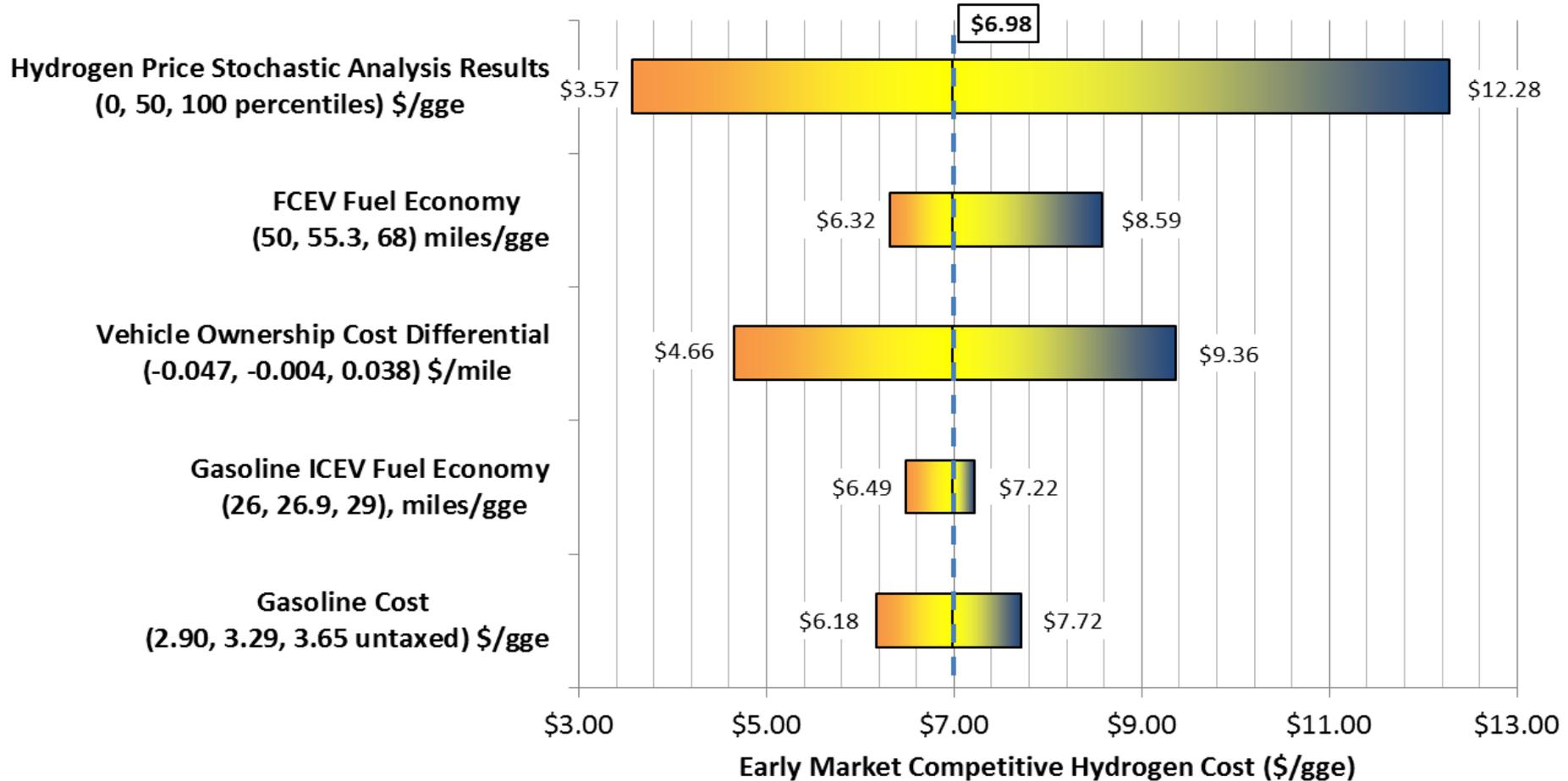
Earnings & Incentives

■ Earnings before Interest, Taxes, and Depreciation
— New Capital Incentives
— New Production Incentives

Returns

— Return on Investor Equity
— Return on Total Equity
— Real After Tax IRR

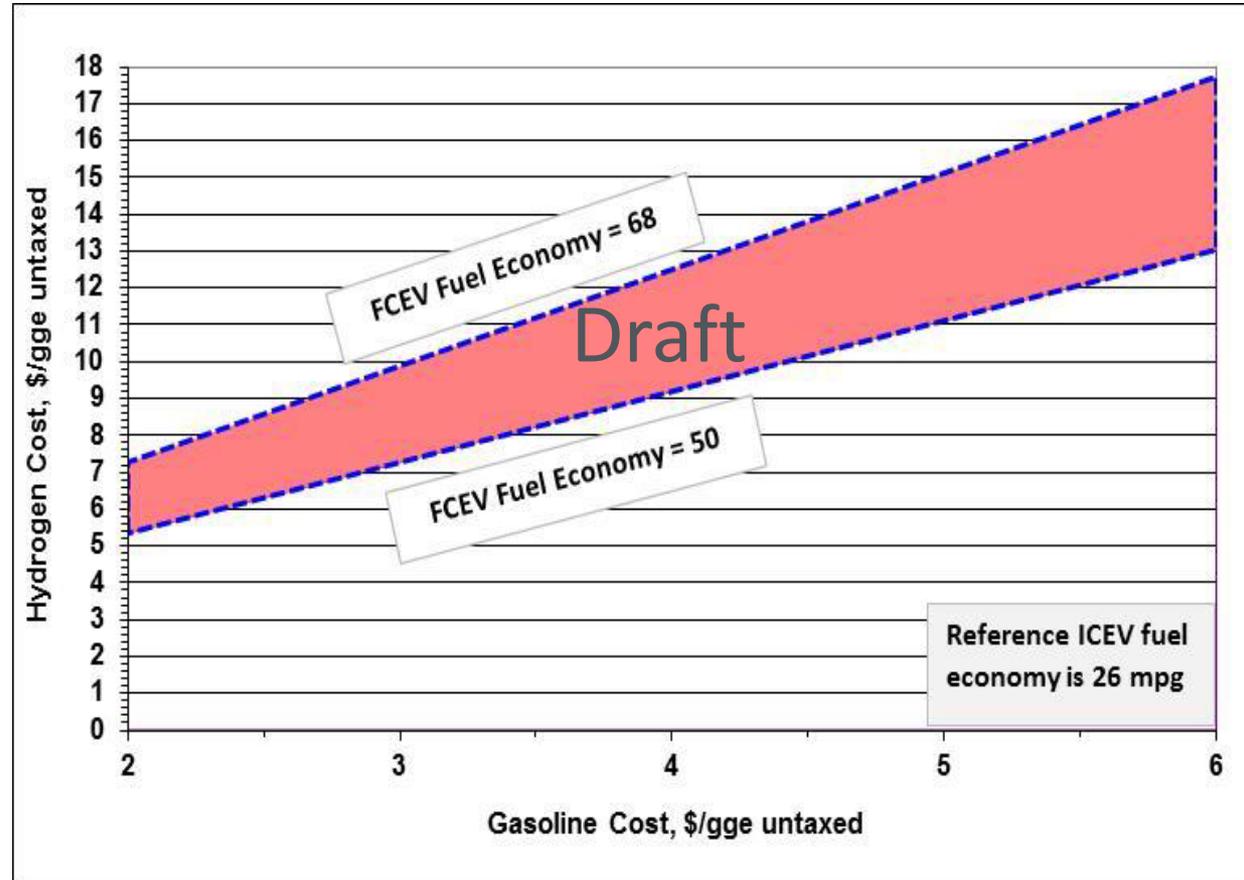
Early Market Competitive Hydrogen Cost Sensitivity Analysis



H₂ would be competitive with gasoline at a cost of ~\$7.00/gge in the early markets.

Interim H₂ Cost Target Methodology

- “top-down” analysis of the cost at which H₂ in the early market would be competitive.
- Target is pathway independent.
- Measure for assessing technology in regions of California and New York where early fuel cell electric vehicle penetration will occur
- FCEV is referenced to the gasoline ICE.



Establishing interim H₂ cost target for early market applications

SOFC Program – Industry Teams

➤ Current Status

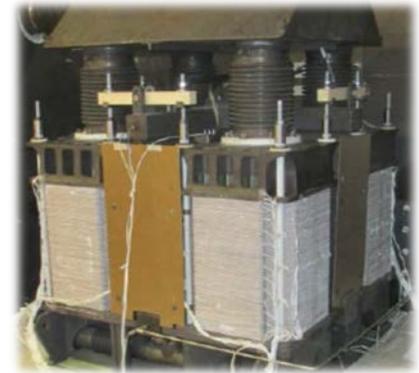
- 20 to 60 kWe Stack Tests - Completed
 - Degradation rates of 1.0 to 1.5% per 1,000 hrs
 - Supplemental heating
 - TRL 5



~20 kWe Stack
(~300 cells)
LGFCs

➤ In-progress

- 60 kWe-class Stack Tests
 - Thermally self-sustaining
 - Expected degradation rate <0.5% per 1,000 hrs
 - Planned operation \geq 1,000 hrs
 - TRL 6



60 kWe Stack
(~400 cells)
FCE

➤ Planned (Two new awards FY2014)

- 125 kWe-class System Tests
 - Thermally self-sustaining
 - PNG, AC to grid
 - Planned operation >2,500 hrs
 - Commercial-scale sub-systems
 - TRL 7



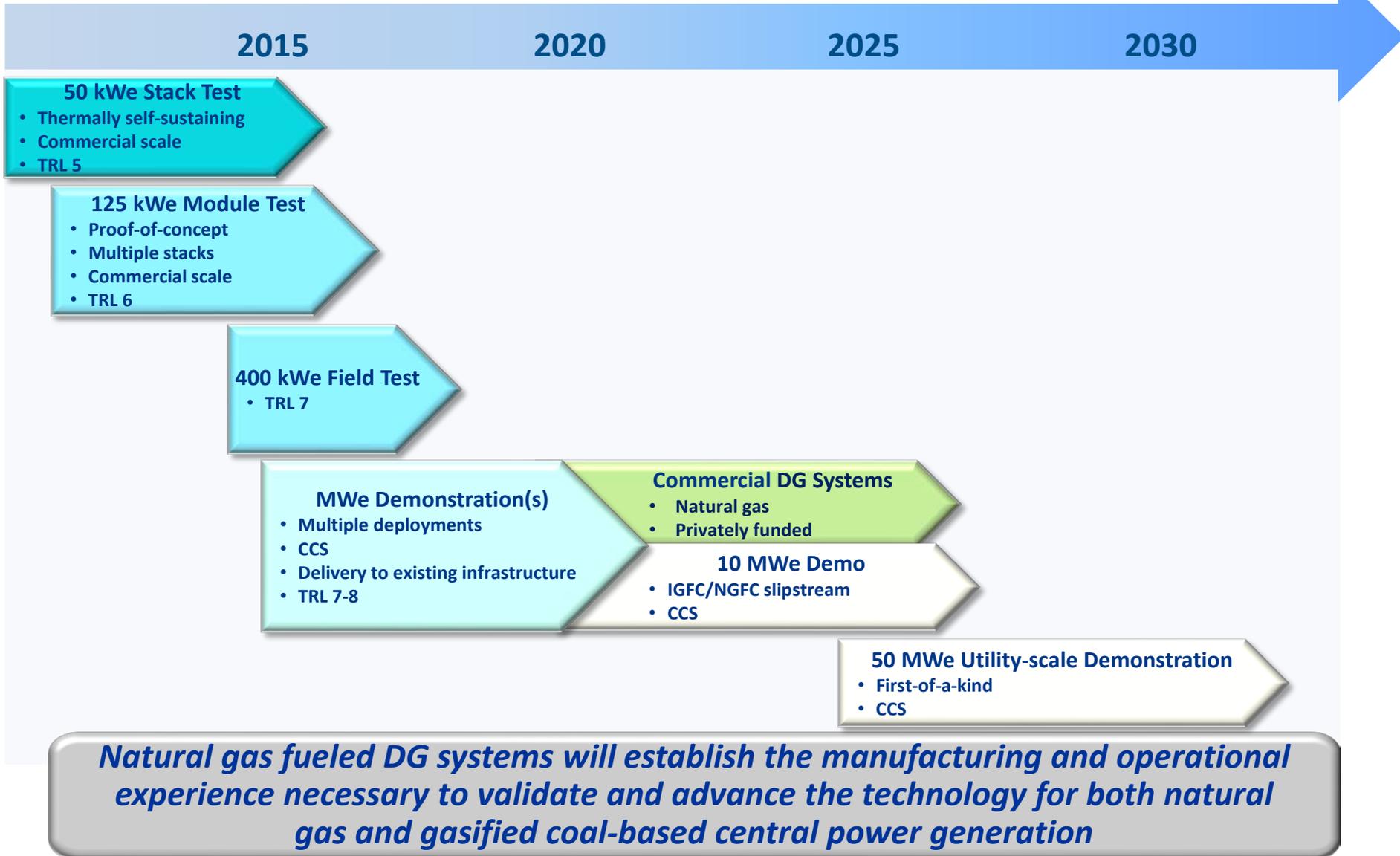
7 kWe Gen 4 Stack
(38 cells)
Delphi

Industry Teams are validating stack technology through progressively larger stack and system tests

FY14 SOFC Program Update

- **Two competitive solicitations**
 - 11 projects selected
 - 2 Industry Teams, 9 Core Technology
- **Increased emphasis on system level testing**
- **Increased emphasis on Industry Team – Core Technology collaboration**
- **Peer Review of 7 Projects**
- **Updated NETL and SOFC Program website**
- **Web-based SOFC Program Portfolio**
- **Three new SBIR projects**

SOFC Technology Development Timeline



SOFC Program - In Summary

- **Emphasis on cost reduction and increased reliability**
- **Focused on system-level testing**
- **Facilitating Industry Team - Core Technology collaboration**
- **Taking advantage of revolutionary advances in materials and manufacturing processes**
- **Issued an RFI on October 31, 2014 for a 400 kWe prototype system test – responses due November 28**

A technically and economically viable SOFC system will create market-pull for natural gas distributed generation applications in the 2020 timeframe

Reliable Electricity Based on ELeetrochemical Systems (REBELS)

Intermediate temperature operation enables load-following fuel cells for distributed generation applications and grid support

Nearer-term to market

Longer-term to market

FUEL CELL



Redox Power Systems, LLC



SAFCeLL



FUEL CELL + BATTERY MODE



An Allied Minds Company



FUEL CELL + FUEL PRODUCTION



Ultra-Clean, Efficient, Reliable Power



————— Duration of stored energy —————>

Nanoframes with 3D Electrocatalytic Surfaces

Scientific Achievement

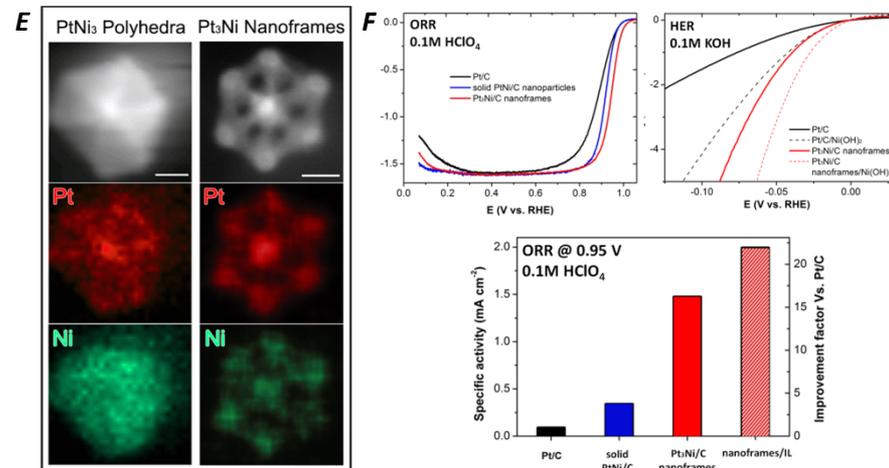
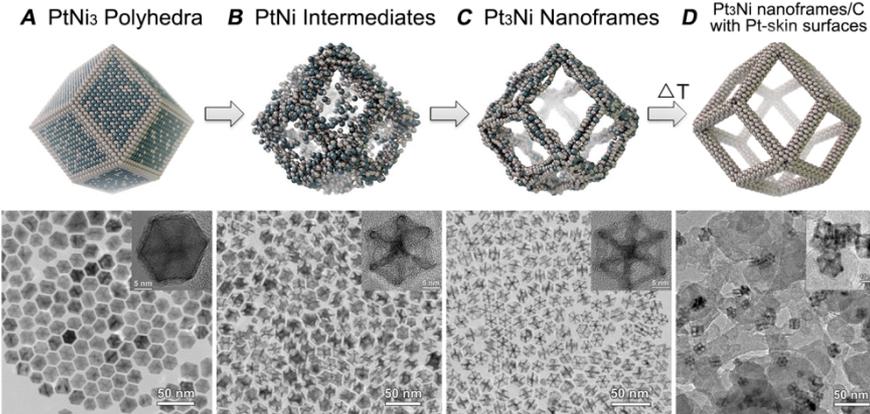
Nanoframe architecture with controlled surface structure, compositional profile and surfaces with three dimensional molecular accessibility

Significance and Impact

Superior electrocatalytic properties of highly crystalline multimetallic nanoscale materials

Research Details

- Structural evolution from PtNi_3 solid bimetallic polyhedra to Pt_3Ni hollow nanoframes
- Surface is tuned to form desired Pt-Skin structure
- Superior catalytic activities for the oxygen reduction and hydrogen evolution reactions have been achieved for highly crystalline multimetallic nanoframes
- Collaborative effort between Lawrence Berkeley National Laboratory and Argonne National Laboratory



Multimetallic nanoframes with 3D surfaces:

Structural evolution of nanoparticles from: (A) polyhedra, (B) intermediates, (C) nanoframes and (D) nanoframes with multilayered Pt-Skin structure; (E) elemental mapping and (F) superior electrochemical activities for ORR and HER

C. Chen et al., "Highly Crystalline Multimetallic Nanoframes with Three-Dimensional Electrocatalytic Surfaces", *Science* **343**(2014) 1339-1343
DOI: 10.1126/science.1249061



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Work was performed at Lawrence Berkeley and Argonne National Laboratories



Argonne
NATIONAL LABORATORY

Leaky TiO₂-stabilized Photoanodes for Solar Fuel Production

Scientific Achievement

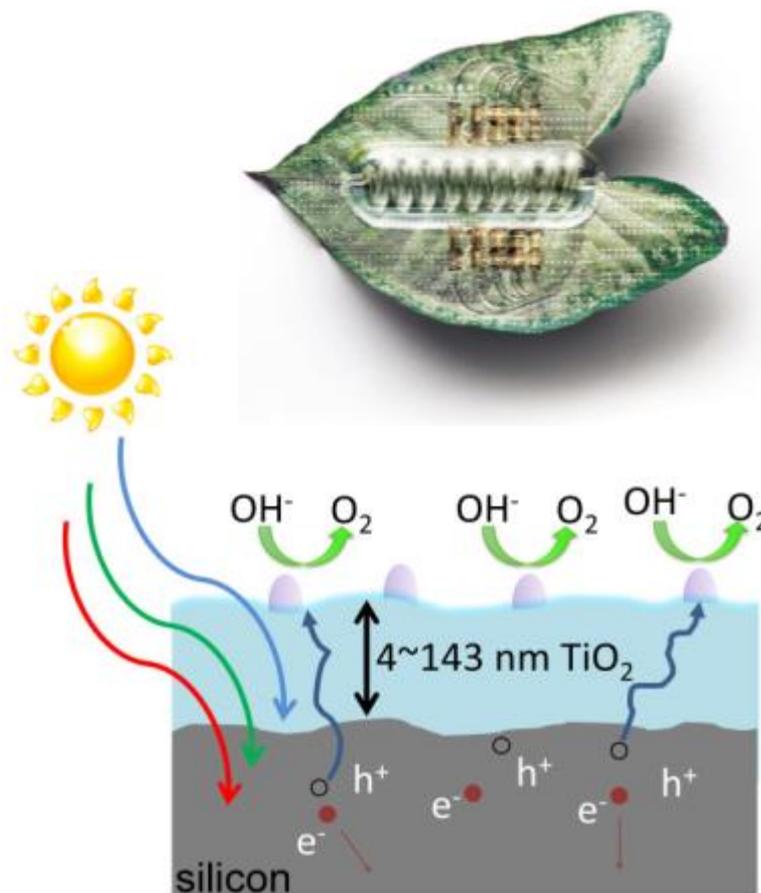
JCAP researchers devised a new method to protect common semiconductors from corrosion in basic aqueous solutions, while still maintaining excellent electrical charge conduction to the surface.

Significance and Impact

Highly light-absorbing semiconductors like silicon and gallium arsenide, which corrode when unprotected, can now be incorporated in photoanodes for solar fuel generators.

Research Details

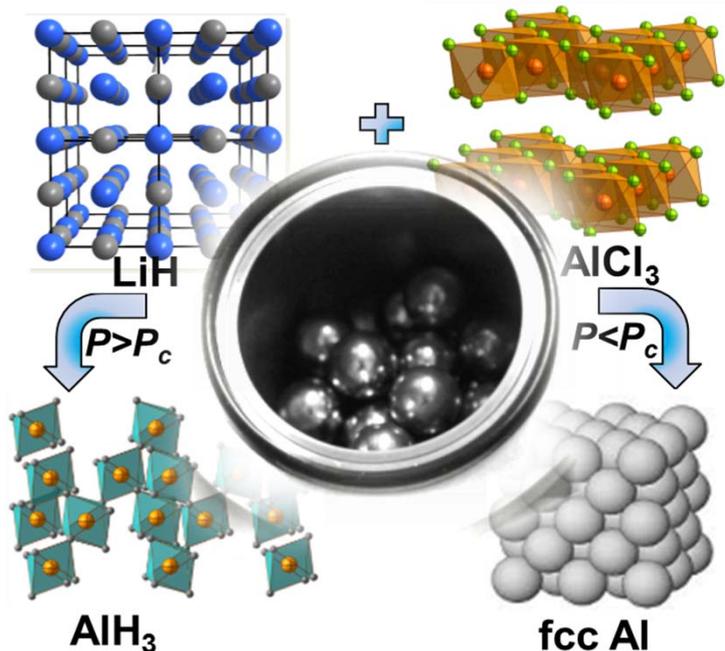
- Semiconductors are protected by an electronically defective layer of ~100 nm thick, unannealed TiO₂ using atomic layer deposition
- In conjunction with islands of nickel oxide electrocatalysts, protected Si can continuously and stably oxidize water for over 100 hours at photocurrents of >30 mA cm⁻² under 1-sun illumination



Photoanode stabilized against corrosion in an aqueous KOH electrolyte by a thick, electronically defective layer of unannealed TiO₂ produced by atomic layer deposition.

Hu, S., *et. al*, *Science*, 344, 1005-1009 (2014). DOI: 10.1126/science.1251428

Mechanochemical preparation of Alane (AlH_3): Exploiting the non-equilibrium pathways



Ball-milling LiH and AlCl₃ at pressures (P) exceeding a critical pressure (P_c) leads to the formation of AlH₃

Ball-milling LiH with AlCl₃ at pressures below P_c leads to conversion of nearly all aluminum to the metal

I.Z. Hlova, S.Gupta, J.F.Goldston, T.Kobayashi, M.Pruski and V.K.Pecharsky, "Dry Mechanochemical Synthesis of Alane from LiH and AlCl₃" *Faraday Discuss.*, 2014, DOI: 10.1039/C3FD00161J

Work was performed at Ames Laboratory, Iowa State University.

Scientific Achievement

A successful strategy for the solvent-free, room temperature mechanochemical synthesis of AlH₃ via a solid state metathesis reaction of LiH and AlCl₃ has been developed.

Significance and Impact

The course of mechanochemical reactions and, hence, the final products can be controlled by gradual addition of reactants and gas pressure, thus opening up possibilities to access new materials by mechanochemistry.

Research Details

- By adding AlCl₃ to LiH in three steps and applying gas pressure, quantitative yield of AlH₃ – an important energetic material – has been achieved.
- Using x-ray diffraction, solid state NMR, and temperature programmed desorption analyses established the mechanism of mechanochemical transformation: $3\text{LiH} + \text{AlCl}_3 \rightarrow 3\text{LiCl} + \text{AlH}_3$.