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
Agenda

• HTAC Charter & Membership
• Program Overview
  – Budget & Organization
• HTAC Recommendations
  – Key Accomplishments & Program Responses
• National Lab Impact Initiative and Next Steps
HTAC Members

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)
• Commissioner 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, Aretè Corporation

New Members
To advise the Secretary of Energy on:

1. The implementation of programs and activities under Title VIII of EPACT

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
Title VIII Sec. 802

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

**Mission:** Enable widespread commercialization of a portfolio of $H_2$ and fuel cell technologies through basic and applied research, technology development and demonstration.

<table>
<thead>
<tr>
<th>Fuel Cell Cost</th>
<th>$40/kW</th>
<th>$1,000/kW* $1,500/kW**</th>
</tr>
</thead>
<tbody>
<tr>
<td>Durability</td>
<td>5,000 hrs</td>
<td>80,000 hrs</td>
</tr>
<tr>
<td>H$_2$ Storage Cost (On-Board)</td>
<td>$10/kWh</td>
<td></td>
</tr>
</tbody>
</table>
| H$_2$ Cost at pump | <$4/gge *For Natural Gas **For Biogas
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
Guiding Documents

Stakeholder input

- Toward a More Secure and Cleaner Energy Future for America
- National Hydorin Energy Roadmap
- Fuel Cell Report to Congress

Strategy

- Hydrogen Posture Plan
- Hydrogen from Coal RD&D Plan
- Multi-Year RD&D Plan

Planning

- The Department of Energy Hydrogen and Fuel Cells Program Plan
- Basic Research Needs for the Hydrogen Economy
Each subprogram has detailed milestones, inputs, outputs, go-no go decision points and technical targets.

Example - Target Table for Electrocatalysts

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

\(^a\) single cell status – will require scale-up
\(^b\) preliminary targets – approval pending
\(^c\) after 30,000 cycles from 0.6 – 1.0 V; after 400 hours at 1.2 V
\(^d\) after 400 hours at 1.2 V
\(^e\) baseline @ 900mV\(_{IR}\)-free
\(^f\) baseline @ 800mV\(_{IR}\)-free

Update of Multiyear RD&D Plan in process
In addition to above partnerships, advice & peer review provided by Federal Advisory Committee (HTAC), NAS, GAO, IG, AMR
Key HTAC Recommendations

• 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*

<table>
<thead>
<tr>
<th>Year</th>
<th>Cost ($/kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>$134</td>
</tr>
<tr>
<td>2007</td>
<td>$106</td>
</tr>
<tr>
<td>2008</td>
<td>$95</td>
</tr>
<tr>
<td>2009</td>
<td>$85</td>
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<tr>
<td>2010</td>
<td>$75</td>
</tr>
<tr>
<td>2011</td>
<td>$67</td>
</tr>
<tr>
<td>2012</td>
<td>$55</td>
</tr>
<tr>
<td>2013</td>
<td>$44</td>
</tr>
</tbody>
</table>

Status Today ($55/kWh)

Goal $30/kWh)

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

*At 500,000-unit production

DOE’s RDD&D activities are enabling commercialization of fuel cells
## Hydrogen & Fuel Cell Budget

### Key Activity

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

### Office FY 2014

<table>
<thead>
<tr>
<th>Office</th>
<th>FY 2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>EERE</td>
<td>$93M</td>
</tr>
<tr>
<td>Basic Science$^2$</td>
<td>$20M to $25M</td>
</tr>
<tr>
<td>Fossil Energy, SECA</td>
<td>$25M</td>
</tr>
<tr>
<td>ARPA-E$^3$</td>
<td>$33M</td>
</tr>
<tr>
<td><strong>FY14 DOE Total: ~$175M</strong></td>
<td></td>
</tr>
</tbody>
</table>

*Consistent R&D funding request and appropriations in recent years*
## Hydrogen and Fuel Cell Summary

### FY15 Senate and House Language

<table>
<thead>
<tr>
<th>SENATE</th>
<th>HOUSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total recommendation: $93,000,000</strong></td>
<td><strong>Total recommendation: $100,000,000</strong></td>
</tr>
</tbody>
</table>
| • 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. | Technology Validation:  
• $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. |
| • DOE should focus on consumer acceptance and strategic locations. |  |
| No specific direction on allocation of $93M (consistent with request). | Advanced demonstration and deployment:  
• $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. |
| H2USA: Committee is encouraged by the collaborative approach reflected in H2USA. | No direction. |
DOE funding has led to ~500 patents and 45 commercial technologies
Revenues and additional investment valued at >4X and >5X the DOE investment.
Catalyzing early markets enables broader commercialization of FCEVs
Fuel Cell Cost Reductions Enabled by R&D

Fuel Cell Cost Reductions

50% from 2006

30% from 2008

5X

Platinum Catalyst

Fuel Cell Cost Status and Goal

• $55/kW* for high volume
• ~$280/kW† for low volume
• $40/kW by 2020 is the goal

Catalyst accounts for >45% of total system cost

*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

Fuel Cell System Cost*

Cost Breakdown

- Bipolar Plates
- Membranes
- Catalyst + Application
- GDLs
- MEA Frames/Gaskets
- Balance of Stack

*For PEMFC Stack cost, 500,000 units per yr.
Cost is shown as $/kW-net.
ANL and UC Berkeley scientists develop a high-mass activity nanoframe
Synthesis & Evaluation of Nanoframes

C Pt₃Ni Nanoframes

D Pt₃Ni nanoframes/C with Pt-skin surfaces

Dispersible cathode catalyst with extended thin film catalyst properties
Synthesis & Evaluation of Nanoframes

Microscopy demonstrates nanoframe hollow structure
Catalyst mass activity >30X higher than conventional Pt/C

Synthesis & Evaluation of Nanoframes

Reference:
“Highly Crystalline Multimetallic Nanoframes with Three-Dimensional Electrocatalytic Surfaces”
Vojislav Stamenkovic (ANL) & Peidong Yang (LBNL/UCB)
Science, 343 (2014) 1339

*Catalyst only in RDE tests
Future plans: Demonstrate MEAs
H₂ Infrastructure Development and Status

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

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

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, NE States and Hawaii have H₂ infrastructure efforts underway
H₂USA Public-Private Partnership to address H₂ Infrastructure Challenges

3X increase in partners and growing since 2013
Hydrogen Fueling Infrastructure Research Station Technology

$1.4M DOE Funding
Leveraging Expertise of National Labs

DOE’s $2FIRST project supports H2USA goals to address infrastructure

In Support of

Reference Station Design

Fuel Contaminant Detection

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

HyStEP Device
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.

Promoting H₂ fueling system development in the community

Visit http://hydrogenprize.org/
International Partnerships

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

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

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
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 risked-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 OIML$^1$ 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
Hydrogen Refueling Station Analysis Model (HRSAM)

Uses discounted cash flow analysis to estimate cost ($/kg) of H₂ dispensing at a given station based on equipment costs.

**Primary inputs:**
- Analysis period (years)
- Debt-to-equity ratio
- Debt interest and real after-tax discount rate
- Capital and operating costs of equipment (compressors, storage, dispensers, refrigeration, etc.)*
- Projected annual utilization

* Default values are based on early market data

**Output**
- Mode of hydrogen delivery (tube trailer vs. pipeline, liquid vs. gas)
- Number of consecutive fills station can complete
- Number of dispensers
- Station size (kg/day)

Developed at Argonne National Laboratory (ANL)
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**
Safety Codes and Standards | Communication and Outreach

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

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
FCEVs are Here!

Available for Public Purchase soon....

Now Leasing...

Hyundai Tucson Fuel Cell SUV

In Auto Shows...

Toyota Fuel Cell Electric Vehicle

Honda Fuel Cell Electric Vehicle

OEMs bringing fuel cells to showrooms and driveways
Outreach and Communication Efforts

- **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**

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*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)*

Innovation from LANL can be found in most fuel cells today
DOE funded R&D has advanced the state of technology for FCEV systems.
Fuel Cells Tech-to-Market (T2M) Strategy

Activities

Increase Industry Contact
- Business-to-Business Product Theater (Eleven Labs)
- Manufacturing Road Show

Listen to the Voice of the Customer
- Key Staff Exchange with Industry

Develop Technology Transfer Skills
- Business Plan Development Training
- Lab Corps

Increase Market Understanding

Improve Private Sector Relationships

Improving technology transfer and targeted impact from lab to market
T2M Activities at the Fuel Cell Seminar and Exposition (FCS&E)

• 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

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
Going Forward

• **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
HTAC Input Requested:

- 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.
Draft goals continued

• 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
Recent Webinars

- SAE Hydrogen Fueling Standardization (Sep 11, 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)
- 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)
Recent Workshops

• 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 $H_2$
- Solar-based water splitting
- Photolytic Bio-hydrogen

$H_2$ from natural gas is available now while $H_2$ from renewables is a longer-term focus.
Hydrogen Delivery Cost Reductions

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

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

* 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**

- Compression and Storage comprise approximately 75% of CSD costs

R&D has enabled H\(_2\) delivery reduction costs but compression is still a key challenge.
700 bar compressed H\textsubscript{2} 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*
New Selections for Hydrogen Storage RD&D

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

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

DOE/EERE/FCTO
- Fuel Cell Cost
- H₂ Production
- H₂ Delivery
- Tanks and Storage
- Safety Codes and Standards
- Tech Validation (NFCTEC)
- Market Transformation
- H2FIRST
- H2USA
- CaFCP
- IPHE

“Collaboration for Success”
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

### Hydrogen Station Financing Advisor

#### Station Inputs
- Station Utilization [%]: 65
- Maximum hydrogen price [$/kg H₂]: 10
- Total Capacity [kg/day]: 360
- Total Capital Cost [$]: 2,090,000
- Total Installation Cost [$]: 490,000

#### Scenario Inputs
- Capital Incentive [$/Station]: 150,000
- Duration of Capital Incentive [years]: 2
- Initial Production Incentive [$/Station]: 100,000
- Annual Decrement of Production Incentive [$/Station]: 10,000
- Duration of Production Incentive [years]: 5

#### Financing Inputs
- Debt Interest Rate [%]: 7.0
- Maximum Return on Equity [%]: 10.0
- Minimum Debt to Equity Ratio: 0.5
- Minimum Debt Coverage Service Ratio: 2

**Download hydrogen station finance calculator**
**Download results**
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

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

- **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

*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
Natural gas fueled DG systems will establish the manufacturing and operational experience necessary to validate and advance the technology for both natural gas and gasified coal-based central power generation.
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 ELectrochemical Systems (REBELS)

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

**FUEL CELL**
- REDOX
- SAFCell
- OAK RIDGE National Laboratory

**FUEL CELL + BATTERY MODE**
- United Technologies Research Center
- Colorado School of Mines
- parc®
- Georgia Tech

**FUEL CELL + FUEL PRODUCTION**
- Si Energy Systems, LLC
- University of South Carolina
- UCLA
- FuelCell Energy
- MSRI
- Argonne National Laboratory

Nearer-term to market

Longer-term to market

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$_3$Ni 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
**Leaky TiO$_2$-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 TiO$_2$ 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 TiO$_2$ produced by atomic layer deposition.

Mechanochemical preparation of Alane (AlH\textsubscript{3}): Exploiting the non-equilibrium pathways

Scientific Achievement

A successful strategy for the solvent-free, room temperature mechanochemical synthesis of AlH\textsubscript{3} via a solid state metathesis reaction of LiH and AlCl\textsubscript{3} 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 AlCl\textsubscript{3} to LiH in three steps and applying gas pressure, quantitative yield of AlH\textsubscript{3} – 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: 3LiH + AlCl\textsubscript{3} \rightarrow 3LiCl + AlH\textsubscript{3}.


Work was performed at Ames Laboratory, Iowa State University.