Hydrogen and Fuel Cells Enabled through the U.S. Department of Energy

Dr. Sunita Satyapal, Director, Fuel Cell Technologies Office

ECS Meeting
May 27, 2019 – Dallas, TX
The Beginning of the DOE Fuel Cell Program...

1970s

A group from labs, government and industry met at Los Alamos to set the foundation for DOE fuel cell programs.

Lab researchers taught scientists around the world how to fabricate fuel cell electrodes. Group from GM relocated to Los Alamos.
LANL: Ian Raistrick- 1988 Patent

“...represented a huge step forward and became the foundation upon which virtually all subsequent research in platinum loading was based.”¹

“...Mahlon Wilson and Shimshon Gottesfeld developed increasingly effective means of reducing platinum loading...eventually produced an MEA...” with only 0.12 to 0.17 mg/cm²

4-10 mg/cm² ➔ 0.5 mg/cm² ➔ 0.12 to 0.17 mg/cm²

Progress
DOE Program Impact - Examples

**Innovation**
- Approx. 960 patents for H₂ and fuel cell technologies enabled by FCTO funds.
- Approx. 37% 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% in fuel cell R&D.
- Quadrupled durability in fuel cell R&D.
- Cut electrolyzer costs 80% in H₂ Production R&D.
Fuel Cell Shipments - Growth by Application

Fuel Cell Power Shipped (MW)

- Approximately 68,500 fuel cell units shipped worldwide
- Over $2.3 Billion in fuel cell power revenue
- 800 MW of fuel cell power shipped worldwide

Source: DOE and E4Tech
Growth by Fuel Cell Type

Fuel Cell Power Shipped (MW)

PEM fuel cell deployments continue to grow

Source: DOE and E4Tech
Fuel Cell Passenger Vehicles Status

Fuel Cell Cars in the U.S.

More than 6,800 fuel cell cars on the road

Over 6,600
Apr. 2019

Jun-14  Jun-16  Jun-18
Example of a Commercially Available FCEV

Power Control Unit
The PCU has two roles: managing the power from the fuel cell stack and the battery, and readying its supply to the motor.

Battery
The Mirai’s nickel-metal hydride battery stores the energy that is recovered while decelerating, and also assists the fuel cell stack when you need more power during acceleration.

Hydrogen Storage Tanks
Two-high-pressure carbon fiber tanks store the hydrogen as fuel.

Fuel Cell Stack
The Toyota fuel cell stack features a compact size and produces the electricity that powers the Toyota Mirai.

Vent
Large intake grills within the front bumper deliver the car’s vital ingredient, air, to the Mirai’s fuel cell stack.

Fuel Economy: 66/66/66
Driving Range: 312 miles
H₂ Tank Capacity: 5.0 kg
Hydrogen Infrastructure Status

More than 40 retail stations. Plans for many more.

Retail Hydrogen Stations in the U.S.

- 40 stations
- Apr. 2019

Graph shows an increase from 0 stations in 2015 to 40 stations in 2019.
Automotive Executives Survey Results

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

Source: KPMG Global Automotive Executive Survey 2018
Real World Applications & World’s Firsts

Fuel cell delivery and parcel trucks starting deliveries in CA and NY

First fuel cell tow truck fleet at airport in Memphis

World’s first fuel cell for maritime ports in Hawaii
More Real World Applications

Industry demonstrates heavy duty fuel cell trucks

ZH2: U.S. Army and GM collaboration
First of its kind

Fuel cell powered lights at Super Bowl in CA

Fuel cell buses in California surpass 19M passengers
More than 25,000 forklifts

Over 19 million refuelings
Real World Applications

World’s first 4-seater fuel cell plane takes off at German Airport

Hydrogen fuel cell trains in passenger service in Germany

Fuel cells provided backup power during Hurricane Sandy in the U.S. Northeast

Fuel cells for stationary backup power for cell phone towers
Fuel cells operating all over the U.S.

Fuel cells used for backup power in more than 40 states

Over 240MW in stationary fuel cell power installed

Over 8,000 backup power units deployed or on order

Six years ago...

AMFC Technology Status

Cellera Technologies, Caesarea, Israel

Shimshon Gottesfeld, CTO

ECS Meeting in SF
November 1st 2013
Another World’s First...

Telecom pilot installation – April 2013

World’s first AMFC pilot installation with local telecom operator
Other Examples from Shimshon

High- and Low-Power DMFCs (1999-2000)

80 W near-ambient DMFC stack for automotive applications: 30 cells, 45 cm² MEA, 1.8 mm per cell

Two-cell air-breathing 10 mW/cm² DMFC for portable electronics (LANL-Motorola collaboration)
DOE Hydrogen and Fuel Cell Program
Program Mission and Strategy

Early R&D Focus

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

- Energy security
- Energy resiliency
- Strong domestic economy

Key R&D Sub-Programs in Budget Request

<table>
<thead>
<tr>
<th>Fuel Cells</th>
<th>Hydrogen Fuel</th>
<th>Infrastructure R&amp;D</th>
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<tbody>
<tr>
<td>- Cost, durability</td>
<td></td>
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<tr>
<td>- Components - catalysts, electrodes, etc</td>
<td></td>
<td></td>
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<tr>
<td>- Increase focus beyond LDVs</td>
<td></td>
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<tr>
<td>- Cost of production across pathways</td>
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<tr>
<td>- Cost and capacity of storage, including bulk/energy storage</td>
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<td></td>
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<tr>
<td>- Cost and reliability of infrastructure</td>
<td></td>
<td></td>
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<tr>
<td>- Delivery components, supply chain</td>
<td></td>
<td></td>
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<tr>
<td>- Safety</td>
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New in FY19 Budget Request

Enabling
H₂@Scale: Enabling affordable, reliable, clean, and secure energy across sectors
Hydrogen Clusters: Opportunities in Texas

Increased renewable (wind) capacity

![Diagram showing installed capacity in Texas](image)

Source: ERCOT

Increased interest in hydrogen as an energy storage

World's largest salt cavern for hydrogen storage commissioned in TX in 2017

H₂ delivery infrastructure is present

![Map showing hydrogen production units in the United States](image)
Assessing resource availability. Most regions have sufficient resources.

Red: Only regions where projected industrial & transportation demand exceeds supply.
U.S. energy mix covers wide of energy sources

U.S. energy consumption by energy source, 2017

Total = 97.7 quadrillion
British thermal units (Btu)

- Petroleum: 37%
- Natural gas: 29%
- Coal: 14%
- Nuclear electric power: 9%
- Renewable energy: 11%
- Hydroelectric: 25%
- Biomass: 45%
- Biofuels: 21%
- Wind: 21%
- Solar: 6%
- Geothermal: 2%

Note: Sum of components may not equal 100% because of independent rounding.

Source: U.S. Energy Information Administration, Monthly Energy Review, Table 1.3 and 10.1, April 2018, preliminary data.
Fuel Cell R&D
Fuel Cell Cost Improvements for Light Duty Vehicles

Fuel Cell Cost Status

- $50/kW* for 100,000 units/year
- $45/kW* for 500,000 units/year
- $181/kW* for 1,000 units/year
- $210/kW† for currently commercialized on-road technology at 1,000 units/year

67% cost reduction since 2006

Cost analysis is not adjusted to account for durability

* SA Inc., bottom-up analysis of model system manufacturing cost, high volume manufacturing with next-gen lab technology
† SA Inc., bottom-up analysis of model system based on commercially available FCEVs
Durability Adjusted Cost Status

Coming soon: combined durability-system cost metric for state of the art light-duty vehicles

* Preliminary Durability-Adjusted Cost Status: $75/kW

1 DOE Cost Targets based on 500,000 systems per year
2 Estimated value for cost

* SA Inc., bottom-up analysis of model system manufacturing cost, high volume manufacturing with next-gen lab technology
Challenges and Strategy

Durability and cost are the primary challenges to fuel cell commercialization and must be met concurrently.

Early-stage materials and components R&D to achieve low-cost, high-performance fuel cell systems.

Improvements in multiple components are required to meet targets.

R&D portfolio focused on PEMFCs, but also includes longer-term technologies (e.g. AEMFCs) & higher temp fuel cells (e.g. MCFCs) for stationary applications.
## Fuel Cell Targets and Status

<table>
<thead>
<tr>
<th>Application</th>
<th>Power (kW)</th>
<th>Cost ($/kW)</th>
<th>Durability (h)</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-duty vehicles</td>
<td>80</td>
<td>30</td>
<td>8,000</td>
<td>70% efficiency, (\leq 0.125 \text{ mg}<em>{\text{PGM}}/\text{cm}^2) (\sim 0.35 \text{ mg}</em>{\text{PGM}}/\text{cm}^2)</td>
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<tr>
<td></td>
<td></td>
<td>75*</td>
<td>5,000</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>120*</td>
<td>4,100</td>
<td></td>
</tr>
<tr>
<td>Medium and Heavy-duty vehicles</td>
<td>160 to &gt;360</td>
<td>60</td>
<td>25,000</td>
<td>70% efficiency, (\leq 0.2 \text{ mg}<em>{\text{PGM}}/\text{cm}^2) 0.35 \text{ mg}</em>{\text{PGM}}/\text{cm}^2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>92*</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td>Stationary</td>
<td>1 to 1,000</td>
<td>1,000</td>
<td>80,000-130,000</td>
<td>&gt;50% electrical efficiency</td>
</tr>
<tr>
<td>Reversible (RFCs)**</td>
<td>1 to 1,000</td>
<td>1,250</td>
<td>5,000 cycles</td>
<td>&gt;50% roundtrip efficiency</td>
</tr>
</tbody>
</table>

**Green: target; black: lab-demonstrated tech; blue: on-road/installed tech**

*Projected system cost for 100,000 units/year

**Technical targets under development
Strategic Analysis Guides Fuel Cell R&D Priorities

2018 PEMFC Stack Cost Breakdown

Catalyst cost is projected to be the largest single component of the PEMFC stack cost at high volume

Strategy
- Reduce or eliminate PGM levels in catalysts *
- Improve MEA performance

* PGM elimination mitigates US dependence on precious metal imports
MDV Cost Analysis Highlights R&D Needs

- Based on 2018 cost estimate for 160 \( kW_{\text{net}} \) system suitable for buses and medium-duty trucks
- High-volume manufacturing cost: \$92/kW_{\text{net}} \ (100,000 \text{ systems/year})

PEMFC stack cost breakdown

- Bipolar Plates 20%
- Catalyst and Application 53%
- Frame/Gaskets 8%
- Membrane 9%
- Balance of Stack 5%
- MEA 20%
- GDLs 5%

*Manufacturing volume: 100,000 systems/year

To be released: Heavy-duty fuel cell truck cost analysis
DOE Cost Status and Targets for R&D

### Fuel Cell R&D
- **Fuel cell system**
  - $210/kW*
  - $180/kW*
  - ~$75/kW (Durability adjusted (preliminary))
  - $50/kW 100K/yr
  - $45/kW 500K/yr
  - $30/kW

### Hydrogen R&D
- **On-board storage**
  - $21/kWh
  - $17/kWh 100K/yr
  - $15/kWh 500K/yr
  - $8/kWh

- **H₂ cost at the pump**
  - $16/kg*
  - $13/kg
  - $10/kg* to $5/kg**
  - <$4/kg

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

Notes: Graphs not drawn to scale and are for illustration purposes only.
Strategy: Leveraging National Labs and Partners

Consortium Approach

Multi-lab core capabilities with steady influx of new partners

Core Consortium Team
(Consortium Lead, Deputy Lead, & Technical Partners: National Labs)

Labs

University & Non-Profit
Industry
National Lab

FOA

Guiding Principles of EMNs

Predictive Simulation Across Scales
Synthesis & Characterization
Rapid Screening
End Use Performance

Process Scalability
Process Control
Real-time Characterization
Reliability Validation

Data Management & Informatics

Energy Materials Network
U.S. Department of Energy
FCTO Strategic and Tactical Update

**Lab-Based Consortia**
- HydroGEN
- H2MARC
- ElectroCat
- FC PAD

**Labs- Industry Bridge**
- H2@Scale Consortium
- CRADAs
- SPPs (WFOs)
- L’Innovator
- Technology Commercialization Fund

**Private Sector**
- FOA projects
- SBIRs
- Prizes
- State funding
- Demos & Deployments
- Partnerships
- US National Roadmap (planned)

**H2 materials R&D, enable codes & standards, reduce regulatory barriers**

**Safety – Lessons learned, best practices, enable safe infrastructure**

**Examples of Applications**
Strategy: Focus on Innovation

Innovative concepts: PGM-free, AEMs, non-mechanical compression, new ideas, etc.
Electrochemical Hydrogen Compression (EHC)

Non-mechanical concepts are in early stages of research, but have potential for higher reliability than conventional reciprocating compressors.

How it Works

Electrical potential drives redox reactions and hydrogen permeation across cell membrane. Pressurized H\(_2\) accumulates at the cathode. Catalysts disassociate and reconstitute H\(_2\)

Images courtesy of Giner
Recent EHC Accomplishment

Giner, Inc and collaborators reduced EHC electricity required for 100 to 350 bar by 50% through novel membranes and stack designs. Achieved 2kWh/kg.

R&D Needs

- **Maintain** efficiency at 40X higher flow rates (up to 40 kg/hr) and >2X higher pressure (up to 875 bar)
- Address losses caused by: temperature rise, membrane resistance, and H₂ backflow
- Enhance conductivity through membrane and catalyst R&D.

Collaborators: NREL, RPI, and Gaia Energy Research Institute
RFC R&D Innovation Targets Low- and High-T Technologies

Low-T PEM Example:

WUSTL Supported Bifunctional ORR/OER catalyst

- Ru doped TiO₂ (RTO)
- Nb doped TiO₂ (NTO)
- Sb doped SnO₂ (ATO)

WUSTL Advanced Membranes

- Reinforced PFSA based membrane

Ballard + Proton
50 cm² performance and durability validation

Materials/component R&D to advance both fuel cell and electrolyzer performance

N. Danilovic et al., LBNL
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
Collaboration & Resources
Example of International Government Collaboration

www.iphe.net

Working Groups: Education & Outreach
Regulations, Codes, Standards & Safety

Find IPHE on Facebook, Twitter and LinkedIn
Follow IPHE @The_IPHE

Formed 2003
Over 20 Countries
Collaboration: New H₂ Safety Partnership

New global partnership to promote collaboration on safety

www.aiche.org/chs
Help Us to Spread the Information

Celebrate National Hydrogen & Fuel Cell Day
October 8 or 10/8
(Held on its very own atomic-weight-day)

Give an “Increase your H2IQ” presentation in your community

Learn more at: energy.gov/eere/fuelcells

Download for free at:
energy.gov/eere/fuelcells/downloads/increase-your-h2iq-training-resource

• Builds on H2 Challenge in Netherlands
• Teams drive 10.08 hours and score points along the way
• Start in Japan, continue in Europe and finish in the U.S.
• Players share experience in social media
DOE-wide STEM Initiative
Hydrogen and Fuel Cells Career Map Online

Sectors Identified:

- Research and Development
- Engineering and Manufacturing
- Installations, Operations, and Management
- Communications, Training, and Outreach

Visit online
www.energy.gov/eere/fuelcells/education
Postdoc & Postmasters Fellow Positions Available

Applicants selected will be mentored by EERE Fuel Cell Technologies Office staff and be part of the team.

- Hydrogen Fuels R&D
- Fuel Cells R&D
- Infrastructure and Systems R&D
  - Technology Acceleration
  - Safety, Codes & Standards
  - Systems Analysis

FCTO is currently seeking 4 candidates:

- 1 for Fuel Cells R&D
- 2 for Technology Acceleration
- 1 for Safety, Codes & Standards

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$\Delta t$

$\sim 2000$ to Today

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Today to 2040
In Recognition of your Invaluable Contributions to Fuel Cell Science and to the United States Department of Energy
Thank you

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energy.gov/eere/fuelcells