Hydrogen and Fuel Cell Program Overview

Dr. Sunita Satyapal, Director - Fuel Cell Technologies Office

2018 Annual Merit Review

Washington D.C. - June 13, 2018
Exciting time for hydrogen & fuel cells
Fuel Cell Shipments - Growth by Application

Fuel Cell Power Shipped (MW)

- 650 MW fuel cell power shipped worldwide
- 70,000 fuel cell units shipped worldwide
- Approximately $2 Billion fuel cell revenue

Source: DOE and E4Tech
Growth by Fuel Cell Type

Fuel Cell Power Shipped (MW)

Source: E4Tech
Nearly 5,000 fuel cell cars in the U.S. since 2015
2018 U.S. Snapshot

More than 20,000 forklifts

Over 12 million refuelings
2018 U.S. Snapshot

Over 30 buses in 4 states

19 million passengers
35 retail stations open today

Over 200 planned
Hydrogen and Fuel Cell Applications in the U.S.

U.S. Snapshot

- **>240MW** Backup Power
- **>20,000** Forklifts
- **>30** Fuel Cell Buses
- **35** H₂ retail stations
- Nearly **5,000** fuel cell cars

States with Growing Interest

- **More than $180M**
  - The total amount states have invested in H₂ infrastructure in the past decade*

Recent News: 200 stations by 2025 in CA

- **HI, OH, SC, NY, CT, MA, CO, UT, TX, MI, and others with interest**
  - Over $27M invested
  - 12-25 stations planned in the NE

- **CA**
  - 200 stations planned
  - Over 30 public stations open
  - $150M invested
  - $235M announced in 2018

*Excludes recent announcement from CA to invest $235M in electric vehicles
Electrolyzers

Global sales estimated at 100 MW/year*

Potential production capacity in 2020 by manufacturer (anonymised). Depending on corresponding growth in demand.

Order of Magnitude:
- 5 MW/a
- 50 MW/a
- 500 MW/a

*Courtesy of NOW, E4tech and partners: A collaborative effort to assess electrolyzer market potential

© Fraunhofer ISE
Automotive Executives Survey Results

First time fuel cell electric mobility ranks #1 trend among automotive executives

Source: KPMG Global Automotive Executive Survey 2018
Program Overview
Strategy

R&D and innovation to enable affordable and reliable hydrogen and fuel cell technologies.

Increase focus on infrastructure.
Targets Guide R&D
## DOE fuel cell system cost vs. targets

<table>
<thead>
<tr>
<th>Category</th>
<th>Light Duty (Truck MD)</th>
<th>Forklifts (5-kW)</th>
<th>Backup Power (5-kW)</th>
<th>Stationary (25-kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Targets</strong></td>
<td>$40</td>
<td>$400</td>
<td>N/A</td>
<td>$1,500</td>
</tr>
<tr>
<td><strong>High-Volume Projection</strong></td>
<td>$230†</td>
<td>$6,100</td>
<td>$7,400</td>
<td>$3,000</td>
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<tr>
<td><strong>Low-Volume Estimate</strong></td>
<td>$180*</td>
<td>$100</td>
<td>$1,000</td>
<td>$1,900</td>
</tr>
<tr>
<td><strong>($/KW)</strong></td>
<td>$50 100K/yr</td>
<td>$2,800 100K/yr</td>
<td>$2,800 100K/yr</td>
<td>$2,000 100K/yr</td>
</tr>
<tr>
<td><strong>($/KW)</strong></td>
<td>$45 500K/yr</td>
<td>$2,400 50K/yr</td>
<td>$2,400 50K/yr</td>
<td>$1,900 100K/yr</td>
</tr>
<tr>
<td><strong>($/KW)</strong></td>
<td>$40</td>
<td>N/A</td>
<td>$1,000</td>
<td>$1,900</td>
</tr>
</tbody>
</table>

*Based on commercially available FCEVs  †Based on state of the art technology

Note: Graphs not drawn to scale and are for illustration purposes only.
Hydrogen fuel cost vs. targets

Production, Delivery & Dispensing

$10/kg to $5/kg

$16/kg to $13/kg

On-board Storage
(700-bar compressed system)

$24/kWh

$17/kWh

100K/yr

$15/kWh

500K/yr

$9/kWh

Note: Graphs not drawn to scale and are for illustration purposes only.
Cost reduction strategies based on analysis

Examples of cost reduction strategies include footprint reduction to enable higher H₂ throughput stations.

Target: $7/kg. by 2025
Key Program Early R&D Focus Areas - FY18

**Fuel Cells**

- PGM- free catalysts
- Durable MEAs
- Electrode performance

**Hydrogen Fuel**

- Production
- Delivery (including dispensing)
- Storage

PGM = Platinum group metals
MEA = Membrane Electrode Assembly
Program Mission and Strategies

### Early R&D Focus

Applied research, development and innovation in hydrogen and fuel cell technologies leading to:

- Energy security
- Energy resiliency
- Strong domestic economy

### Early R&D Areas

<table>
<thead>
<tr>
<th>Fuel Cells</th>
<th>Hydrogen Fuel</th>
<th>Infrastructure R&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td>• PGM- free catalysts</td>
<td>• Production Pathways</td>
<td>• Safety</td>
</tr>
<tr>
<td>• Durable MEAs</td>
<td>• Advanced materials for storage</td>
<td>• Manufacturing</td>
</tr>
<tr>
<td>• Electrode performance</td>
<td></td>
<td>• Delivery components</td>
</tr>
</tbody>
</table>

**Enabling**

**New in FY19 Budget Request**

PGM = Platinum group metals

MEA = Membrane Electrode Assembly
Strategy: Leveraging National Labs and Partners

Consortium Approach

Multi-lab core capabilities with steady influx of new partners

Consortia Launched

- Improved PEM fuel cells
- PGM-free catalysts
- Advanced $\text{H}_2$ materials storage
- Materials for renewable $\text{H}_2$ production
- New Consortium: H-MAT
EMN: A Platform for Accelerated Materials R&D

Energy Materials Network
U.S. Department of Energy

Research Capabilities & Core Principles
guiding EMN

- Predictive Simulation Across Scales
- Synthesis & Characterization
- Rapid Screening
- End Use Performance
- Process Scalability
- Process Control
- Real-time Characterization
- Reliability Validation

Data Management & Informatics

EMN’s initial consortia are focusing on targeted materials tracks aligned with some of industry’s most pressing clean energy materials challenges.
Technical Accomplishments
DOE Program Impact - Examples

Innovation

Approx. 730 H₂ and fuel cell patents enabled by FCTO funds

Approx. 35% of H₂ and fuel cell patents come from National Labs

Market Impact

More than 30 Technologies commercialized by private industry

and over 65 with potential to be commercial in the next 3-5 years can be traced back to FCTO R&D

Examples of Progress enabled by DOE FCTO in the last decade

Reduced cost 60%

Quadrupled durability

Cut electrolyzer costs 80%
Leverage Private Sector to Accelerate Lab IP to Market

L’Innovator= “Lab Innovator” FCTO Pilot

Early stage R&D

Lab 1

Lab 2

Lab 3

Agreements and Selections

- FCTO Inter-lab Agreement
- Lab CRADA call

Manufacturing and Scale up

Company 1

DOE Fuel Cell Technologies (FCTO) Office

Private Sector

$
Examples: R&D 100 Awards and more

2017 R&D 100 Joint Entry
Clean-Energy Electrocatalysts Without Precious Metals
Making Next-Generation Fuel Cells Cost-Effective
Los Alamos National Laboratory and Pajarito Powder, LLC

- Designed to approach the performance of platinum-based electrocatalysts but at a fraction of the cost
- Made using inexpensive, Earth-abundant, and easily sourced precursor materials that eliminate the need for scarce and costly precious materials
- Offer increased stability/durability for continuous operation
- Decrease the time-to-market for technologies that provide clean, reliable, and affordable energy

Science Paper (LANL, ORNL)
Active site(s) in PGM-free Fe-N-C

Ordered core (PtCo) remains intact even after 30K cycles (AST)
(LANL, Brown University, ORNL)

Journal of the Electrochemical Society: Focus Issue on PEM Fuel Cell Durability
Guest Editors: Jean St-Pierre, Debbie Myers, Rod Borup, over 40 papers, many FC-PAD authors
Focus Areas

Emphasize high-throughput + modeling for catalyst R&D

Increase focus on innovative membranes
HydroGEN: High-Impact Computational Research in Catalysis

Self-optimizing, highly surface-active layered metal dichalcogenide catalysts for hydrogen evolution

Yuanyue Liu\textsuperscript{1,3}, Jingjie Wu\textsuperscript{1,3}, Ken P. Hackenberg\textsuperscript{1,3}, Jing Zhang\textsuperscript{1}, Y. Morris Wang\textsuperscript{2}, Yingchao Yang\textsuperscript{1}, Kunttal Keyshar\textsuperscript{1}, Jing Gu\textsuperscript{3}, Tadashi Ogitsu\textsuperscript{2}, Robert Vajtai\textsuperscript{1}, Jun Lou\textsuperscript{1}, Pulickel M. Ajayan\textsuperscript{1}, Brandon C. Wood\textsuperscript{2,*} and Boris I. Yakobson\textsuperscript{1,*}

Steering Committee Member (Tadashi) owns a FCEV and chooses a unique license plate
HydroGEN: High-Impact Research in Photoelectrochemistry

Achieving Record Performance

Addressing Benchmarking Needs
Technology advancement by publishing standards, protocols and reviews.

PEC World Record Benchmarked at >16% STH

Technology Standards to Facilitate Research Progress

Downloads to date 33,000
Focus Areas

Emphasis on water-splitting

Raising the Tide: R&D Test Protocols for Water-Splitting
HyMARC Advanced Hydrogen Storage Materials

Provides **foundational understanding** of thermodynamics and kinetics to advance solid-state hydrogen storage materials

Delivers **community tools and capabilities:**
- High-throughput materials screening
- Surface, bulk, soft X-ray, synchrotron
- Probing nanoscale phenomena
Focus Areas

Adding H₂ Carriers
R&D to HyMARC
Example of Innovation - potential for heavy duty?

Cryo-compression can offer densities higher than liquid hydrogen

ANL analysis (preliminary) shows potential for:

- 90-200% storage capacity increase
- 25% less cost (at 5,000 units/yr)
- 46% less carbon fiber composite
Potential Opportunities for Larger Vehicles/Long Range

FCEVs: Lower cost for large size classes and longer driving range

Year 2040: FCEV minus BEV-X Total Cost of Ownership
Green shows where FCEVs are more cost effective

<table>
<thead>
<tr>
<th></th>
<th>50 mi.</th>
<th>100 mi.</th>
<th>150 mi.</th>
<th>200 mi.</th>
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<td>-$0.06</td>
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<td>-$0.07</td>
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<td>-$0.19</td>
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<tr>
<td>Pass Van</td>
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<td>Small Pickup</td>
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<td>-$0.07</td>
<td>-$0.11</td>
<td>-$0.15</td>
<td>-$0.19</td>
</tr>
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</table>

Preliminary DOE Market Segmentation Study
More liquid stations planned

Based on data from NREL
Safety R&D Accomplishments enabling Infrastructure

Tunnel Safety R&D and Modeling

Relief vent fire doesn’t have a significant impact on tunnel structure elements

Validation of release models

First ever nearfield measurement and validation of temp., concentration and velocity of cryogenic plumes at 50K
Infrastructure R&D related progress - Examples

LANL, LLNL, and H2Frontier R&D 100 award for H2 safety sensor (available for commercialization)

LANL contamination detector (HCD) to alert - in real time - fuel station operator if conditions for potential poor hydrogen fuel quality exist.
Vision

H2@Scale: Enabling affordable, reliable, clean and secure energy across sectors
H₂@Scale System

*Illustrative example, not comprehensive
Source: NREL
H₂@Scale: Linking Natural Gas, Electric and H₂ Grids
Versatility

Volume

Value Proposition
The Duck Curve 101 - Example

Total Load (demand)

Load (net) on commercial utility grid (duck belly forms)

Solar Production
The Duck’s belly is getting bigger

Two Concerns:

- **Low Net Load:** flexibility to reduce baseload generation resources is limited
- **High Ramp Rates in Evening:** flexibility of other generation to ramp up is limited

Source: U.S. DOE Solar Energy Technologies Office

*Real example from California*
Lab testing shows value of electrolyzers for ancillary services

First Ever Validation of Frequency Regulation with Electrolyzers

Lab testing shows dynamic response within seconds and potential for grid services
Scale: Simple Example

How much hydrogen for 1 car?

12,000 miles per year = 200 kg or 0.2 tonnes per year
60 miles per kilogram

How much hydrogen for many cars?

100 M cars = 10M cars

20M tons H₂ per year
20 B kg H₂ per year
Refineries: Where is the H₂ demand today?

2017

H₂ Demand

5.9 MMT

Source: Elgowainy, et al, ANL
Ammonia: Where is the H₂ demand today?

2017

H₂ Demand

2.9 MMT

Ammonia

H₂ demand (1000 MT/yr)

- 100
- 300
- 500

Source: Elgowainy, et al, ANL
Ammonia & Refineries and Potential H₂ Demand

2030

H₂ Demand

11.2 MMT

Source: Elgowainy, et al, ANL
Plus demand from synthetic fuel production...

Source: Elgowainy, et al, ANL
Hydrogen Demand Potential

2030

Nearly 30 million metric tons of potential hydrogen demand in the U.S.

Source: Elgowainy, et al, ANL
H₂@Scale: Value to industrial processes?

Electrical power plant cooling

- Over 16,000 H₂ cooled generators worldwide
- Less delivery logistics, inventory management, 1-2 yr payback and improved efficiency
- Potential $2B addressable market

Source: Proton

Iron Refining, Steel manufacturing

- More energy efficient when hydrogen used as reductant at high temperatures
- Potential annual savings of over $100,000 for a 100,000 ton/year plant

Source: EERE Advanced Manufacturing Office, Berry Metal

Image Credit: Berry Steel
H₂@Scale: Enabling renewable energy transport?

Where we find abundant solar and wind energy
H₂@Scale: Enabling renewable energy transport?

Where we find abundant solar and wind energy
...and deliver it or co-locate distributed generation with demand for certain applications

Where energy is consumed
Preliminary analysis underway to guide future plans

Cost of long distance electricity transmission is high

Can H₂ or H₂ carriers be an option?
Strategy: Partnerships to enable H$_2$@Scale

Early-Stage R&D

- Department of Energy
  - Fuel Cells R&D
  - H$_2$ Fuel R&D
- Other Federal Agencies

Demonstration, Deployment & Commercialization

- Private Sector
  - Industry, Other Agencies, States
- Partnerships
  - FCHEA (H2USA), CaFCP, OFCC, CT, HI, CO, NJ, etc.

H$_2$@Scale Consortium
H₂@Scale Stakeholder Feedback – Examples

2016 Session at Intermountain Energy Summit
Idaho Falls, ID

2017 Session at Fuel Cell Seminar
Long Beach, CA

2017 Workshop
Houston, TX

2016 Workshop
Golden, CO

Hundred of stakeholders engaged
6 DOE Offices engaged
(EERE, FE, NE, OE, SC, ARPA-E)

Examples of additional presentations:
- Utah (2017)
- Michigan (2017)
- Minnesota (2017)
- Germany (2017, 2018)
- Japan (2018)

Planned: 2018 Kickoff
Chicago, IL

Planned: 2018 AMR
Washington, D.C.

2017 Session at FCTO’s Annual Merit Review
Washington, D.C.
H₂@Scale R&D Lab Capabilities—Examples

Techno economic Modeling and Analysis

- Approx. 16,000 jobs today in the fuel cell car sector in the U.S.
- Over 300,000 potential jobs in the future with fuel cell cars in the U.S.

Hydrogen Materials R&D

- Friction & wear
- Pressure cycle aging
- Fundamental property changes

Safety and Infrastructure R&D

Grid simulation and Testing R&D
**H₂@Scale – Lab CRADAs**

- Leverages Lab capabilities and expertise to address challenges- materials R&D, analysis, safety R&D, etc.
- Round 1 in 2017.

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**CRADA = Cooperative Research and Development Agreement**

**SPP- Strategic Partnership Project (‘Work for Others’)**
H₂@Scale 2017 CRADA call selections

**HYDROGEN QUANTITATIVE PERFORMANCE ANALYSIS AND OPERATION R&D**
- Air Liquide
- California Energy Commission
- Connecticut Center for Advanced Technology
- PDC Machines
- Quong & Associates, Inc.

**HYDROGEN DISTRIBUTION COMPONENT DEVELOPMENT R&D**
- California Go-Biz Office
- Frontier Energy
- HyET
- Honda
- NanoSonic
- RIX
- Tatsuno

**ADVANCED HYDROGEN PRODUCTION CONCEPTS R&D**
- Honda
- C4 MCP, Inc.
- GinerELX
- GTA, Inc.

**HYDROGEN INTEGRATION WITH ENERGY GENERATION R&D**
- Electric Power Research Institute
- Exelon
- Southern Company / Terrestrial Energy
- Nikola Motor
- Pacific Gas & Electric
- TerraPower
Energy Systems Integration R&D, NREL Coordinating with INL, SNL and other labs For H2@Scale
Example of End Use & Industry Partnership with Labs

Production of natural gas using H₂

- Utilizes H₂ + CO₂ and salts to generate pipeline quality natural gas (> 97% CH₄)

- Biocatalyst used in the process - Methanothermobacter thermautotrophicus

- Industry and lab partners: Southern California Gas Company, NREL and Electrochaea

Biomethanation Process:

\[ \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \]
First time automotive fuel cell is integrated to a data center
H₂@Scale Future Plans: Focus Areas

MAKE
Increased Low Cost Hydrogen Production

MOVE
More Efficient Hydrogen Transmission

USE
Low Cost Value-added Applications

STORE
Improved Bulk Storage Technologies
August 1

H2@Scale Kickoff Meeting Planned

Chicago

Roadmap Planned
Collaboration and Program Funding
The H₂ and Fuel Cells Program spans other DOE offices

**Funded:**
- 110 companies
- 100 universities & institutes
- 13 national labs

**Program Secretarial Officers**
- Energy Efficiency & Renewable Energy (EERE)
  - Fossil Energy (FE)
  - Nuclear Energy (NE)
- Office of Science (SC)

**DOE Hydrogen & Fuel Cells Program Management (EERE)**

**Hydrogen and Fuel Cells Program Coordination Group**
- EERE: Fuel Cell Technologies Program
  - H₂ and fuel cells R&D
  - Cross cutting activities
  - Infrastructure R&D
- FE Hydrogen Activities
  - H₂ from coal R&D
  - SOFC
- NE Hydrogen Activities
  - H₂ from Nuclear Energy RD&D
- SC Hydrogen and Fuel Cell Activities
  - Basic Energy Sciences

**Interagency Task Force**

**Interagency Working Group**

**Secretary**
- Under Secretary of Energy
- Under Secretary for Science
## DOE Program Funding

### DOE-wide Hydrogen and Fuel Cells Funding

<table>
<thead>
<tr>
<th>Office</th>
<th>FY 2017 ($ in thousands)</th>
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<tbody>
<tr>
<td>EERE</td>
<td>101,000</td>
</tr>
<tr>
<td>ARPA-E</td>
<td>47,000</td>
</tr>
<tr>
<td>Science</td>
<td>22,000</td>
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<tr>
<td>Fossil Energy</td>
<td>30,000</td>
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<tr>
<td>Nuclear</td>
<td>2,000</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>202,000</strong></td>
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### EERE – Fuel Cell Technologies Office

<table>
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<tr>
<th>Key Activity</th>
<th>FY 2017 ($ in thousands)</th>
<th>FY 2018 ($ in thousands)</th>
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<tbody>
<tr>
<td>Fuel Cell R&amp;D</td>
<td>32,000</td>
<td>32,000</td>
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<tr>
<td>Hydrogen Fuel R&amp;D</td>
<td>41,000</td>
<td>54,000</td>
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<tr>
<td>Systems Analysis</td>
<td>3,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Technology Acceleration</td>
<td>18,000</td>
<td>19,000</td>
</tr>
<tr>
<td>Safety, Codes and Standards</td>
<td>7,000</td>
<td>7,000</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>101,000</strong></td>
<td><strong>115,000</strong></td>
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### Coordination across Offices - Examples

#### DOE/EERE AMO
- Prototyping of emerging NG reforming options
- Innovative manufacturing for electrolyzer systems, R2R
- WBS institute: power electronics for H₂ BOP

#### DOE/EERE BETO
- Bio-waste-stream utilization options for H₂
- H₂ options for bio-fuel synthesis

#### DOE/EERE SETO
- Concentrator BOP for solar-thermochemical H₂
- CSP-based solar NG reforming
- Solar to fuels

#### DOE/EERE Wind
- Wind-electrolysis integration R&D

#### NSF
- Academia-based fundamental research relevant to Hydrogen and Fuel Cell R&D (coordination with FCTO consortia)

#### DOE/SC
- Fundamental processes of energy & matter relevant to H₂ manipulations
- Synergies with EFRCs & ongoing projects

#### DOE/FE
- Innovative large-scale coal and NG H₂ options + SOFC

#### DOE/NE
- Integrated and hybrid systems for nuclear H₂

#### DOE/OE
- H₂ for energy storage & grid ancillary services

#### DOE/ARPA-E
- Innovative and disruptive concepts related to hydrogen and fuel cells

### Foundational Early-Stage R&D and H₂@Scale
- Hydrogen production, delivery and storage R&D; fuel cell R&D (PEM, MCFC, PAFC, DMFC, etc.- non SOFC)
- Consortia on hydrogen production, storage, fuel cell catalysts, H₂@Scale
- Technology acceleration (manufacturing R&D, technology validation, market transformation, safety codes and standards)
- Infrastructure R&D
- Systems analysis to guide R&D

#### NIST, DOT DOD, NASA, etc.
- Examples: Standards in H₂ materials & services; next-generation military and space, buses, rail, marine, etc. applications
ARPA-E Hydrogen and Fuel Cells Activities

ARPA-E Programs in Fuel Cells/Electrolyzers for Energy Conversion and Storage

**Power-to-Fuels**
- AEM water electrolysis
- Ammonia synthesis
- NG and CO₂ conversion

**Fuels-to-Power**
- Intermediate temperature fuel cells
- Integrated SOFC/engine systems
- Regenerative fuel cells
- H₂ generation

- OPEN: $17.5*
- IONICS: $6.4*
- REFUEL: $33M
- REBELS: $30M
- IDEAS: $1.5M*
- INTEGRATE: $20M

* - related to FC/electrolyzers/H₂

Source: ARPA-E
Spread the word on H₂ Safety Lessons Learned!

Share at regular team meetings

Provide feedback to FCTO and stakeholders

Find lessons learned at H2tools.org
Collaboration: Announcing New H$_2$ Safety Partnership

Leverages new partnership to promote collaboration on safety
IPHE: International Partnership for H₂ and Fuel Cells in the Economy

• **Share** information on H₂ and fuel cells, lessons learned, best practices

• **Increase** international collaboration to accelerate progress

Launched 2003 and includes 18 countries and the European Commission

- Australia
- Austria
- Brazil
- Canada
- China
- European Commission
- France
- Germany
- Iceland
- India
- Italy
- Japan
- Republic of Korea
- Norway
- Russian Federation
- South Africa
- United Kingdom
- United States

U.S. elected as Chair
May 2018
Save the Date

2019 Annual Merit Review

April 29 - May 1, 2019

Washington, DC
Thank You

Dr. Sunita Satyapal
Director
Fuel Cell Technologies Office
Sunita.Satyapal@ee.doe.gov

energy.gov/eere/fuelcells
DOE Collaboration: H₂ & Fuel Cell Working Group

DOE Program Managers collaborate on hydrogen and fuel cell activities

Points of Contact for Member Offices

**Advanced Research Projects Agency – Energy (ARPA-E)**

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