U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY & RENEWABLE ENERGY

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.

Lab Contributions

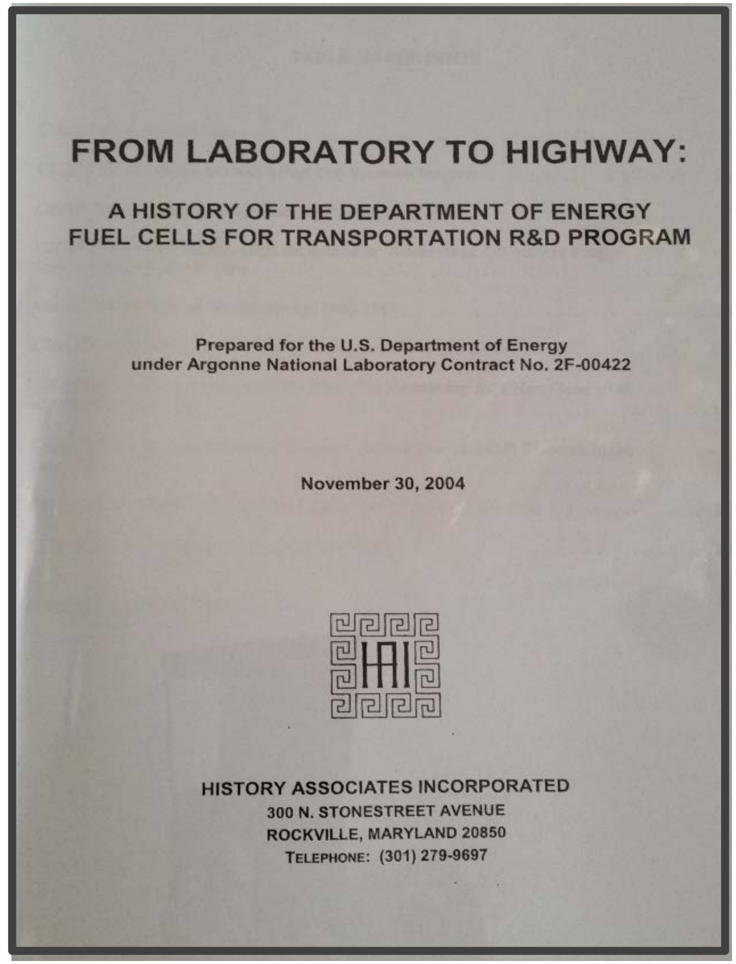
LANL: Ian Raistrick- 1988 Patent

"…**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/cm^2

4-10 mg/cm^2 → 0.5 mg/cm^2

→ 0.12 to 0.17 mg/cm^2


FROM LABORATORY TO HIGHWAY:

A HISTORY OF THE DEPARTMENT OF ENERGY
FUEL CELLS FOR TRANSPORTATION R&D PROGRAM

Prepared for the U.S. Department of Energy
under Argonne National Laboratory Contract No. 2F-00422

November 30, 2004

HISTORY ASSOCIATES INCORPORATED
300 N. STONESTREET AVENUE
ROCKVILLE, MARYLAND 20850
TELEPHONE: (301) 279-9697

1. Source: Laboratory to Highway, p. 106 (2004)

Progress

DOE Program Impact - Examples

Innovation

Approx. **960** H_2 and fuel cell **patents**

enabled by FCTO funds

Approx. **37%** of H_2 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

Fuel Cell R&D

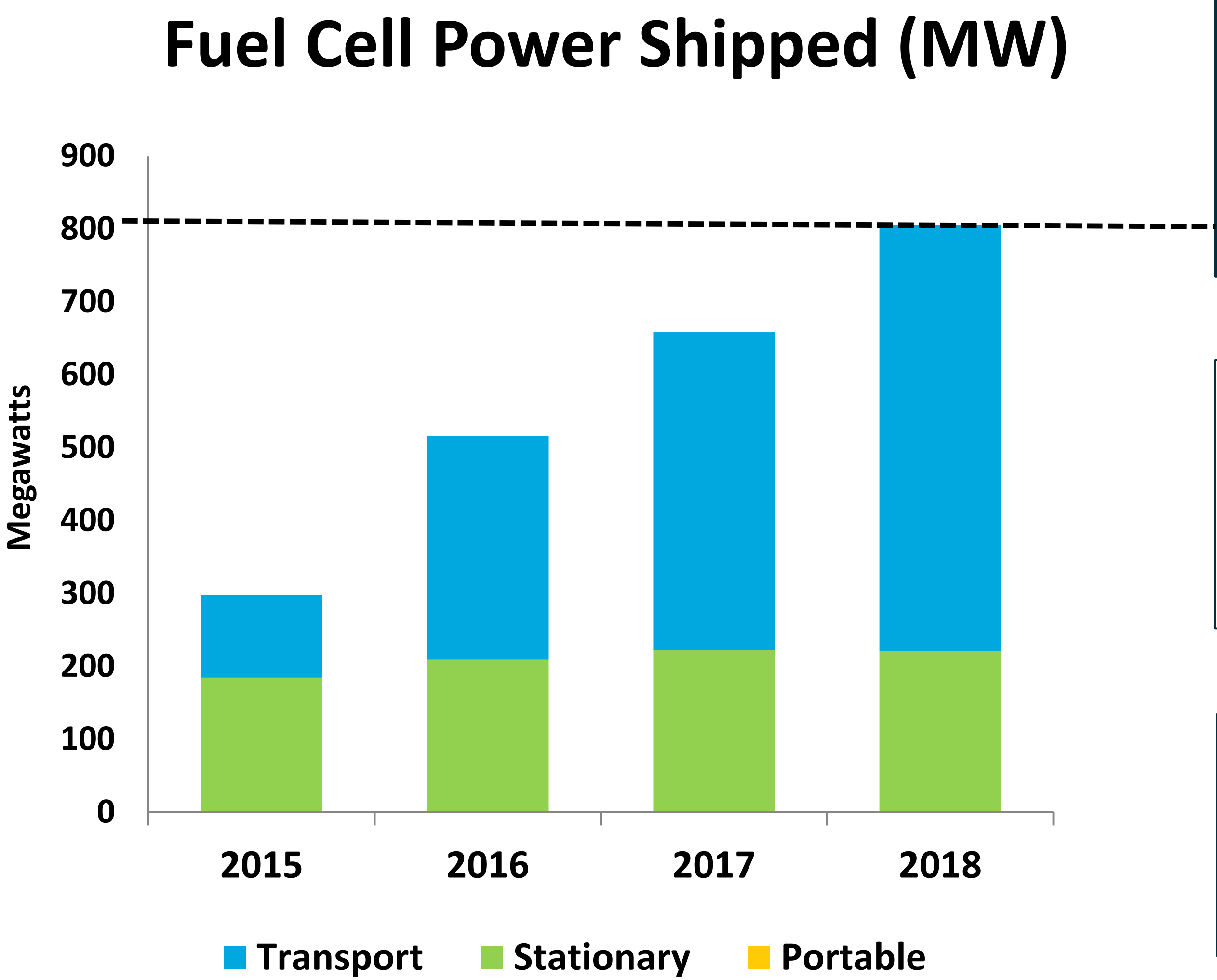
Reduced cost 60%

Quadrupled durability

H2 Production R&D

Cut electrolyzer costs 80%

Fuel Cell Shipments - Growth by Application



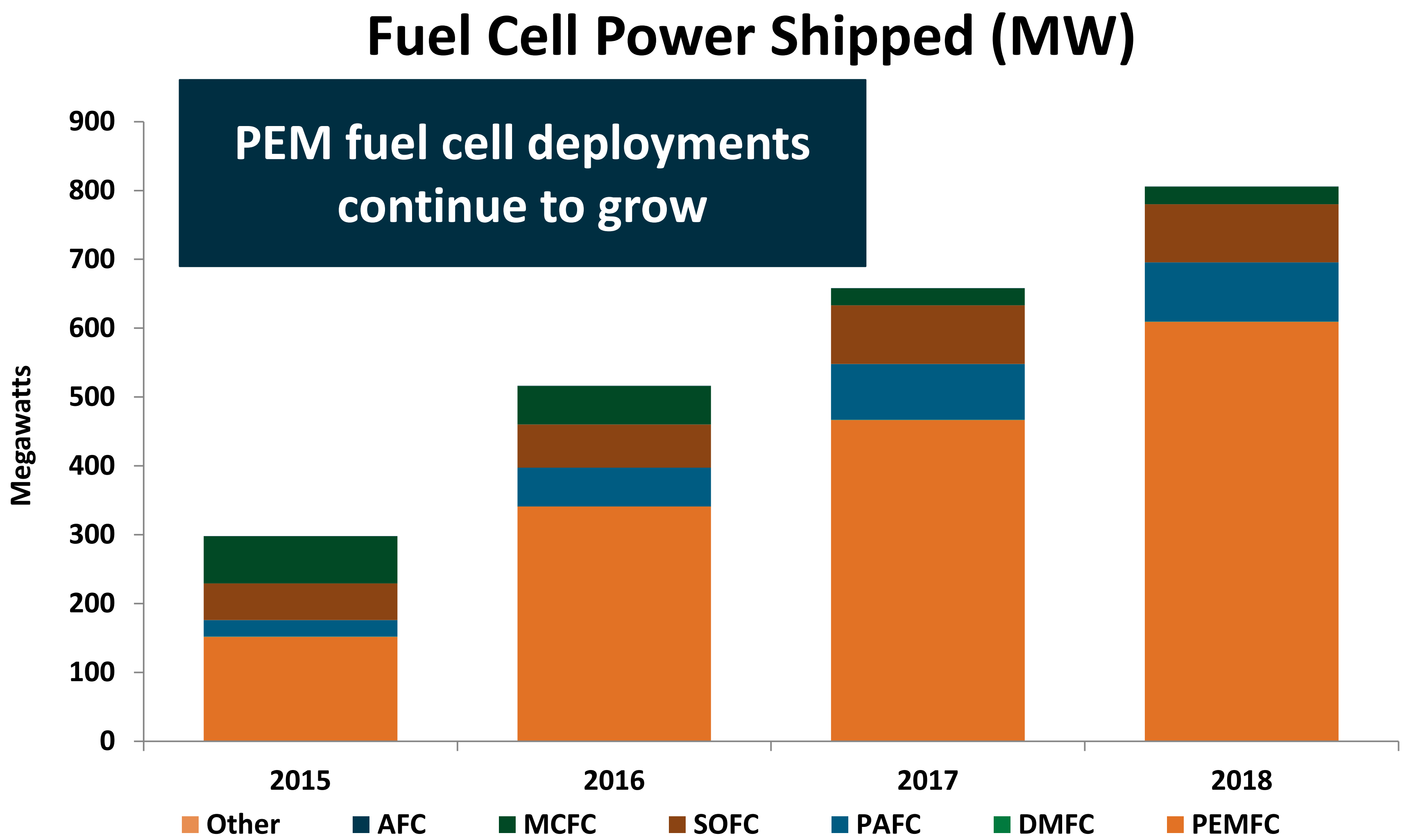
800 MW
fuel cell power
shipped worldwide

68,500
fuel cell units
shipped worldwide

Approximately
$2.3 Billion
fuel cell revenue

Source: DOE and E4Tech

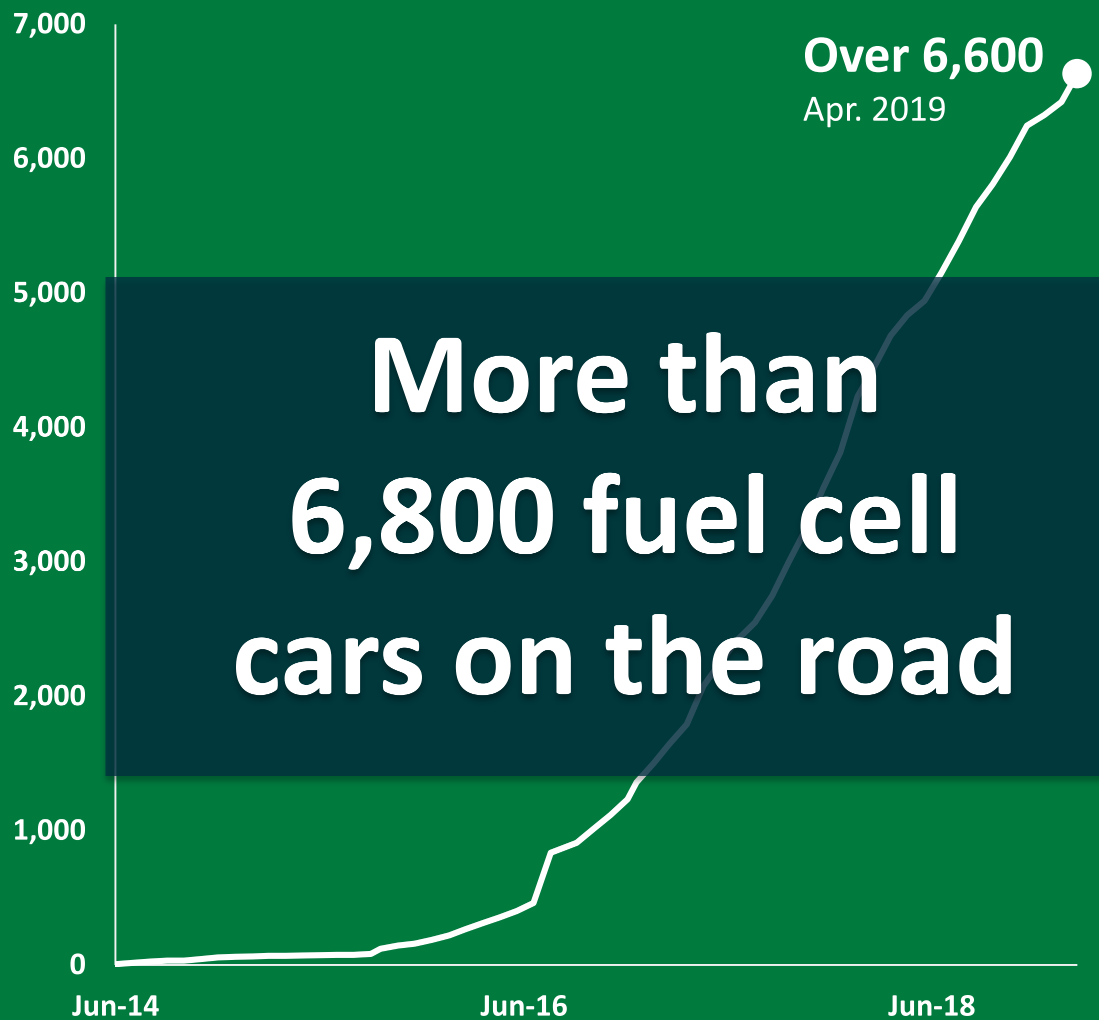
Growth by Fuel Cell Type



Source: DOE and E4Tech

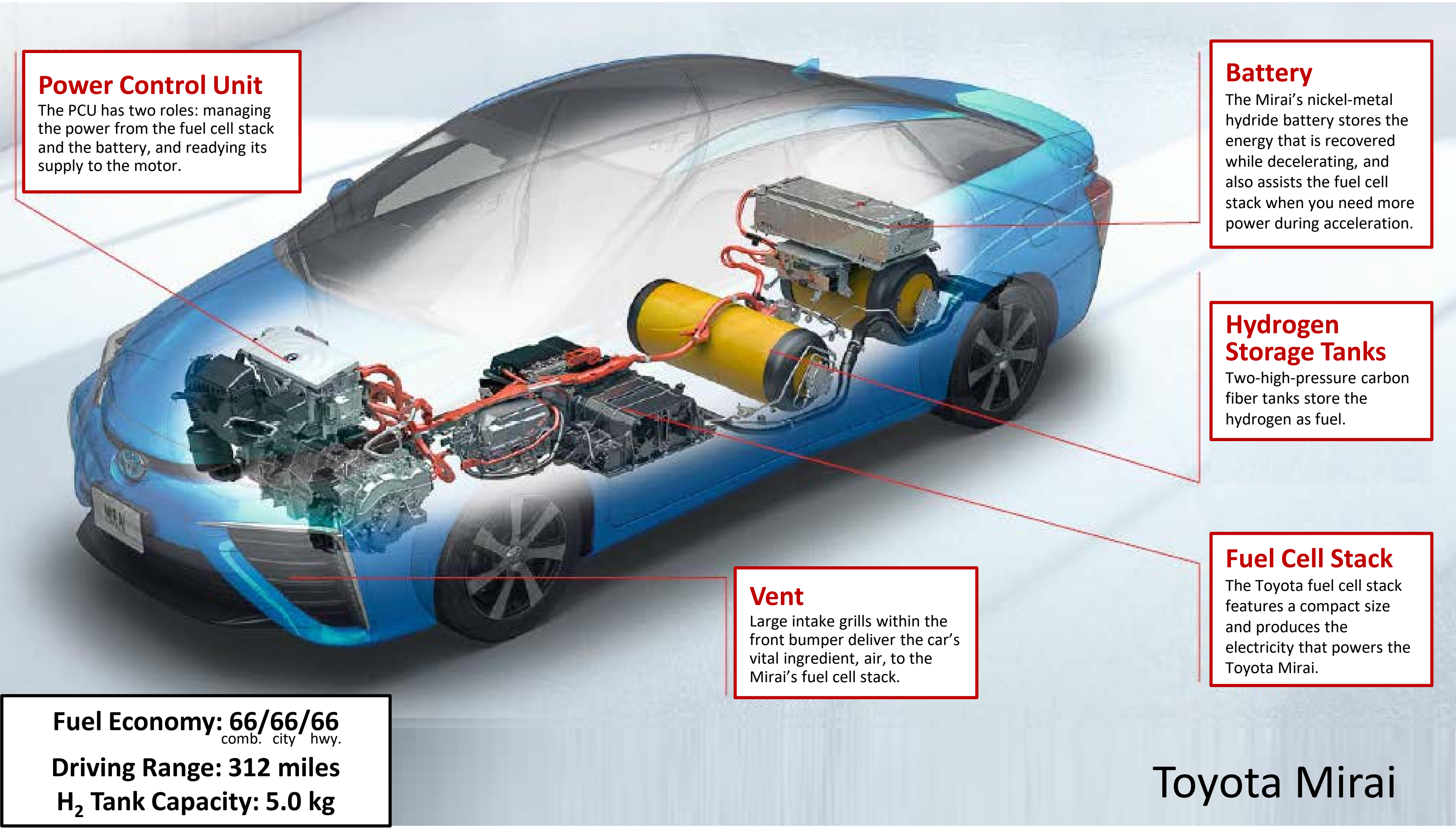
Fuel Cell Passenger Vehicles Status

Fuel Cell Cars in the U.S.



More than 6,800 fuel cell cars on the road

Example of a Commercially Available FCEV



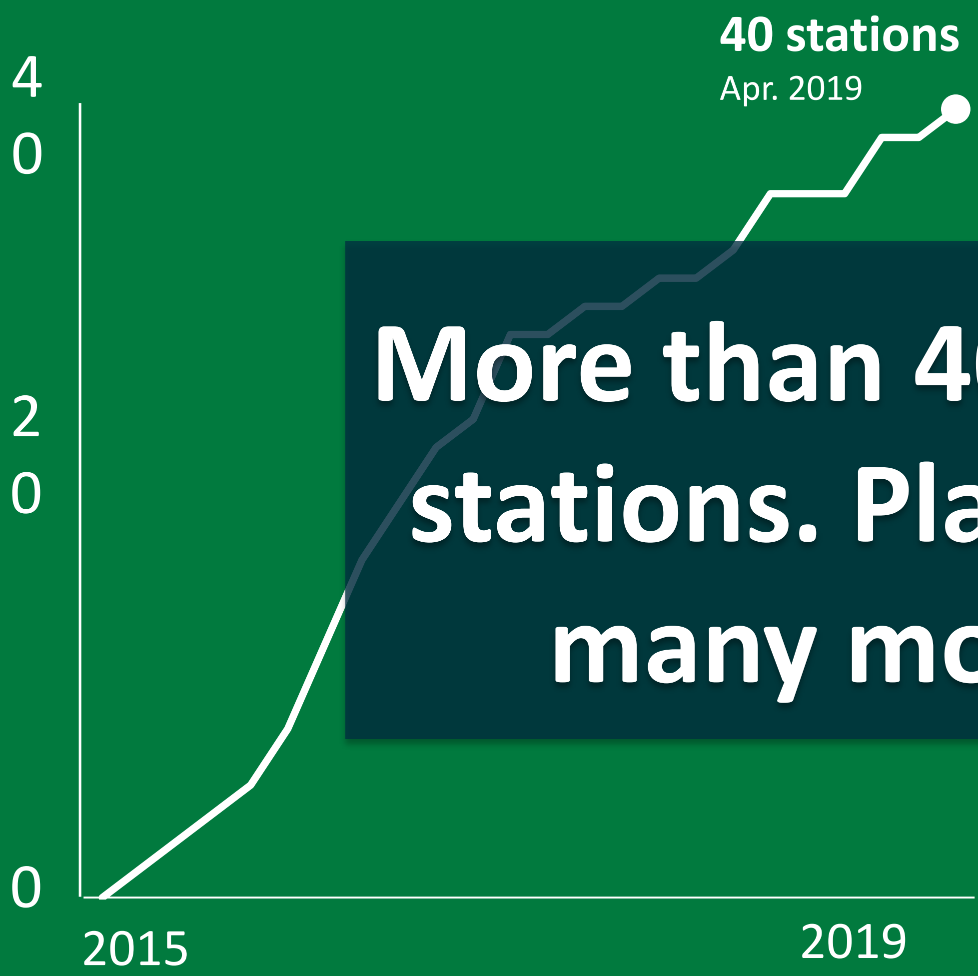
Fuel Economy: 66/66/66 (comb. / city / hwy.)

Driving Range: 312 miles

H_2 Tank Capacity: 5.0 kg

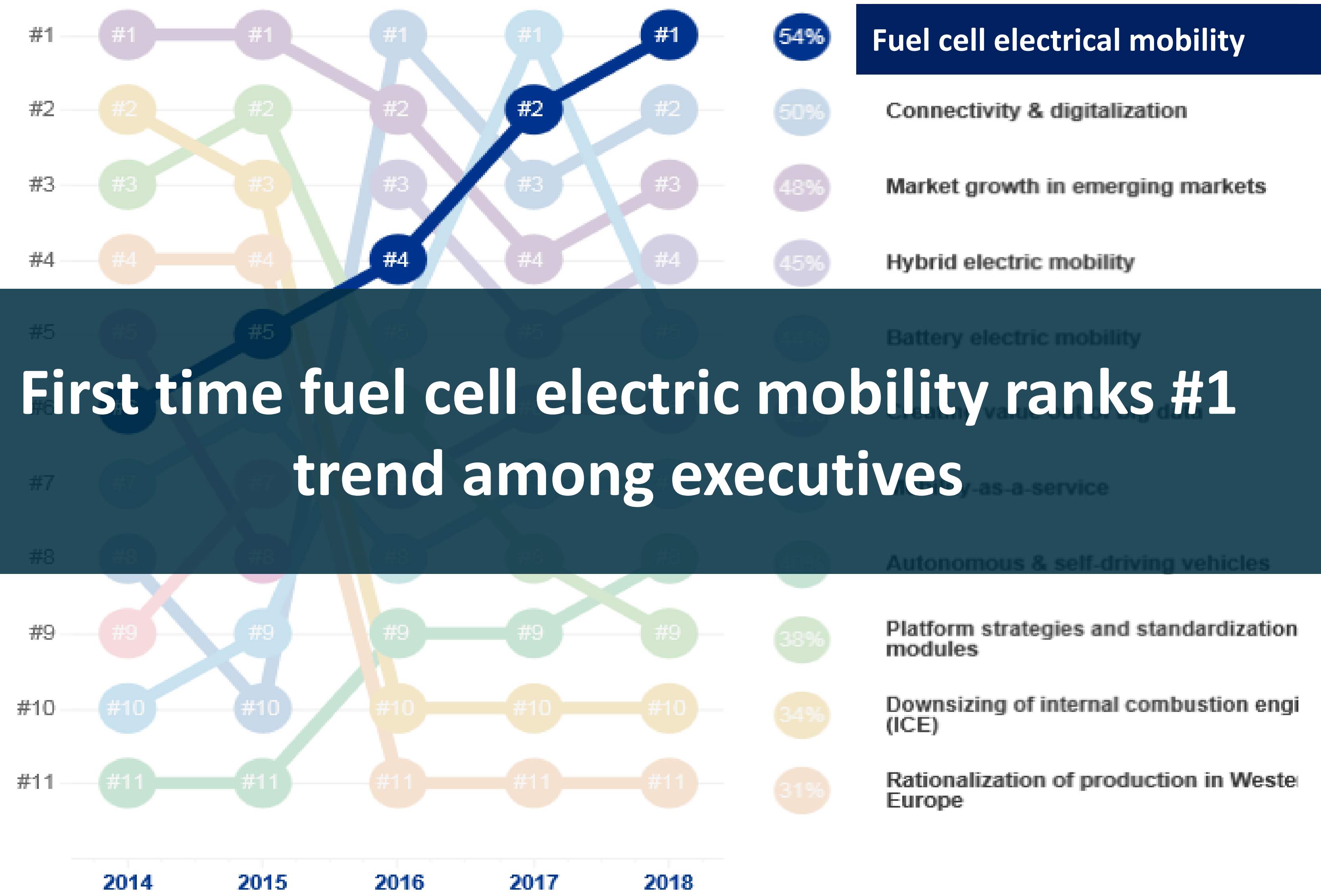
Hydrogen Infrastructure Status

Retail Hydrogen Stations in the U.S.



More than 40 retail stations. Plans for many more.

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

Photo Credit: UPS

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

Photo Credit: FedEx

First fuel cell tow truck fleet at airport in Memphis

World's first fuel cell for maritime ports in Hawaii

Photo Credit: Sandia National Laboratories

More Real World Applications

Industry demonstrates heavy duty fuel cell trucks

Photo Credit: Toyota

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

Photo Credit: General Motors

Fuel cell powered lights at Super Bowl in CA

Fuel cell buses in California surpass 19M passengers

Photo Credit: NREL

Material Handling Equipment Applications

More than **25,000 forklifts**

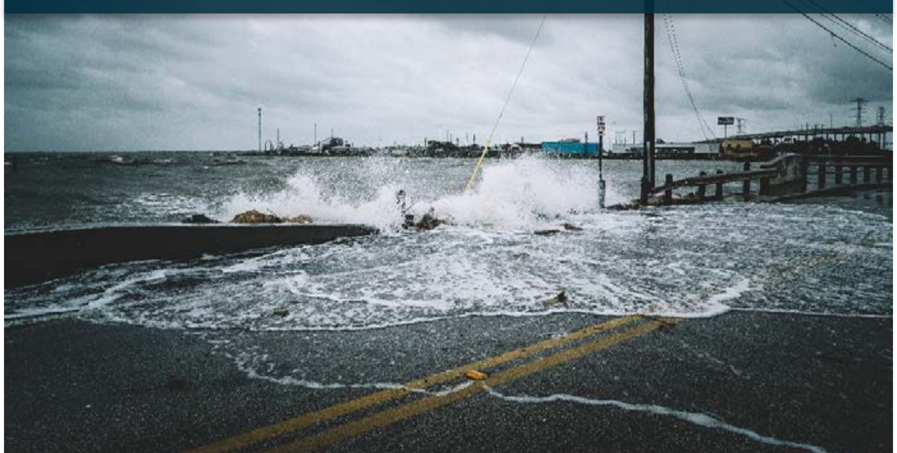
Over **19 million refuelings**

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

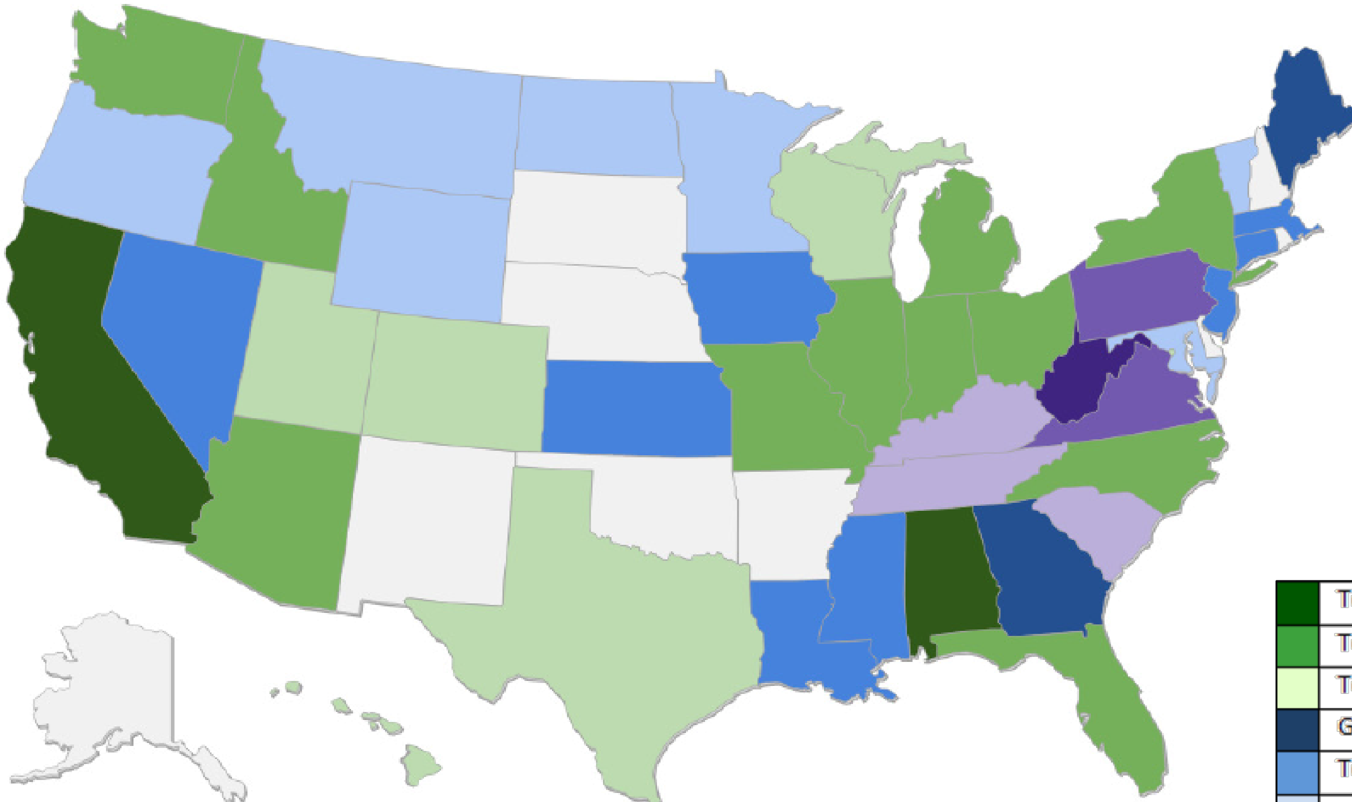
Fuel cells provided backup power during Hurricane Sandy in the U.S. Northeast



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

	Telecom, Government, Railroad, Utility sites
	Telecom, Government, Railroad sites
	Telecom and Government sites
	Government, Railroad, Utility sites
	Telecom sites
	Government sites
	Railroad sites
	Utility sites
	Government and Railroad sites
	Telecom and Railroad sites

Over 8,000 backup power units

deployed or on order

Source: DOE State of the States: Fuel Cells in 2016 Report

Six years ago…

AMFC Technology Status

Cellera Technologies,
Caesarea, Israel

Shimshon Gottesfeld, CTO

ECS Meeting in SF
November 1st 2013

Another World's First…

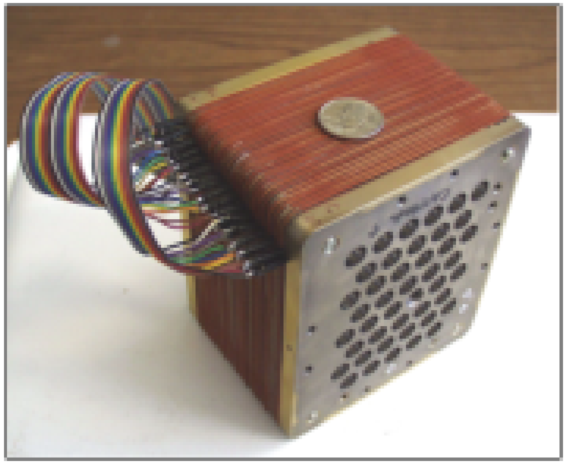
Telecom pilot installation– April 2013

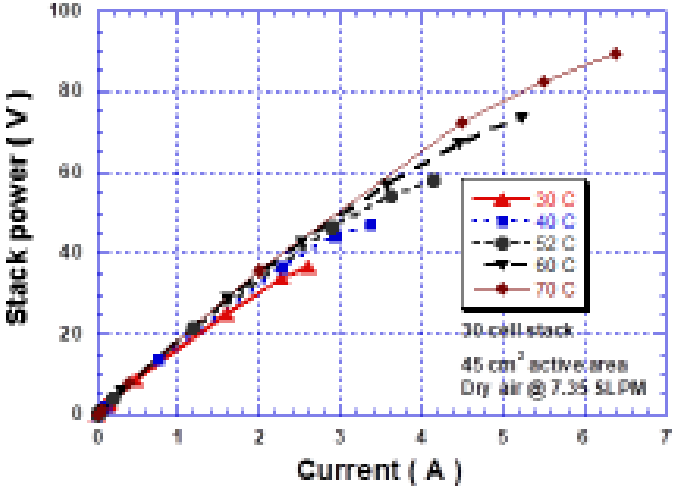
World's first AMFC pilot installation with local telecom operator

Other Examples from Shimshon

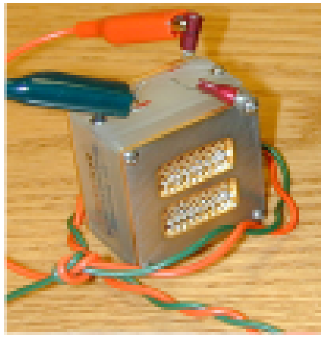
High- and Low-Power DMFCs (1999-2000)

80 W near-ambient DMFC stack for automotive applications: 30 cells, 45 cm^2 MEA, 1.8 mm per cell





Two-cell air-breathing 10 mW/cm^2 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

Fuel Cells	Hydrogen Fuel	Infrastructure R&D
• Cost, durability • Components - catalysts, electrodes, etc • Increase focus beyond LDVs	• Cost of production across pathways • Cost and capacity of storage, including bulk/ energy storage	• Cost and reliability of infrastructure • Delivery components, supply chain • Safety

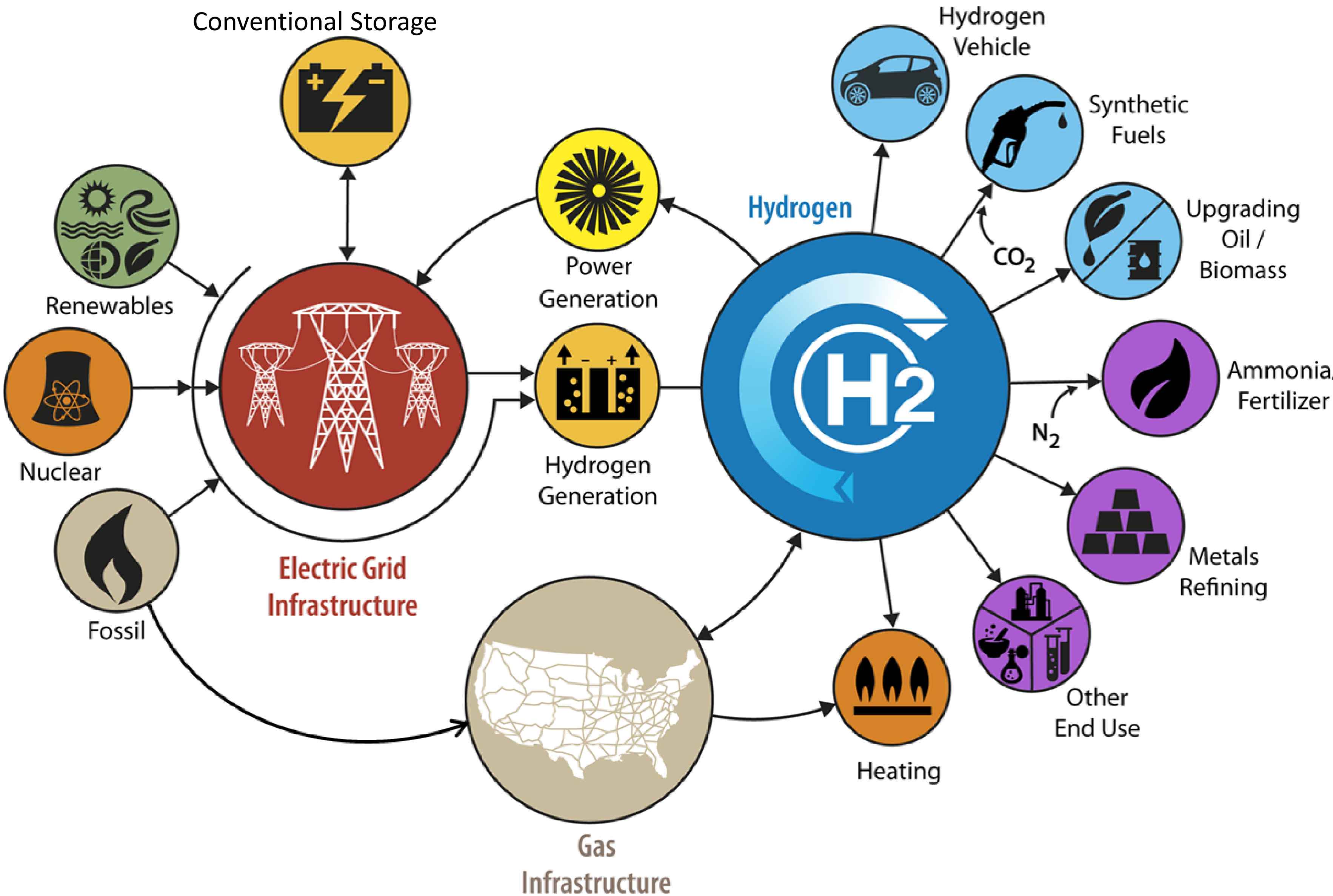
New in FY19 Budget Request

Enabling

H2@Scale

U.S. Department of Energy

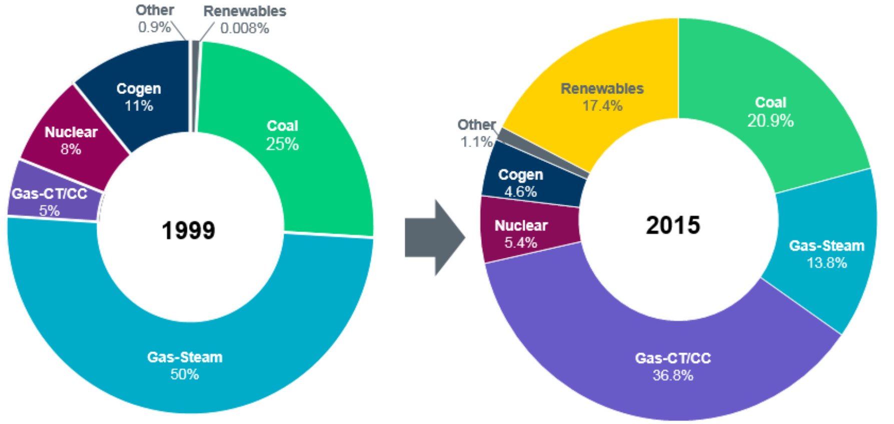
H_2@Scale: Enabling affordable, reliable, clean, and secure energy across sectors



Hydrogen Clusters: Opportunities in Texas

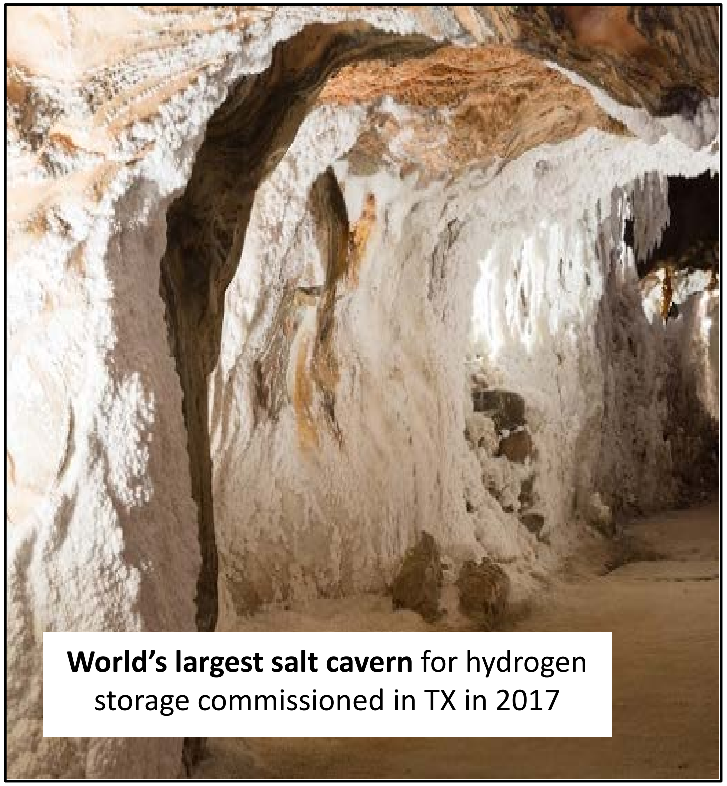
Increased renewable (wind) capacity

Installed Capacity in Texas



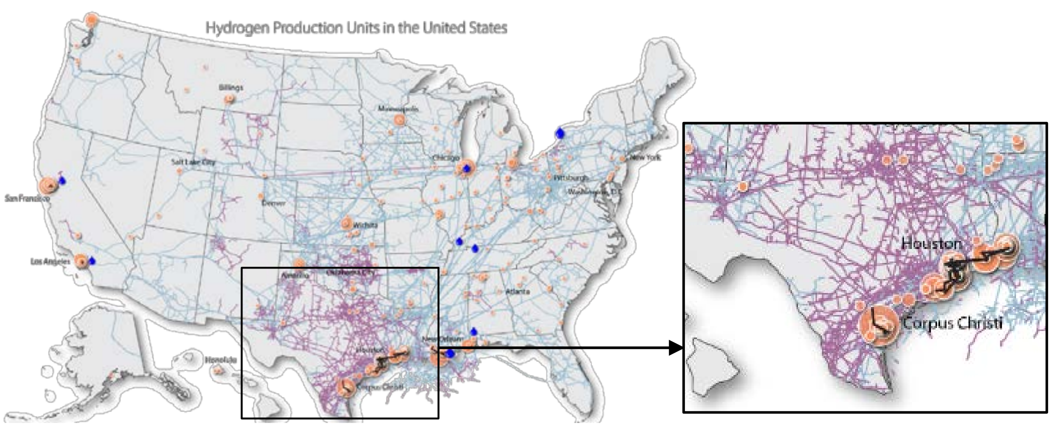
Source: ERCOT

Increased interest hydrogen as an energy storage



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

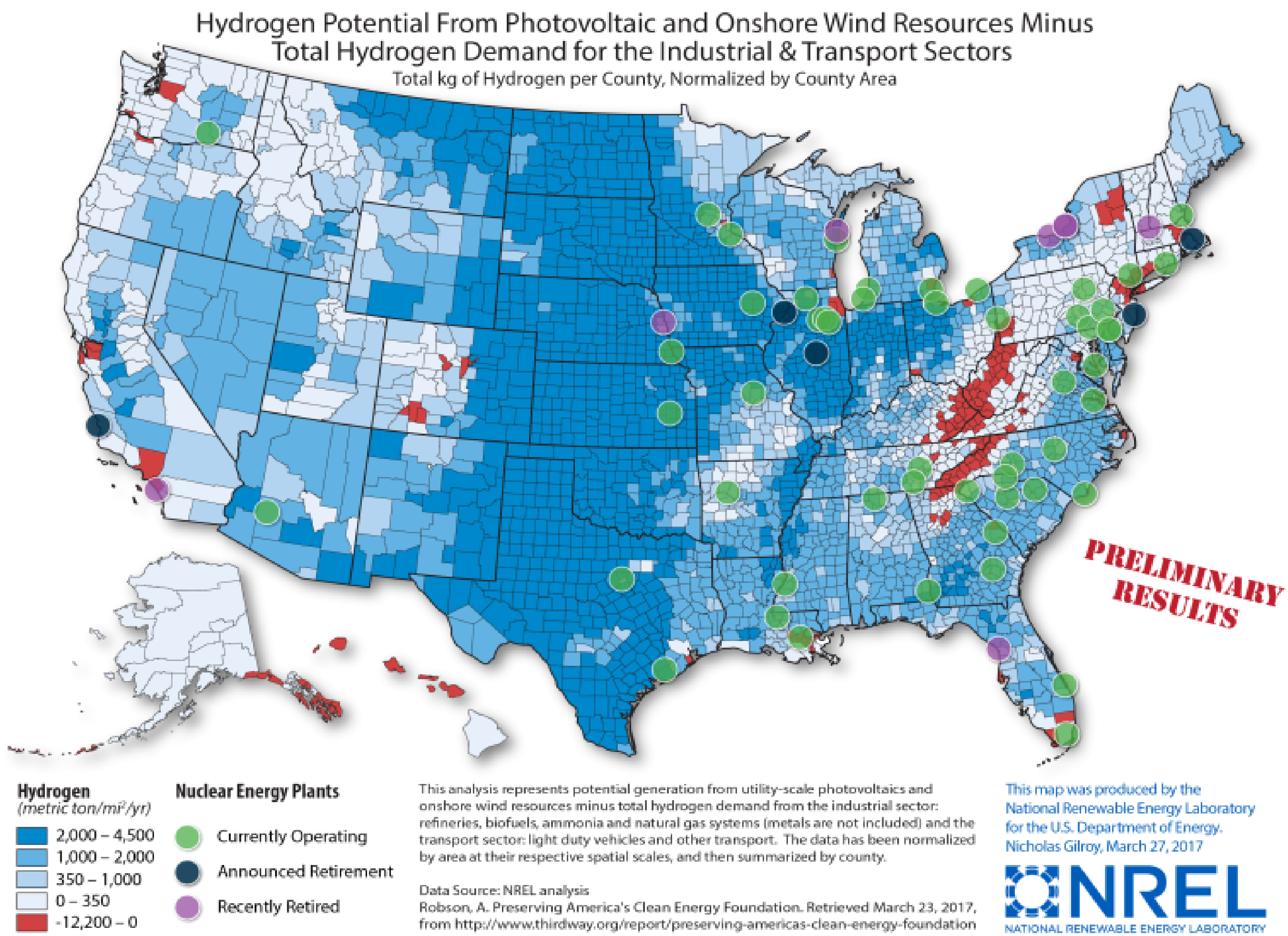
H_2 delivery infrastructure is present



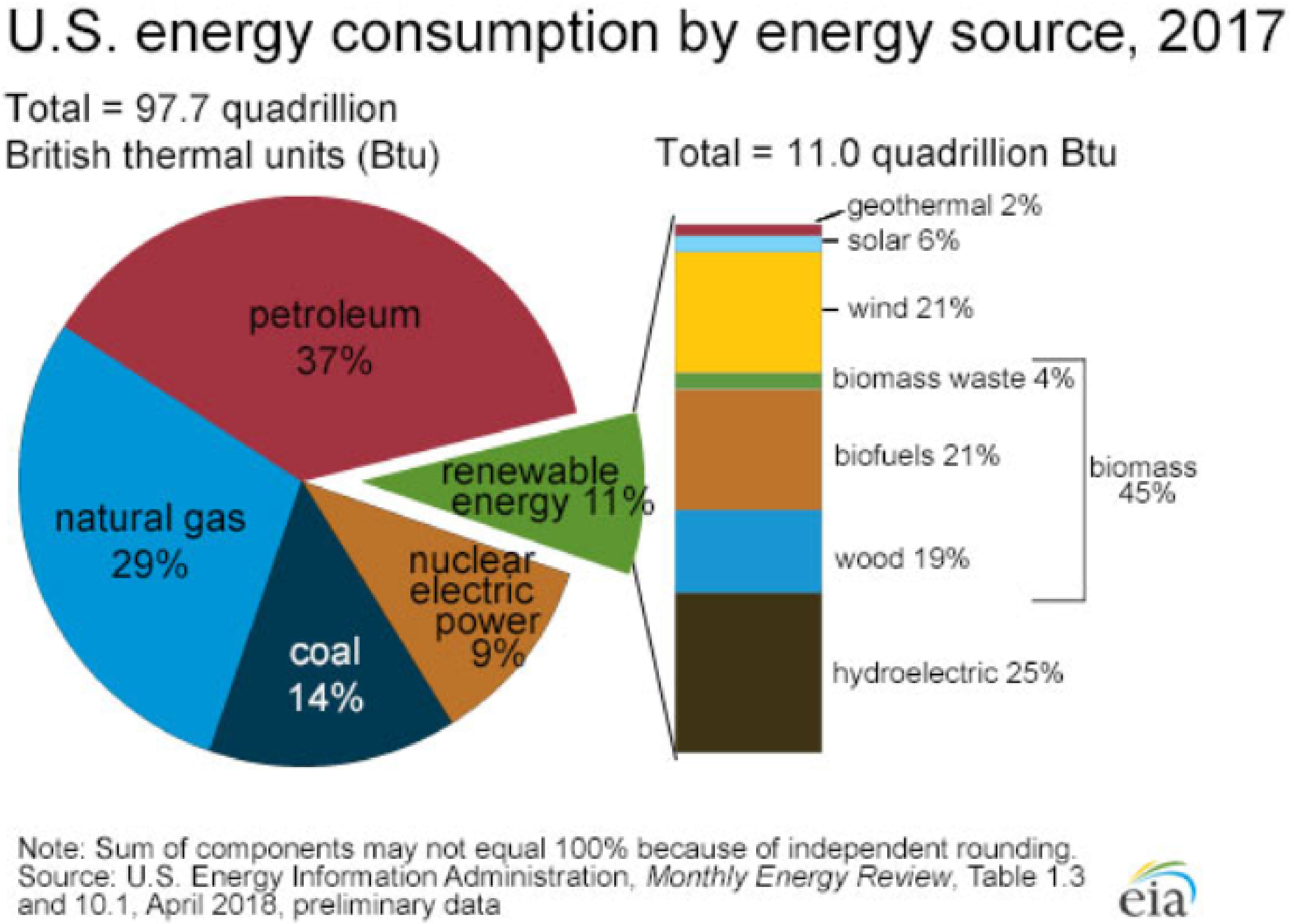
H_2@Scale: Nationwide Resource Assessment

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

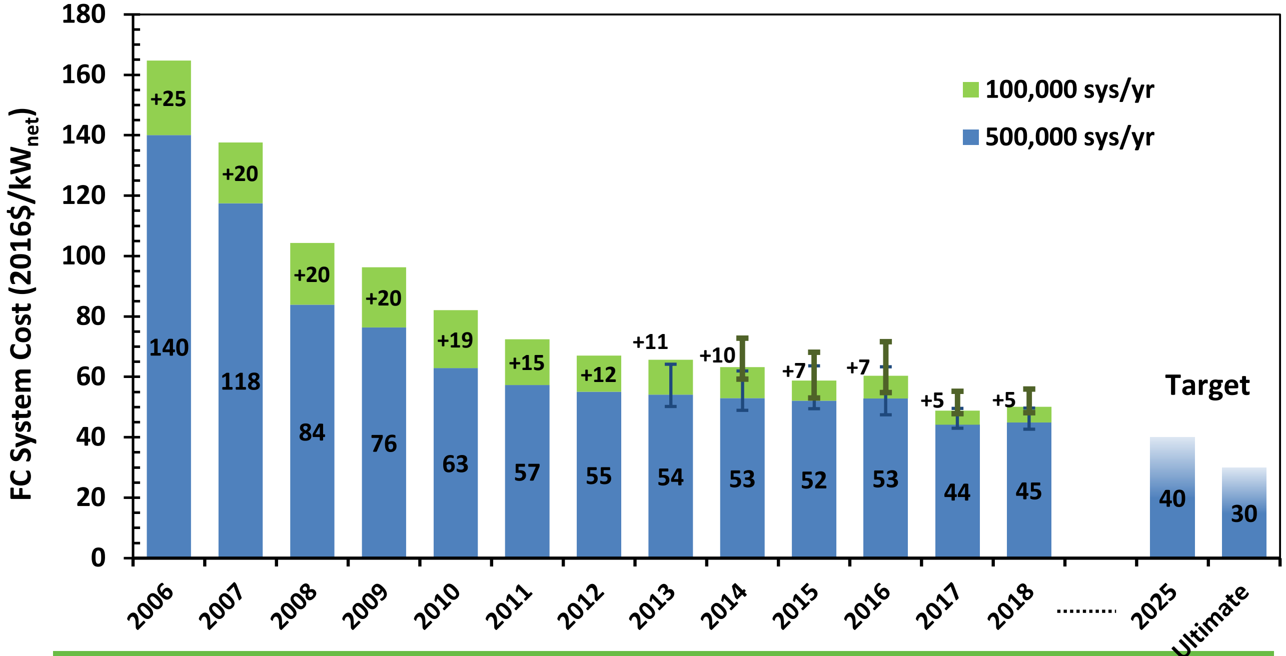


Fuel Cell R&D

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



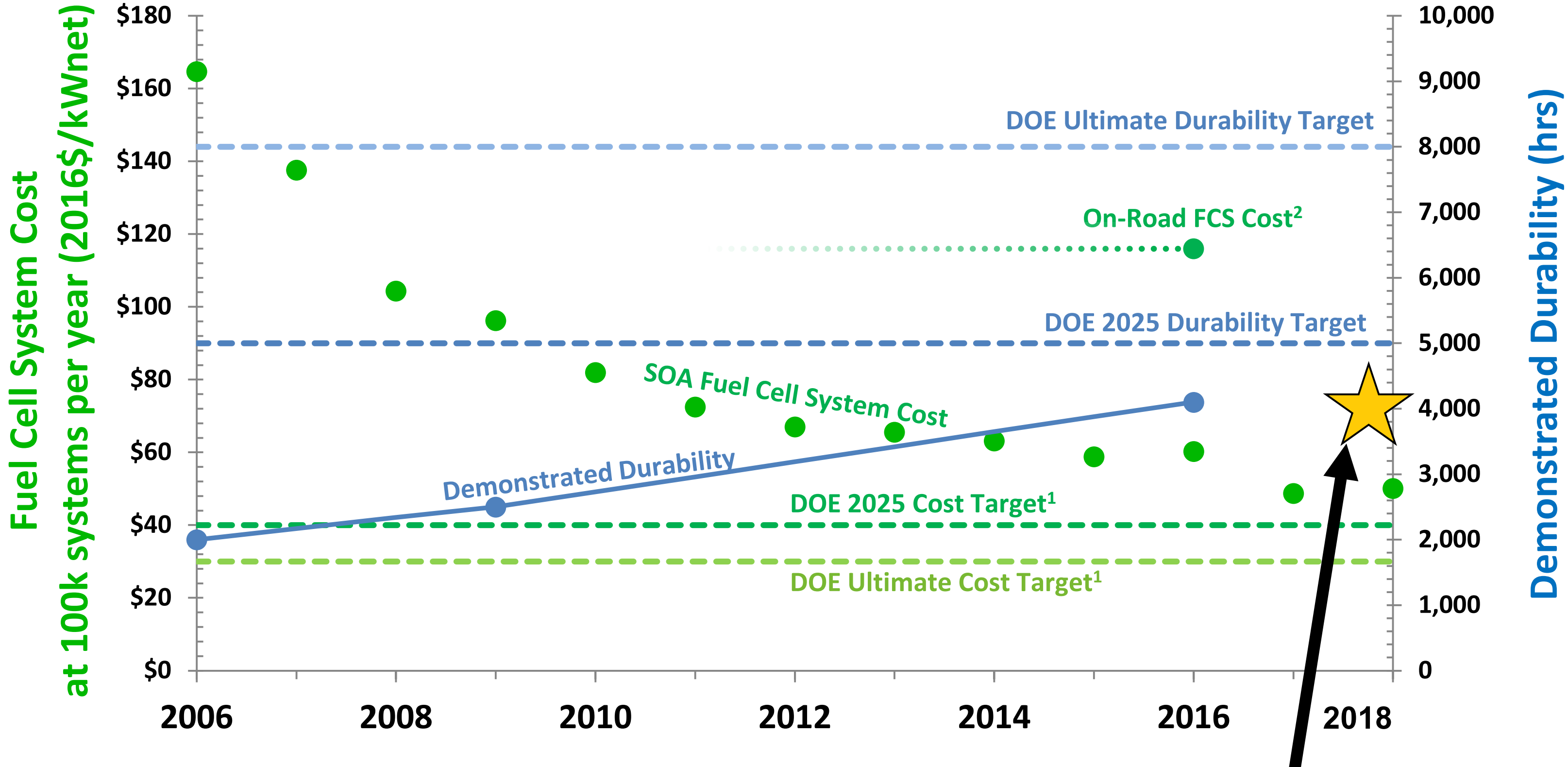
67% cost reduction since 2006

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



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

Preliminary

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

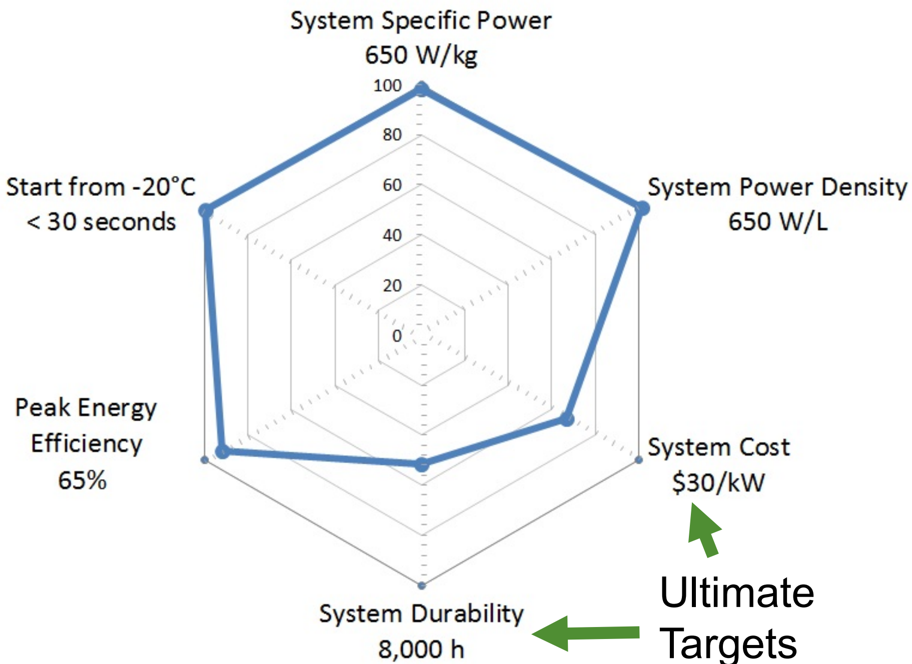
Coming soon: combined durability-system cost metric for state of the art light-duty vehicles

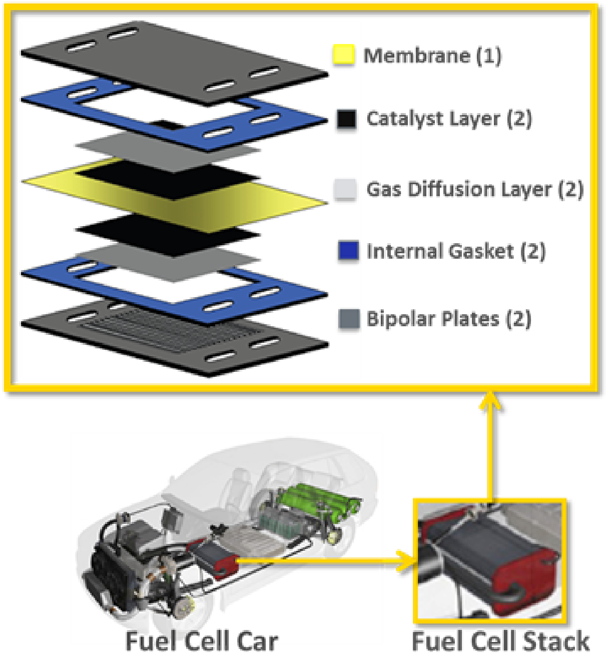
** SA Inc., bottom-up analysis of model system manufacturing cost, high volume manufacturing with next-gen lab technology*

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

Application	Power (kW)	Cost ($/kW)	Durability (h)	Performance
Light-duty vehicles	80	30 75* 120*	8,000 5,000 4,100	70% efficiency, ≤0.125 mg_{PGM}/cm^2 ~0.35 mg_{PGM}/cm^2
Medium and Heavy-duty vehicles	160 to >360	60 92*	25,000 ---	70% efficiency, ≤0.2 mg_{PGM}/cm^2 0.35 mg_{PGM}/cm^2
Stationary	1 to 1,000	1,000	80,000-130,000 40,000-80,000	>50% electrical efficiency
Reversible (RFCs)**	1 to 1,000	1,250	5,000 cycles	>50% roundtrip efficiency

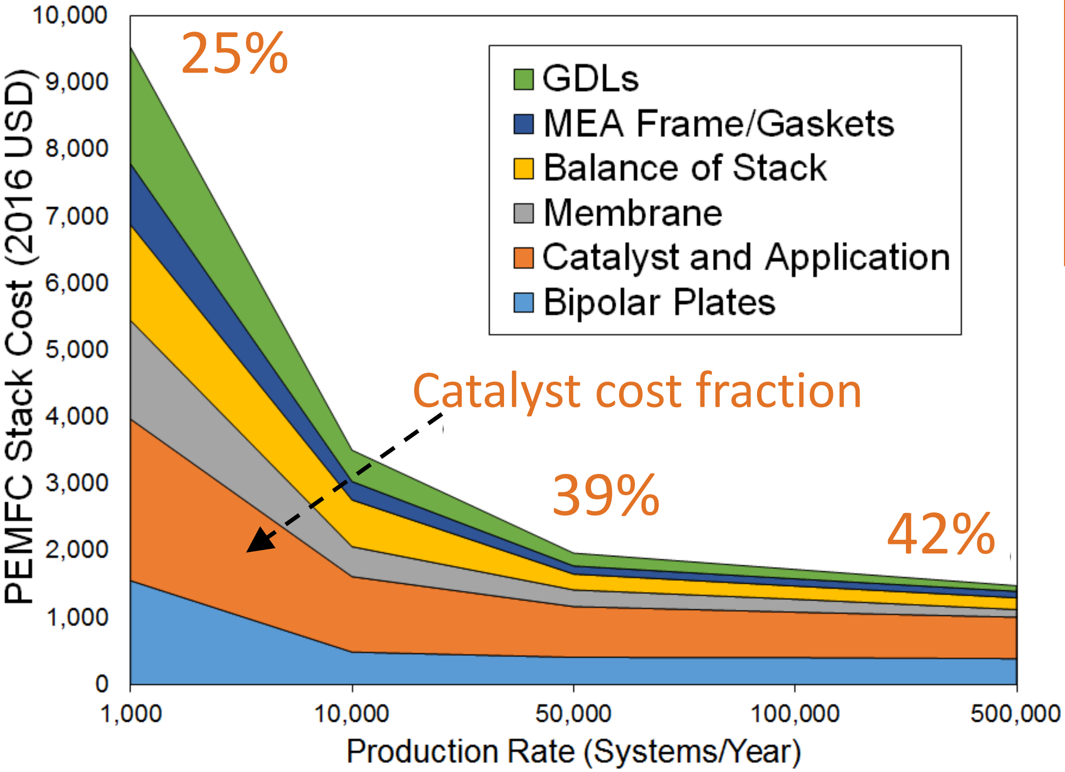
Green: target; black: lab-demonstrated tech; blue: on-road/installed tech

*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

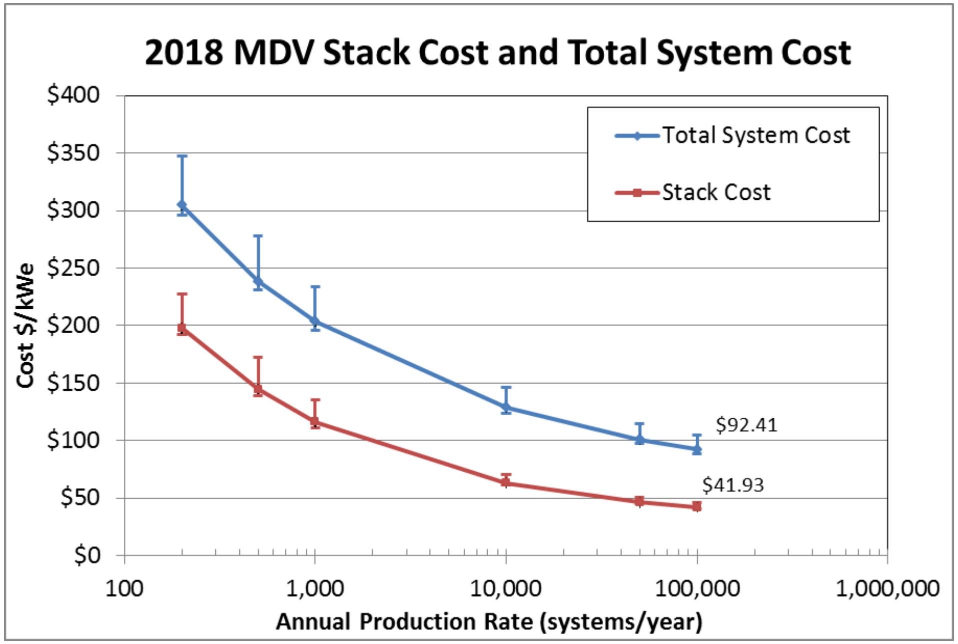
Strategy

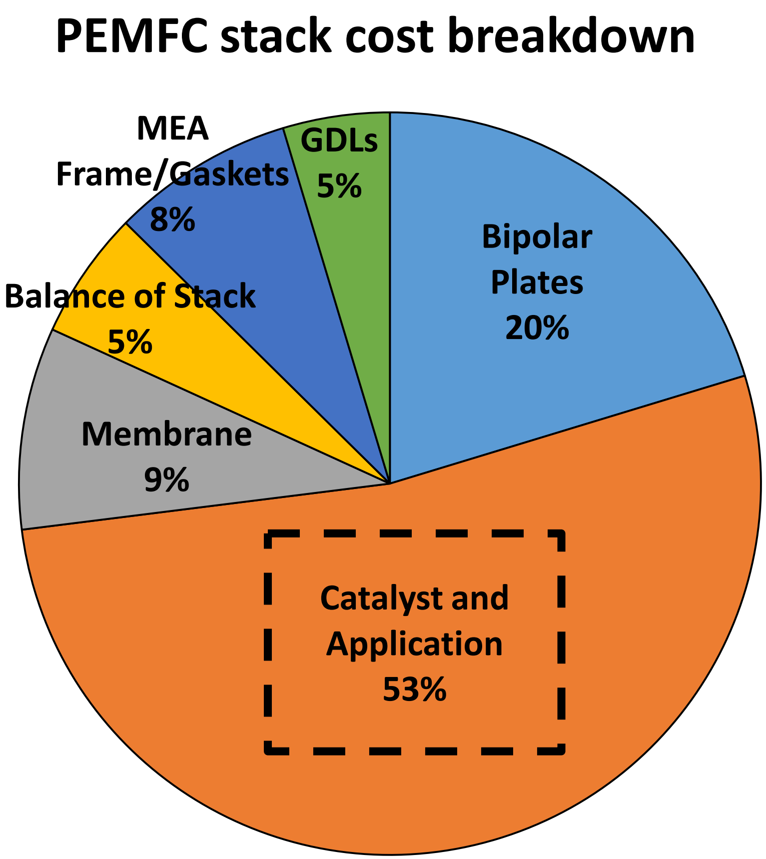
- **Reduce or eliminate PGM levels in catalysts ***
- **Improve MEA performance**

**** PGM elimination mitigates US dependence on precious metal imports***

MDV Cost Analysis Highlights R&D Needs

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





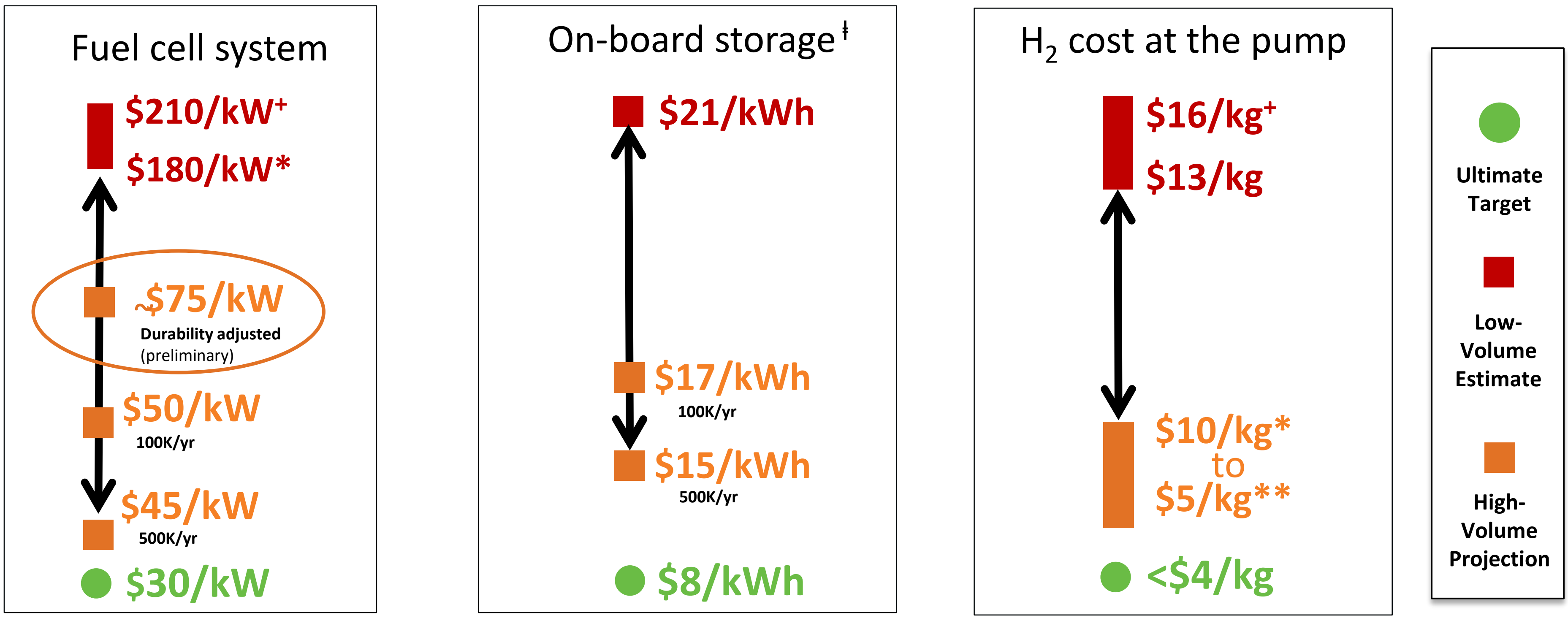
*Manufacturing volume: 100,000 systems/year

To be released: Heavy-duty fuel cell truck cost analysis

DOE Cost Status and Targets for R&D

Fuel Cell R&D

Hydrogen R&D



†Based on commercially available FCEVs

*Based on state of the art technology

ǂStorage costs based on preliminary 2019 storage cost record.

†Range assumes current production from NG and delivery and dispensing

*Highest possible cost at high vol., assumes H2 from electrolysis at $5/gge and delivery via pipelines and liquid tankers at $5/gge

**Lowest possible cost at high vol., assumes H2 from SMR at $2/gge and delivery via tube trailer at $3/gge

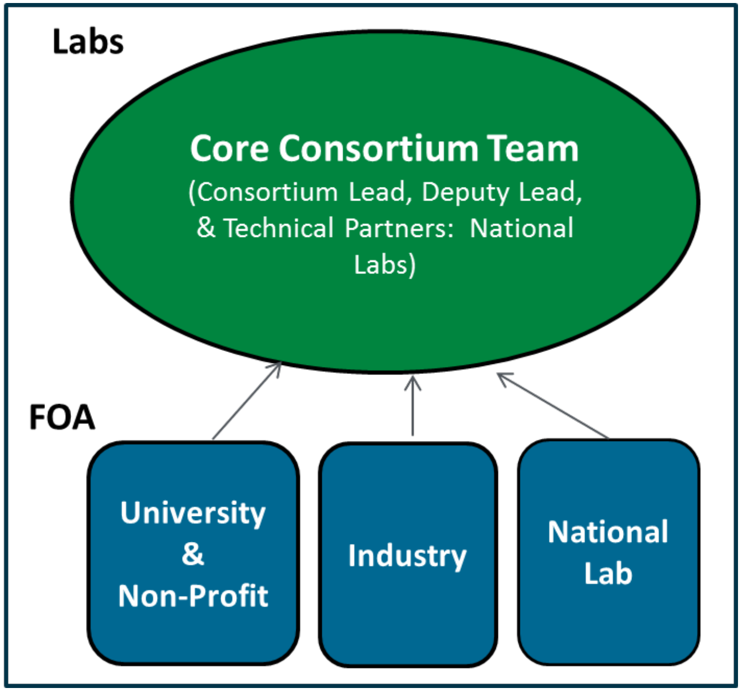
Notes: Graphs not drawn to scale and are for illustration purposes only.

Strategy: Leveraging National Labs and Partners

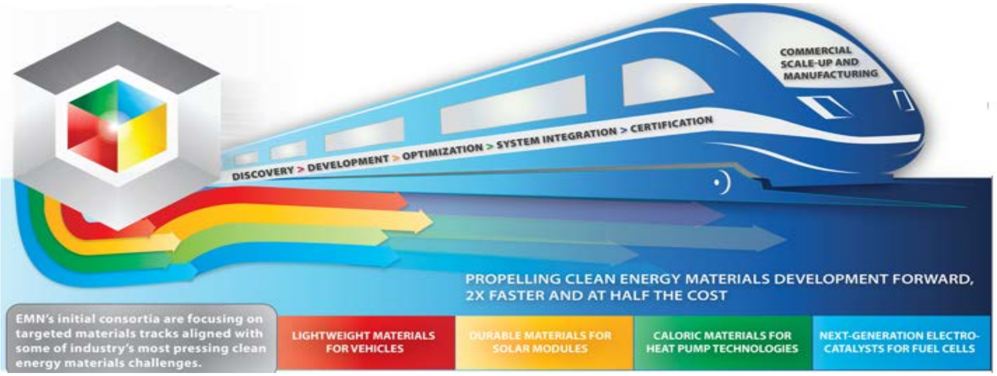
Consortium Approach

Framework to Accelerate Progress

Multi-lab core capabilities with steady influx of new partners



Energy Materials Network
U.S. Department of Energy



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

FCTO Strategic and Tactical Update

Lab-Based Consortia

HydroGEN Advanced Water Splitting Materials

HyMARC

ElectroCat Electrocatalysis Consortium

FCPAD Fuel Cell Performance and Durability

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)

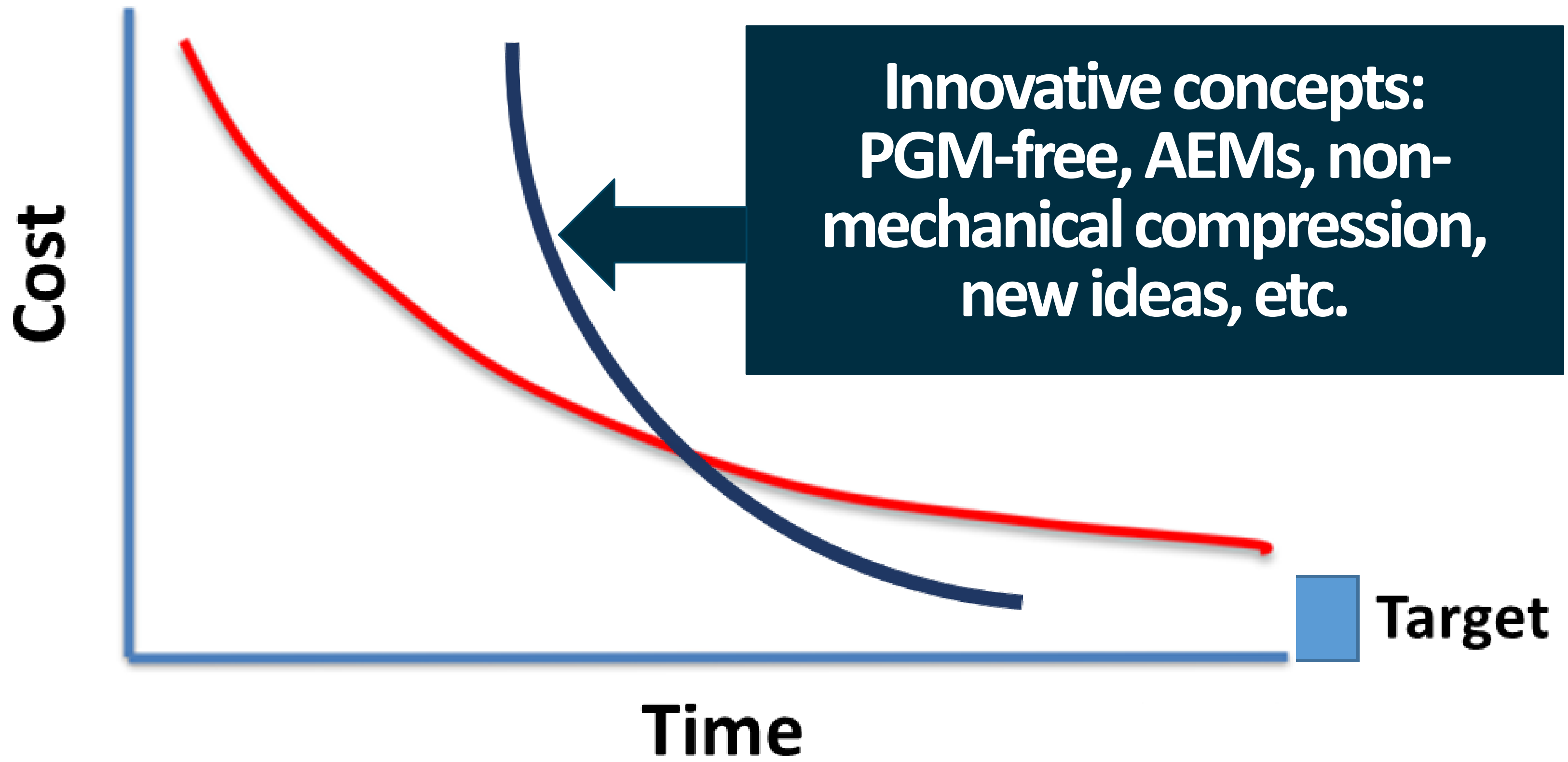
H-Mat™ Hydrogen Materials Compatibility Consortium

H_2 materials R&D, enable codes & standards, reduce regulatory barriers

Safety – Lessons learned, best practices, enable safe infrastructure

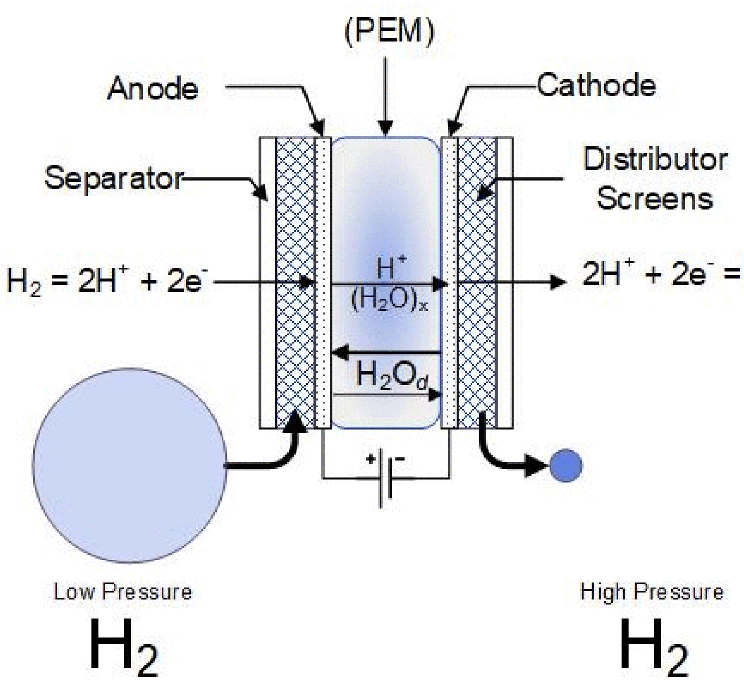
Examples of Applications

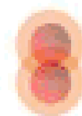
Strategy: Focus on Innovation

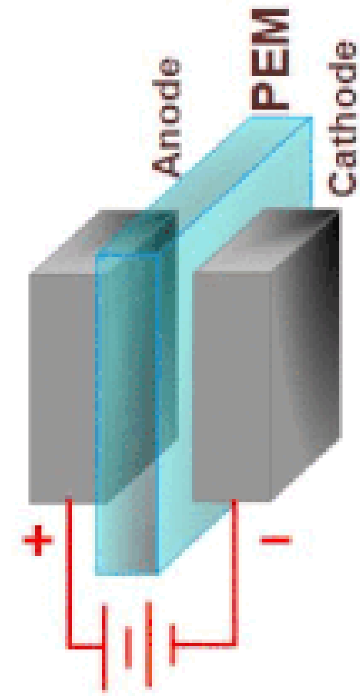


Electrochemical Hydrogen Compression (EHC)

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

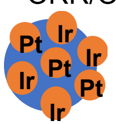
- ***Maintain*** **efficiency at 40X higher flow rates (up to 40 kg/hr) and >2X higher pressure (up to 875 bar)**
- **Address losses caused by: temperature rise, membrane resistance, and H_2 backflow**
- **Enhance conductivity through membrane and catalyst R&D.**

Collaborators: NREL, RPI, and Gaia Energy Research Institute

RFC R&D Innovation Targets Low- and High-T Technologies

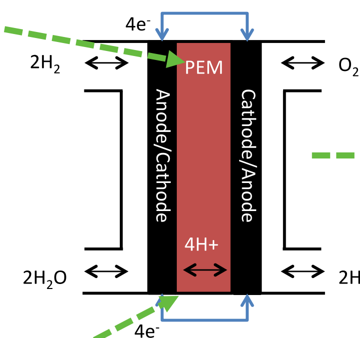
Low-T PEM Example:

WUSTL Supported Bifunctional ORR/OER catalyst



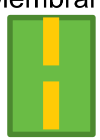
WUSTL supports:
Ru doped TiO_2 (RTO)
Nb doped TiO_2 (NTO)
Sb doped SnO_2 (ATO)

Traditional URFC



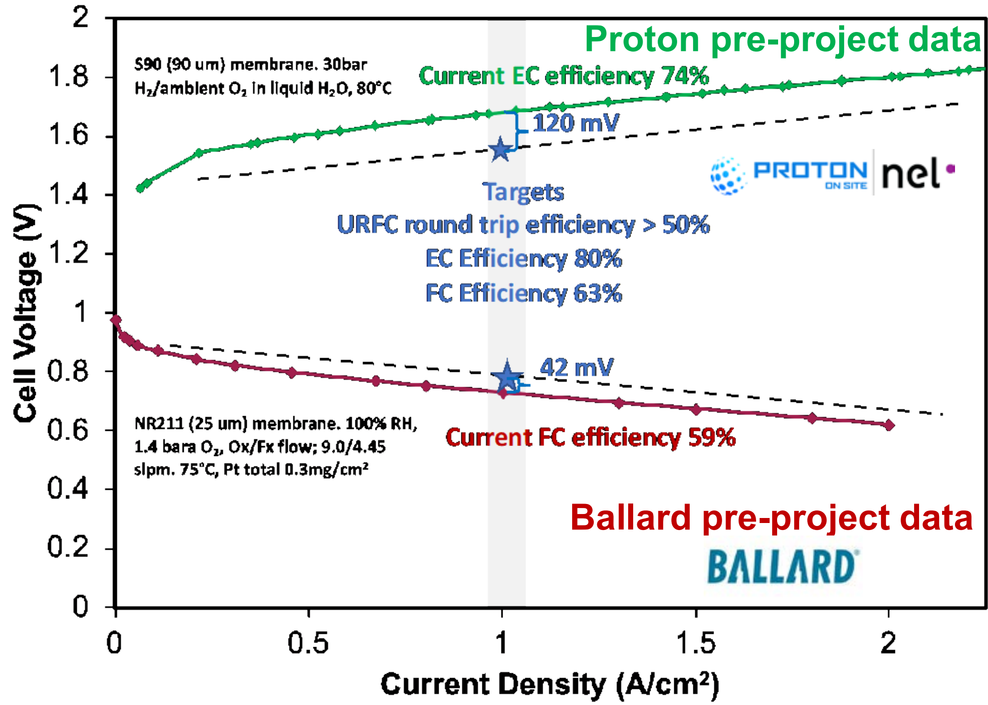
Ballard + Proton
50cm^2 performance and durability validation

WUSTL
Advanced Membranes



Reinforced PFSA based membrane

LBNL + Pajarito Powders
MEA Integration and Optimization
25cm^2 URFC Performance and Durability



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

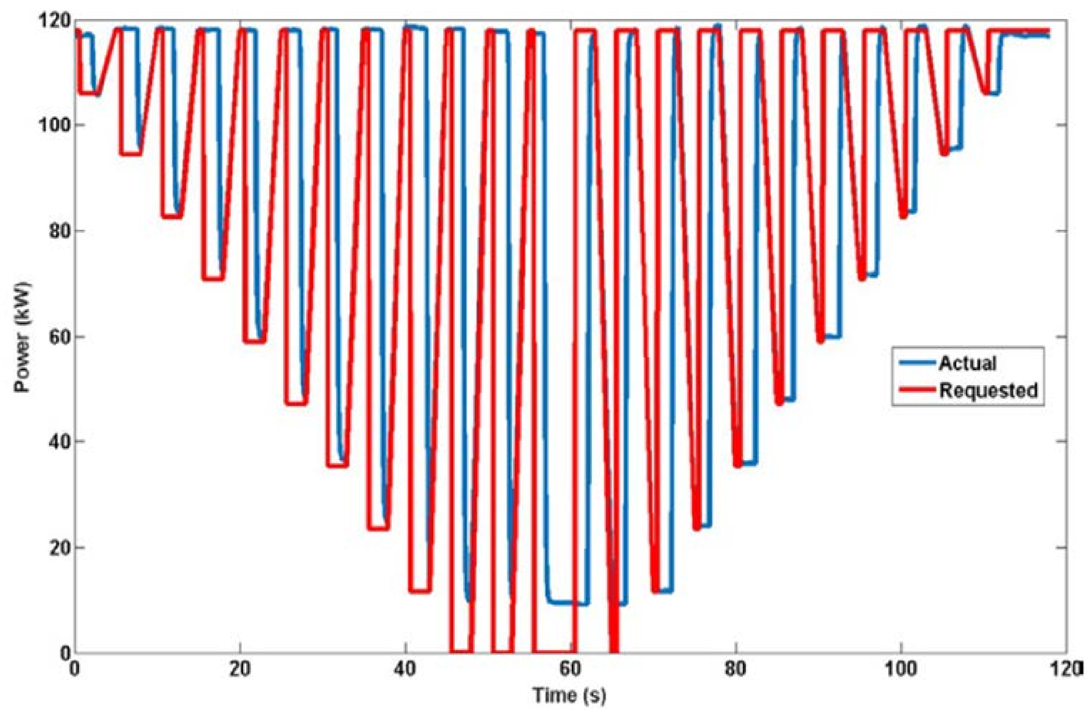
N. Danilovic et al., LBNL

Lab testing shows value of electrolyzers for ancillary services

First Ever Validation of Frequency Regulation with Electrolyzers

Idaho National Lab (INL)

National Renewable Energy Lab (NREL)



Lab testing shows dynamic response within seconds and potential for grid services

Collaboration & Resources

Example of International Government Collaboration

The International Partnership for Hydrogen and Fuel Cells in the Economy

Enabling the global adoption of hydrogen and fuel cells in the economy

www.iphe.net

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

Top Priorities	SHARE INFORMATION	INFORM FUTURE GOVERNMENT RD&D	FOSTER COLLABORATION

Find IPHE on Facebook, Twitter and Linkedin

Follow IPHE **@The_IPHE**

Formed 2003
Over 20 Countries

Collaboration: New H_2 Safety Partnership

New global partnership to promote collaboration on safety

AIChE

Pacific Northwest
NATIONAL LABORATORY

CENTER FOR
Hydrogen
SAFETY

HYDROGEN
Safety Panel

HYDROGEN
Emergency Response
Training Resources

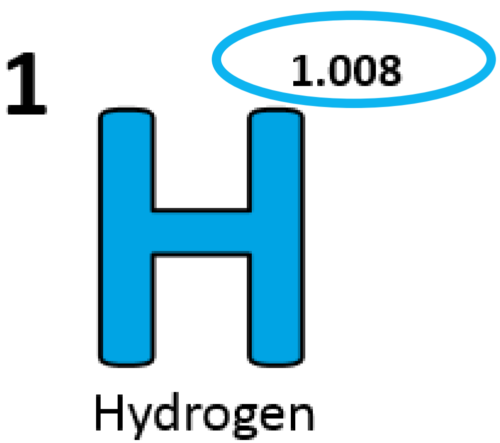
www.aiche.org/chs

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)



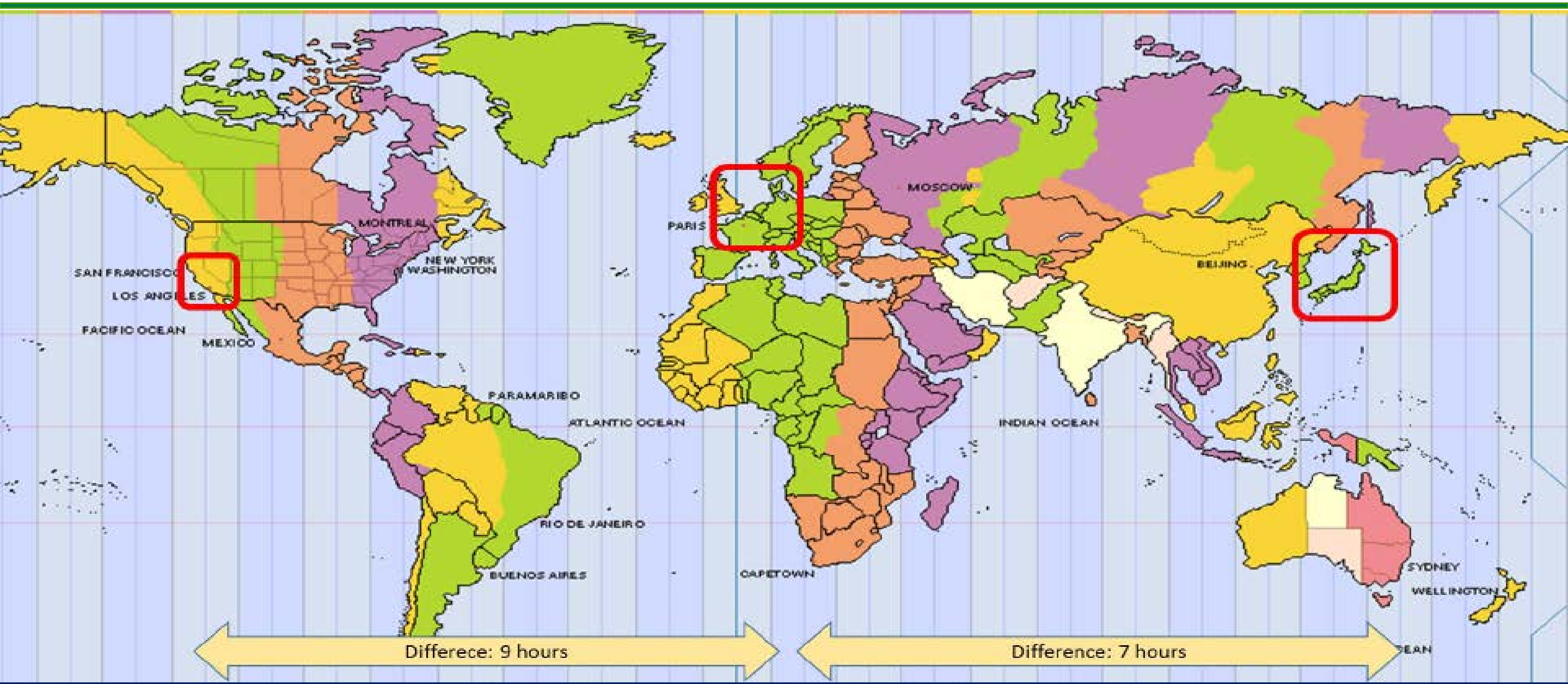
Give an *“Increase your H2IQ”* presentation in your community

INCREASE YOUR H_2IQ

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

Learn more at: energy.gov/eere/fuelcells

Hydrogen and Fuel Cell Day Challenge on Oct 8.



- 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

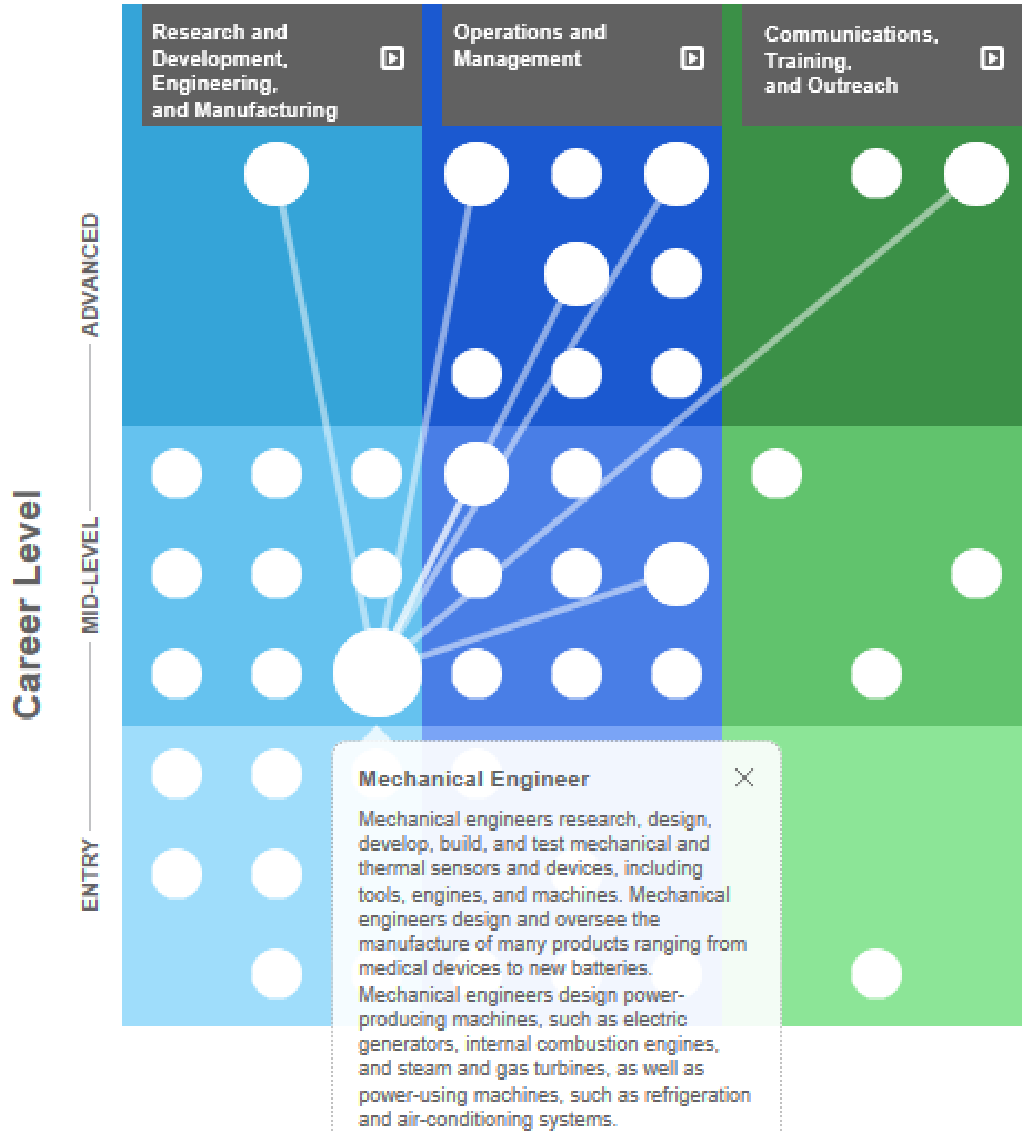
Hydrogen and Fuel Cells Career Map Online

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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Nancy.Garland@ee.doe.gov
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To apply: https://www.zintellect.com/Opportunity/Details/EERE-STP-FCT-2019-1800

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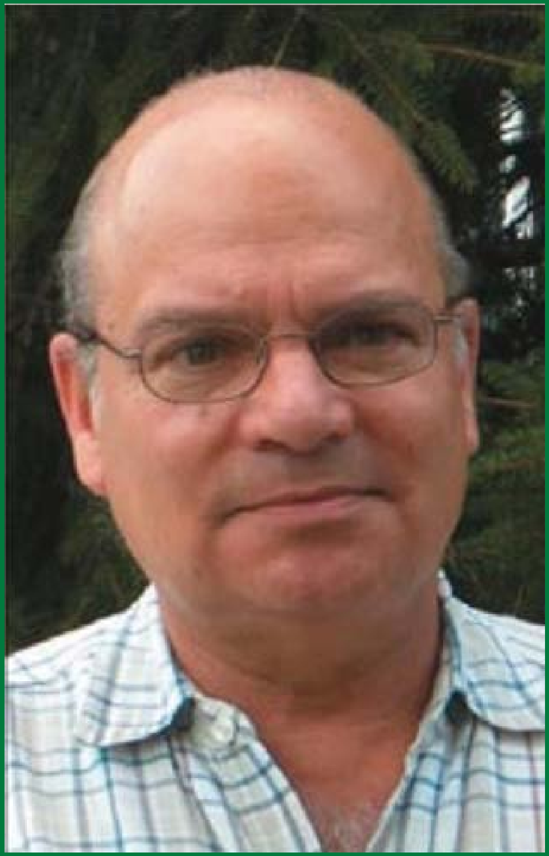
In Recognition of your Invaluable Contributions to Fuel Cell Science and to the United States Department of Energy



Thank you

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energy.gov/eere/fuelcells