U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Fuel Cell R&D Overview

Dr. Dimitrios Papageorgopoulos – Fuel Cell Technologies Office

2019 Annual Merit Review and Peer Evaluation Meeting

April 29, 2019

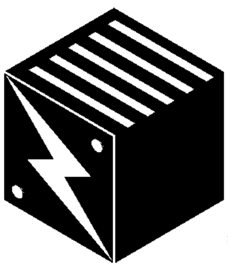
Fuel Cells: Pillar of H_2 & Fuel Cell Technologies R&D

Focus

Early-stage applied R&D and innovation in hydrogen and **fuel cell technologies** leading to:

- Energy security
- Resiliency
- Affordability
- Strong domestic economy

H_2 & Fuel Cells Program: Early-Stage R&D Areas



Fuel Cells

Hydrogen

GOAL: Advance fuel cell technologies for transportation, stationary and cross-cutting applications

Making Fuel Cells our Future, Today

Objectives

Light-duty vehicles

Primary and back-up power

Cross-cutting

R&D to enable fuel cell power systems competitive with incumbent and alternative technologies

Expanded focus includes medium- and heavy-duty applications and energy storage

Fuel Cells MYRD&D Plan

http://energy.gov/eere/fuelcells/downloads/fuel-cell-technologies-office-multi-year-research-development-and-22

Targets

Market-driven targets allow fuel cells to compete with incumbent and advanced alternative technologies

2025 Targets by Application

	Automotive	Stationary
		
Fuel Cell Cost	$40/kW $30/kW*	$1,000/kW** $1,500/kW***
Durability	5,000 hrs 8,000 hrs*	80,000 hrs
Efficiency	65%	50% † 90% ‡

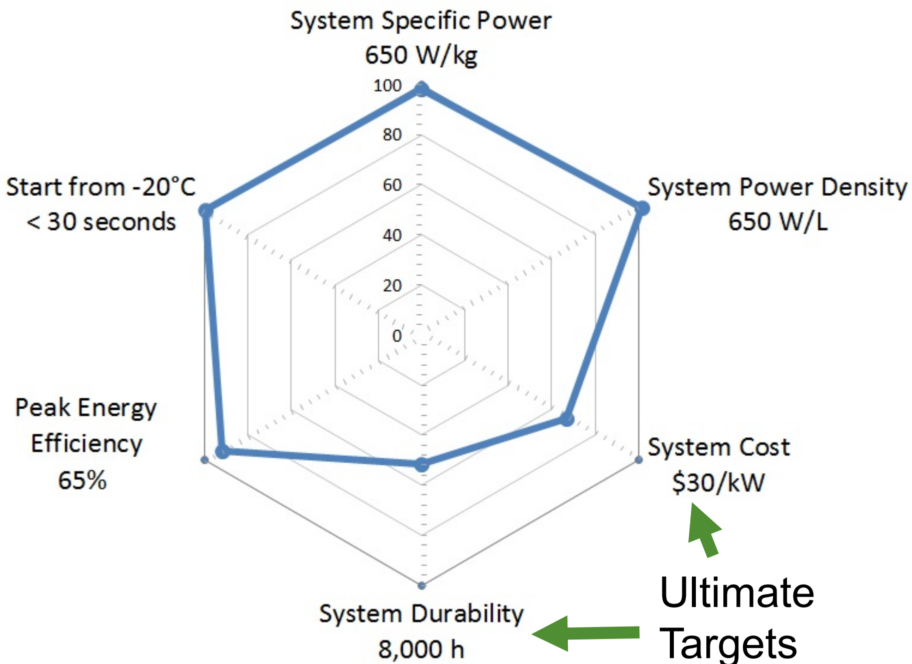
* Ultimate (Beyond 2030)

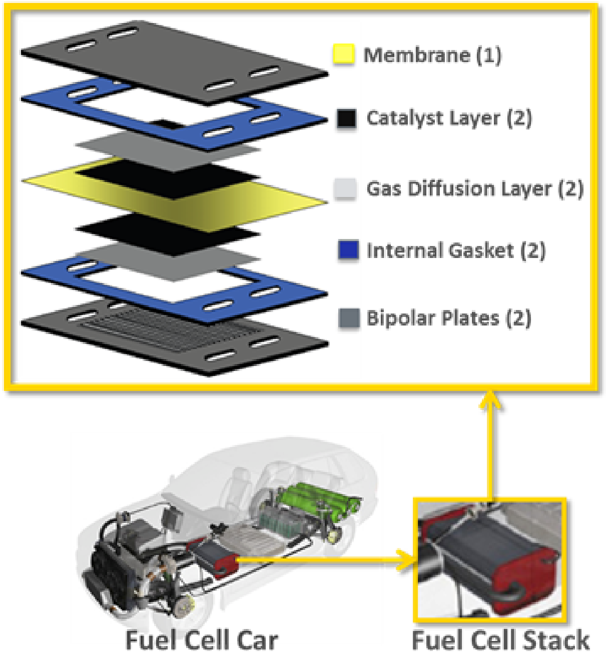
** For Natural Gas
*** For Biogas
† Electrical
‡ CHP

Challenges and Strategy

Durability <u>and</u> 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





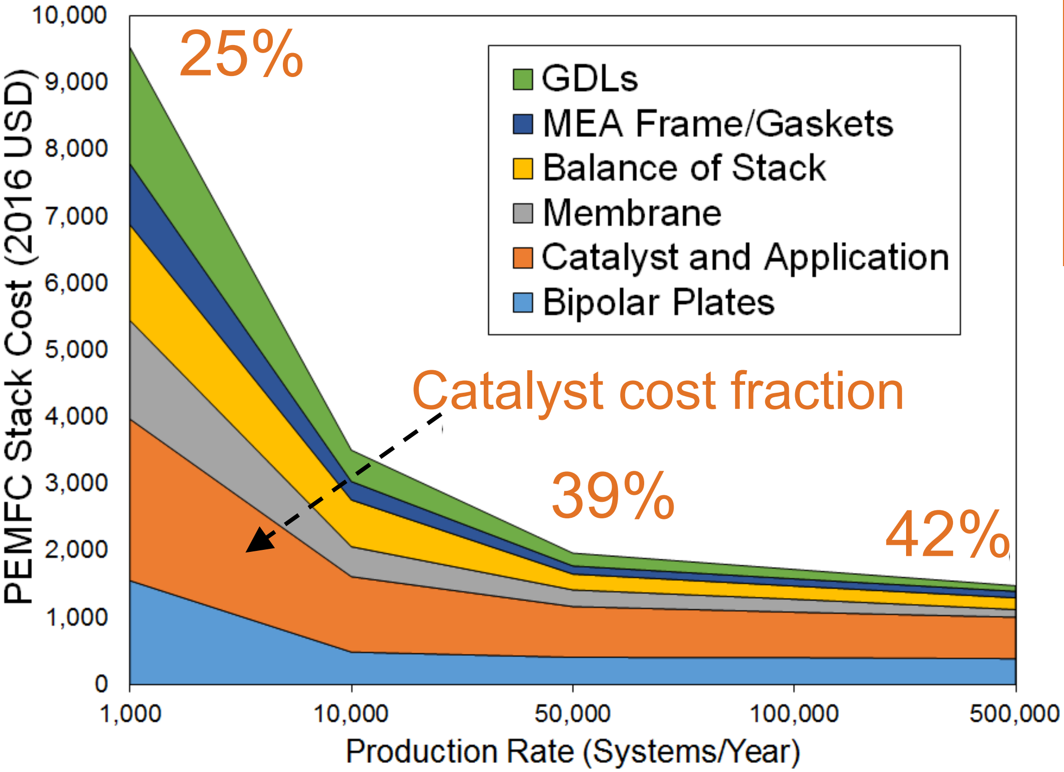
Improvements in multiple components are required to meet targets

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

Light-Duty Vehicle Cost Analysis

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

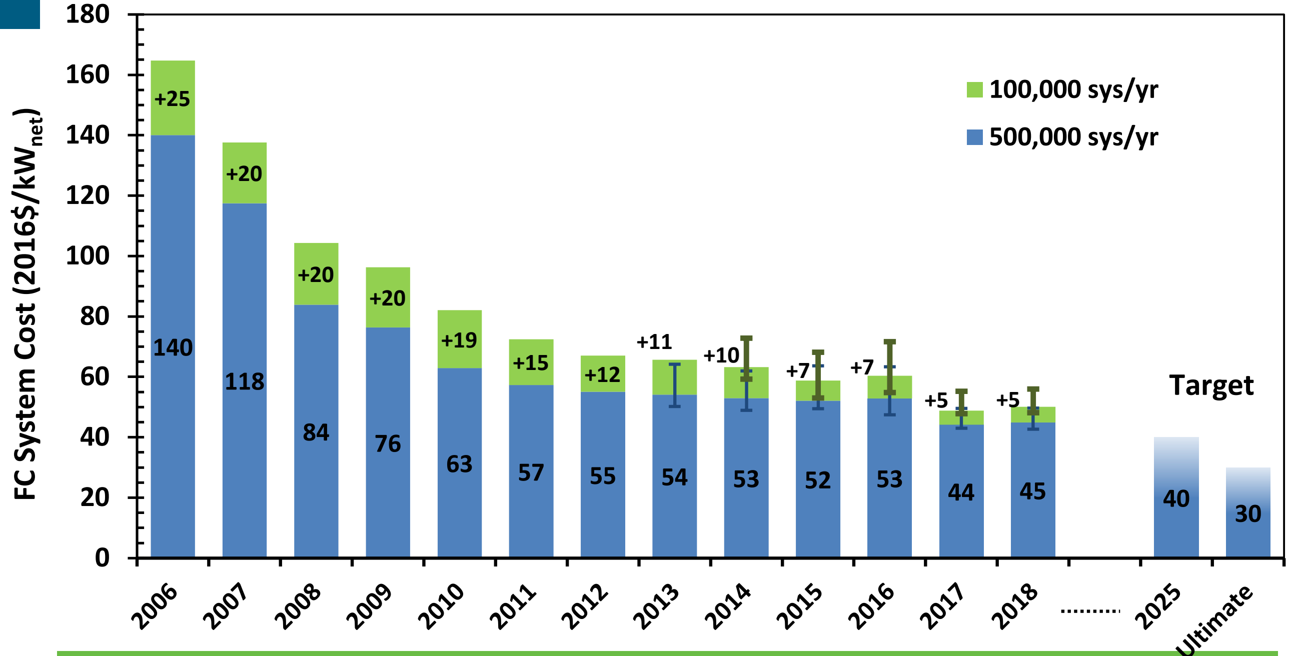
- Reduce or eliminate PGM levels in catalysts *
- Improve MEA performance

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

Light-Duty Fuel Cell Cost Improvements

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



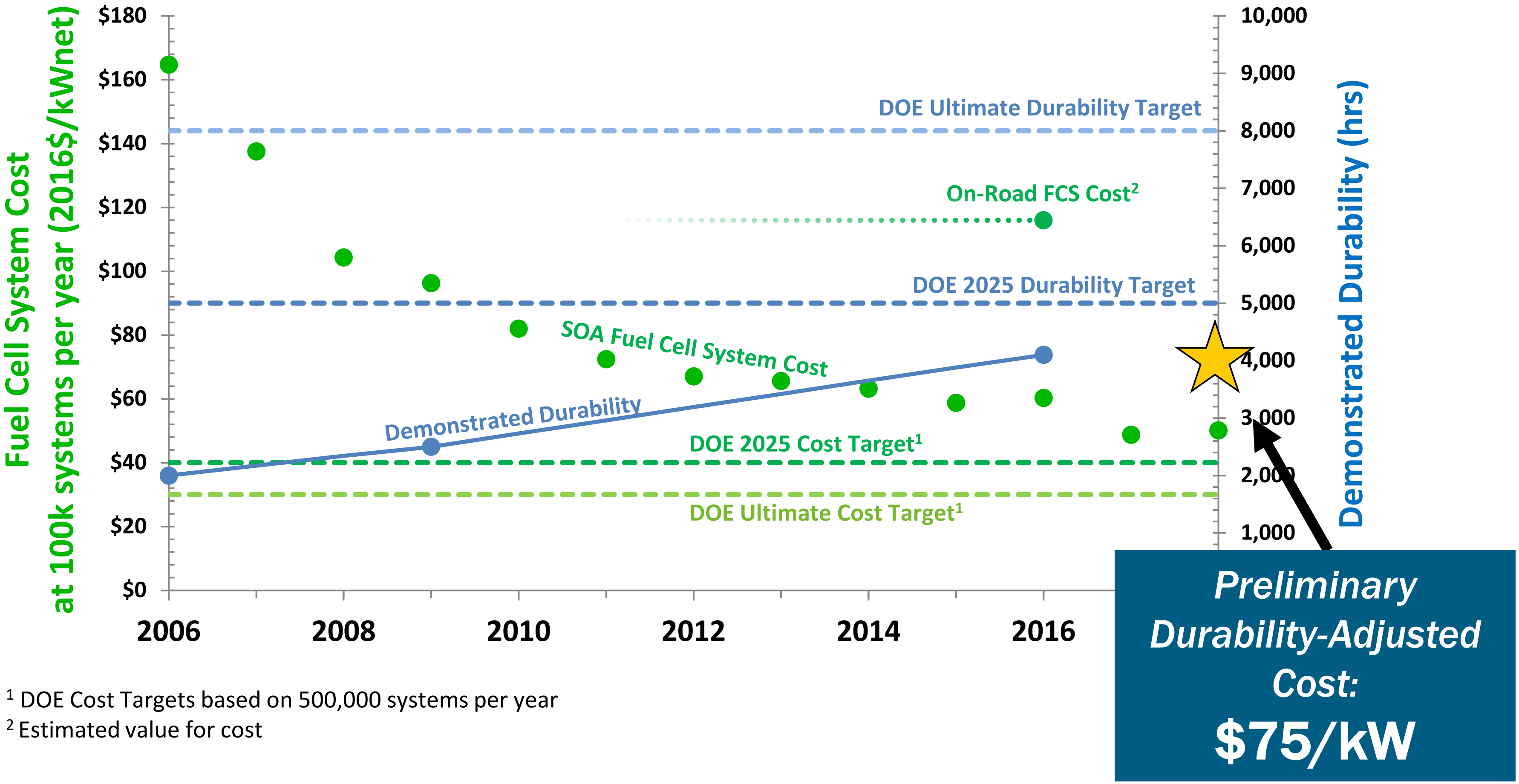
67% cost reduction since 2006

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

Towards a Combined Durability-System Cost Metric



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

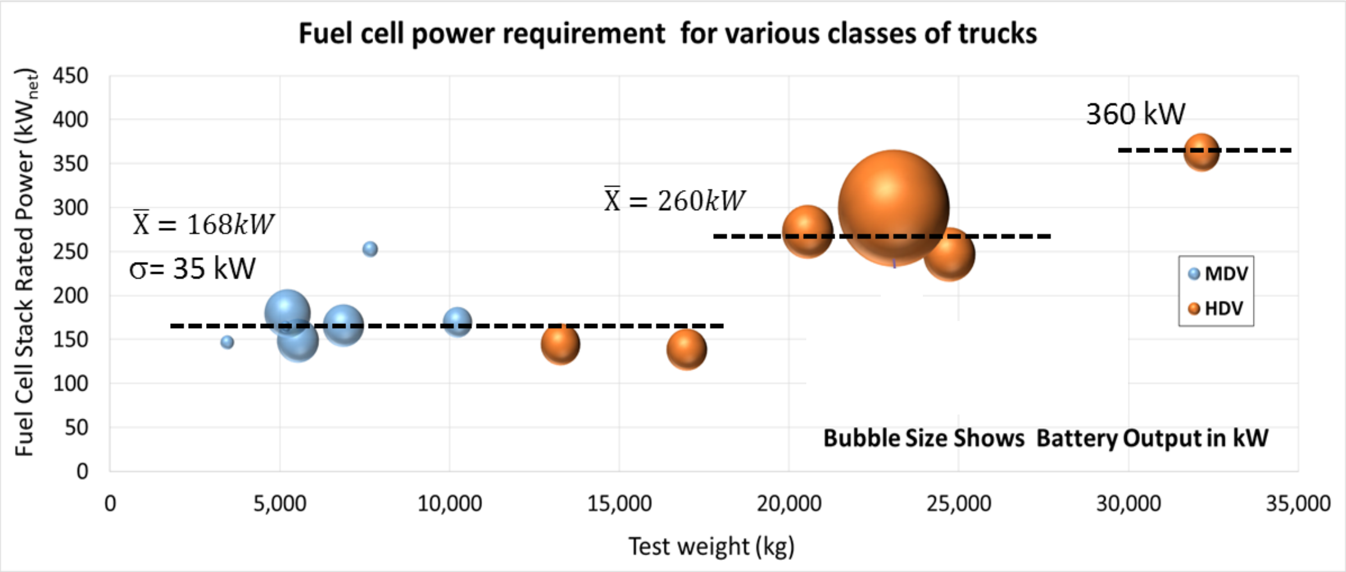
Coming soon: combined durability-system cost metric for state of the art light-duty vehicles

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

Medium- and Heavy-Duty Vehicle Cost Analysis

Medium- and Heavy-Duty Vehicles (MDVs/HDVs)

- Analysis of 12 truck vocations suggests 3 system sizes fit majority
- Needs met with multiple 80 kW fuel cell stacks



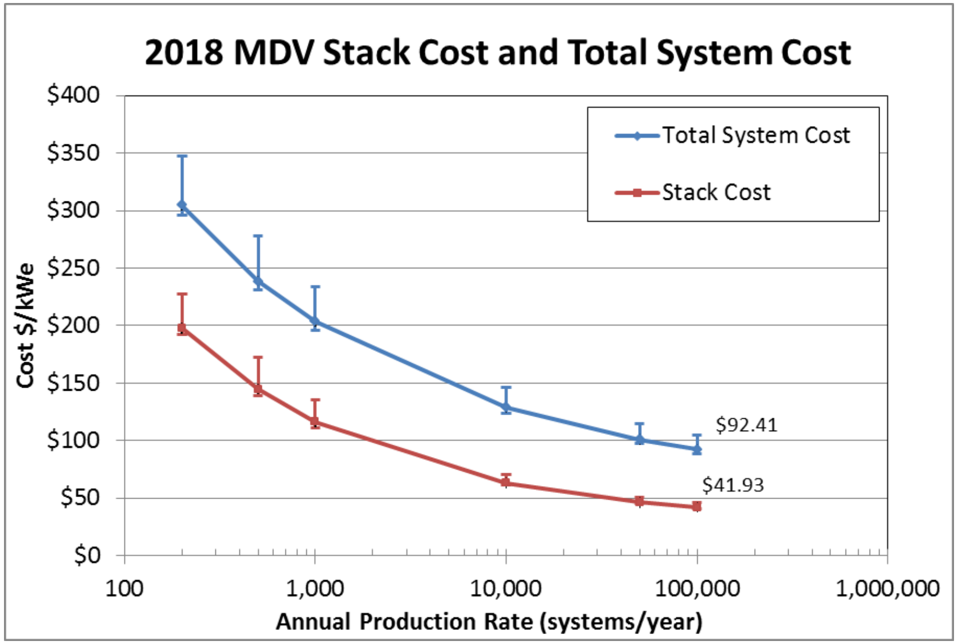
SA Inc. 2017 cost report

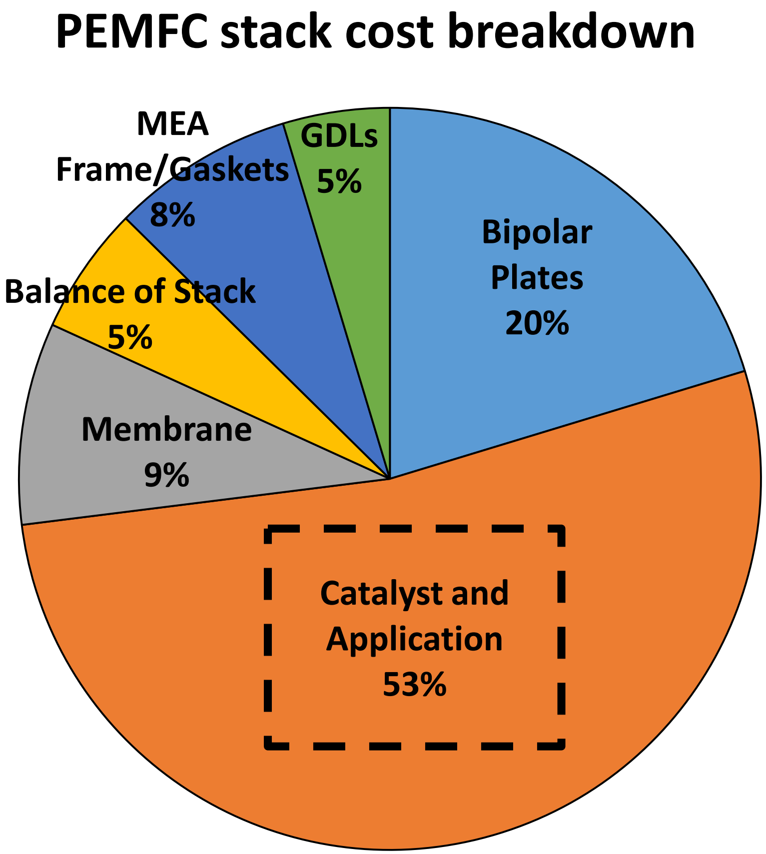
- Domestic MD/HD Truck market is large and growing (~ 400,000 sold in 2016)
- Main stack limitations: durability, cost

Coming soon: Truck targets

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)



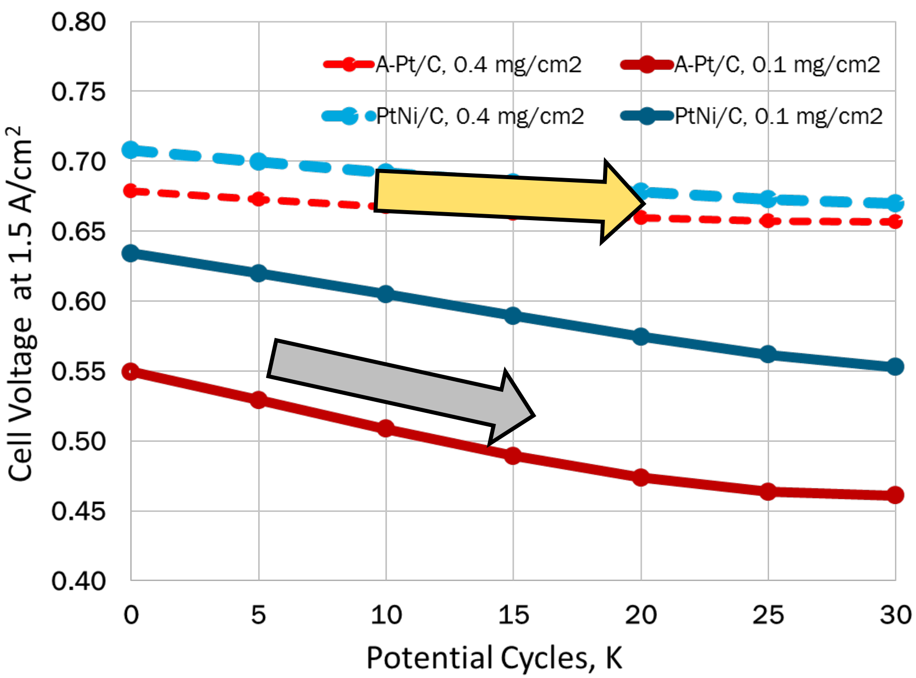


*Manufacturing volume: 100,000 systems/year

Coming in 2019: Heavy-duty fuel cell truck cost analysis

Fuel Cell Systems for HDVs: Catalyst Loading and Durability

High durability demand of HDVs requires increased PGM loading



Ahluwalia, et al.

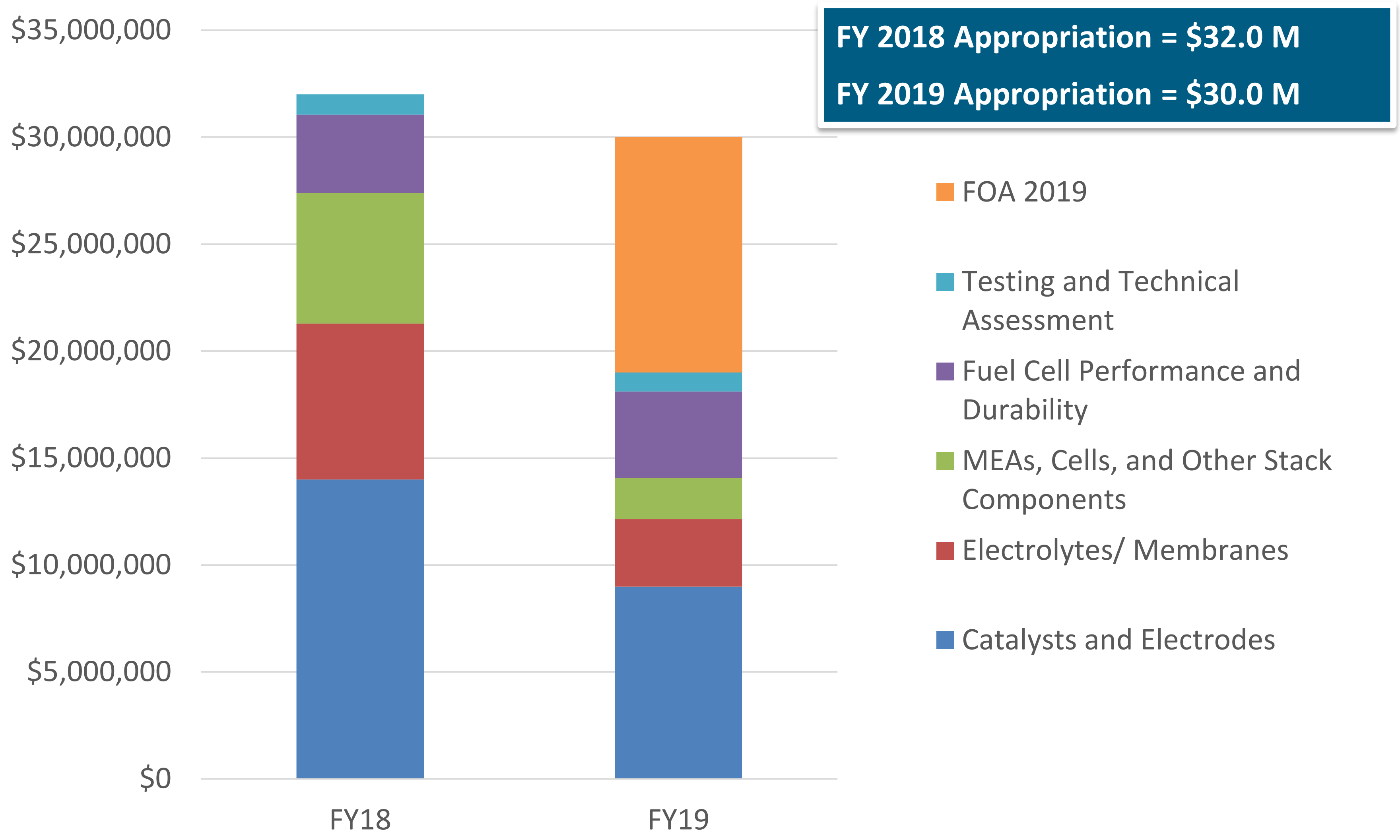
Cost analysis

	Power Output (kW)	Pt content (mg_{Pt}/cm^2)	System Cost ($\$/kW_{net}$) 100k systems/year
LDV	80	0.125	50
MDV*	170	0.35	89
HDV*	230	0.35	95

*2019 Preliminary results

R&D is needed to develop low-cost, efficient MEAs (at low-PGM loading) with durability extending far beyond what is required for light-duty applications

Funding



Funding distribution reflects target oriented emphasis on early-stage applied R&D

ElectroCat (Electrocatalysis Consortium)

ElectroCat (Electrocatalysis Consortium)

Goal

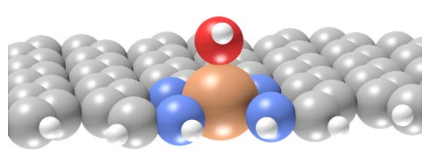
ElectroCat Electrocatalysis Consortium → Energy Materials Network U.S. Department of Energy

Accelerate the deployment of fuel cell systems by replacing platinum-based catalysts with **platinum group metal-free (PGM-free) catalysts**

Core Lab Team

Argonne National Laboratory · Los Alamos National Laboratory · NREL National Renewable Energy Laboratory · Oak Ridge National Laboratory

High-throughput (H-T) materials discovery, characterization, and testing



Design and synthesis of PGM-free catalysts and electrodes, modeling

www.electrocat.org

FC160

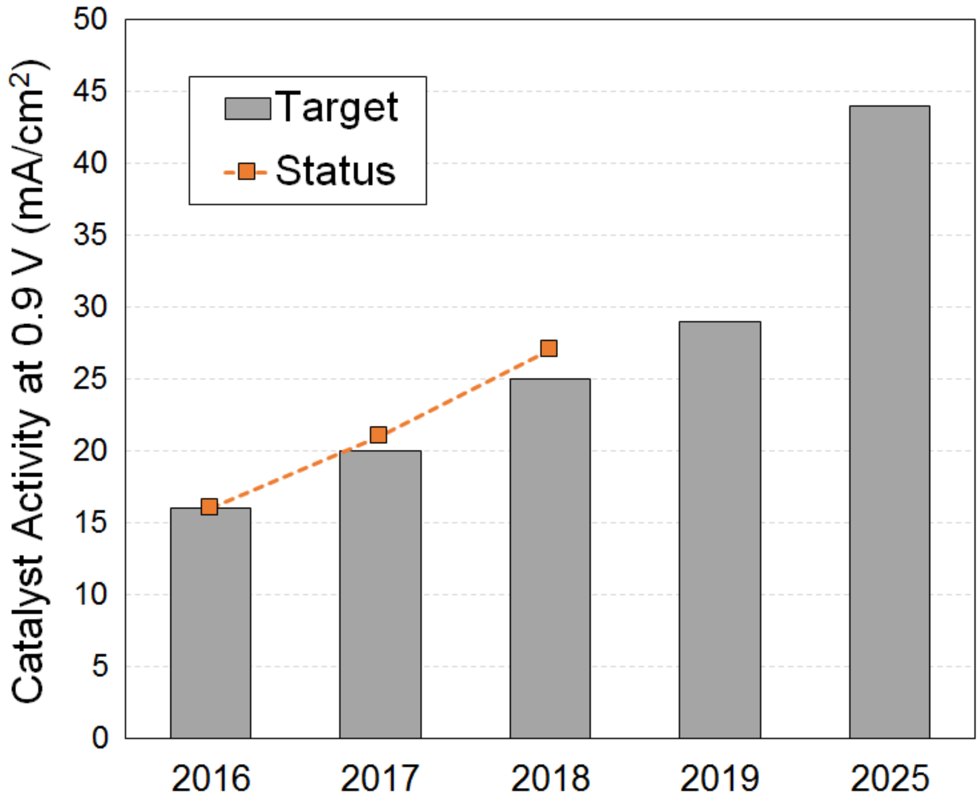
Accomplishments and Next Steps

- Continued significant progress in catalyst and electrode development
- Coupled H-T with machine learning to expedite optimization
- Partnered with 5 newly awarded FOA projects, 1 newly awarded lab call project

Developing and disseminating PGM-free catalyst test protocols and best practices

ElectroCat: Enhancing PGM-Free Mass Activity

Demonstrated MEA performance of 27 mA/cm^2 at 0.9 $V_{IR\text{-}free}$ with H_2/O_2, a nearly 70% improvement over 2016 baseline

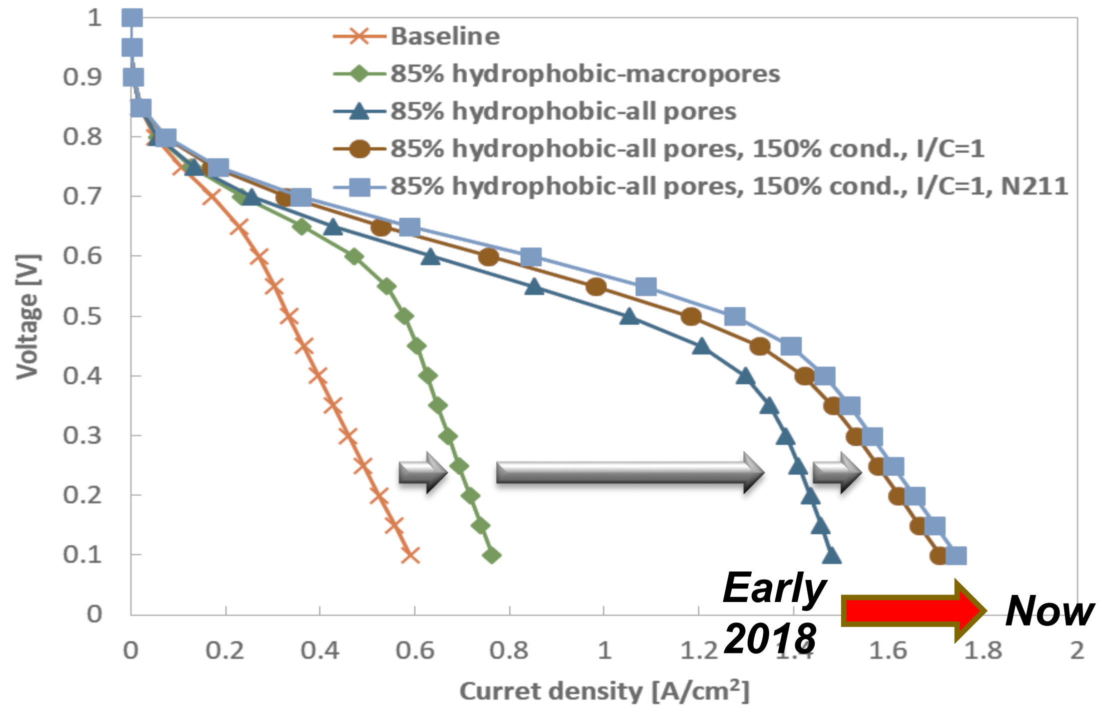


ElectroCat increasing focus on PGM-free catalyst durability and achieving light-duty vehicle-relevant targets

ElectroCat
Electrocatalysis Consortium

ElectroCat: Advancing PGM-free Catalysts Through Partnerships

- Atomically dispersed Fe-N-C catalyst (U. Buffalo)
- **H_2/air** performance: 113 mA/cm² at 0.8 V, **nearly 2.5x the 2018 project baseline**
- **Target** for automotive application:
  - 300 mA/cm² at 0.8 V
- Nearly 85% increase in peak power density over baseline



FC171
Litster, et al. CMU

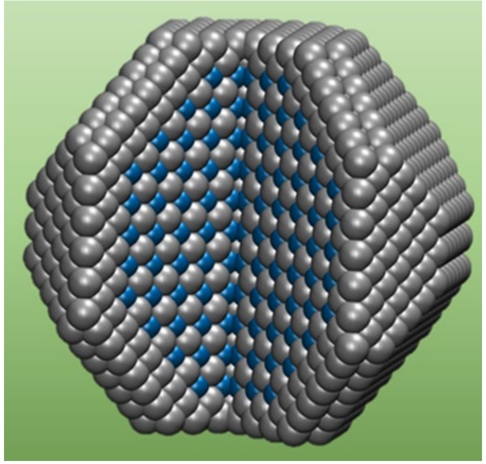
ElectroCat
Electrocatalysis Consortium

Low-PGM Catalyst R&D

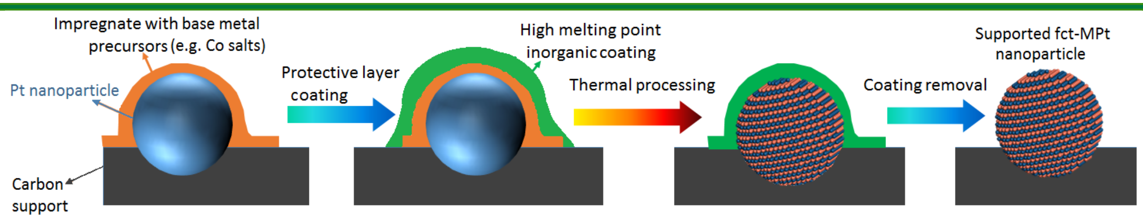
Ordered PtCo Alloys Improve Low-PGM Catalyst Durability

Characteristic	**Units**	**GM** (ordered-PtCo/HSC-f**)**	**LANL (**$L1_0$ PtCo/Vu**)**	**2025 Target**
PGM loading (cathode)	mg_{PGM}/cm^2	0.1 **(anode: 0.025)**	**0.106 (anode: 0.1)**	0.100 (**total: 0.125 mg/cm^2**)
Mass activity @ 0.9 $V_{iR\text{-}free}$	A/mg_{PGM}	**0.7**	**0.6**	0.44
Mass activity loss	%	**45**	**40**	<40%
Performance at 0.8 V	A/cm^2	**---**	**410**	>300
Degradation at 0.8 A/cm^2	mV	**25**	**26**	<30
Power at rated power (150 kPa_{abs})	W/cm^2	**0.94**	**0.89**	>1.0
Power at rated power (250 kPa_{abs})	W/cm^2	**1.29**	**1.10**	
PGM utilization (150 kPa_{abs})	kW/g_{PGM}	**7.5**	**---**	>8

- Both projects cite several examples PGM utilization >8 kW/g_{PGM}
- Have not yet met all targets concurrently



New intermetallic catalysts meet durability targets



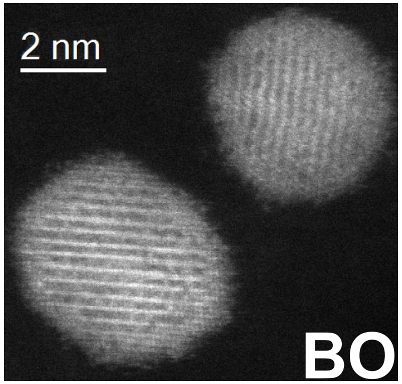
	Units	Measured	Target
Mass Activity	A/mgPGM	**0.60**	**0.44**
Mass Activity Loss [1]	%	**40**	**40**
Degradation at 0.8 A/cm^2 [1]	mV	**26**	**30**
Current Density at 0.8 V	A/cm^2	**0.41**	**0.3**
Power at 0.67 V, 150 kPa_{abs}	W/cm^2	**0.89**	**1**
Power at 0.67 V, 250 kPa_{abs}	W/cm^2	**1.10**	**1**
PGM Loading [2]	mg/cm^2	**0.106**	**0.125**

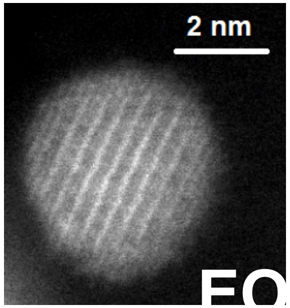
[1] 30K square wave cycles, 0.6-0.95 V

[2] Cathode

Novel $L1_0$-PtCo@Pt/Vulcan catalyst meets or approaches DOE catalyst and MEA targets

	Baseline PtCo	Ordered PtCo
BOL Co%	**48%**	**27%**
EOL Co%	**12%**	**17%**





Ordered PtCo alloy nanoparticles have improved Co retention and retain ordered structure during fuel cell testing, enabling high durability

FC161 J. Spendelow et al., LANL

FC-PAD: Fuel Cell Performance and Durability

FCPAD FUEL CELL PERFORMANCE AND DURABILITY

Mission

Enhance the performance and durability of polymer electrolyte membrane fuel cells while simultaneously reducing their cost

Consortium fosters sustained capabilities and collaborations

Core Consortium Team

Argonne National Laboratory, Los Alamos National Laboratory, Berkeley Lab, NREL National Renewable Energy Laboratory, Oak Ridge National Laboratory

Prime Partners

3M, GM, United Technologies Research Center, Vanderbilt

New FOA partners expected in FY2020

New in FY2019

Increased focus on heavy-duty applications, especially increasing MEA durability towards ultimate target (preliminary 25,000 h)

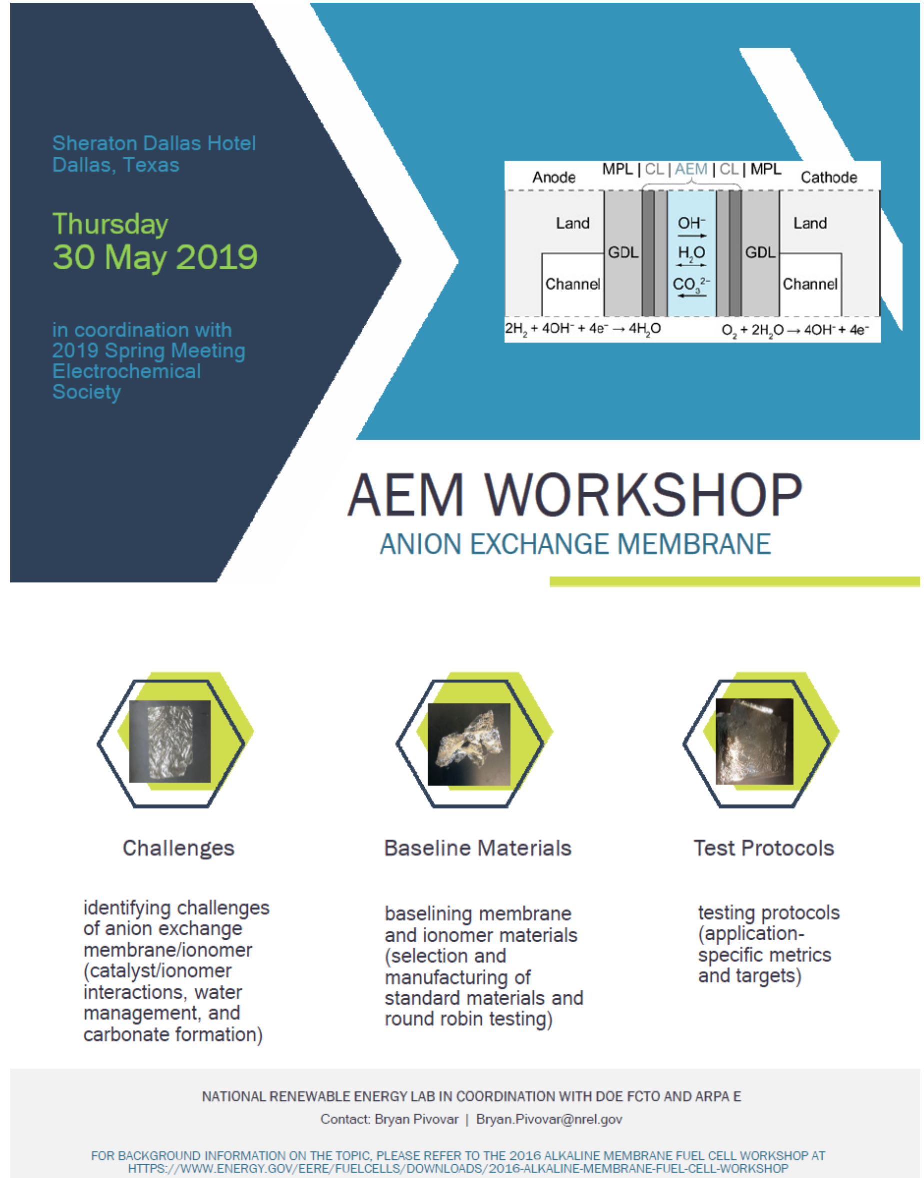
FC135
www.fcpad.org

Expediting Membrane R&D

Membranes Working Group

- In collaboration with ARPA-E IONICS program
- Serves to coordinate and accelerate the research community investigating polymer electrolyte membranes for energy conversion (and storage) devices.
- Initial focus AEMFCs

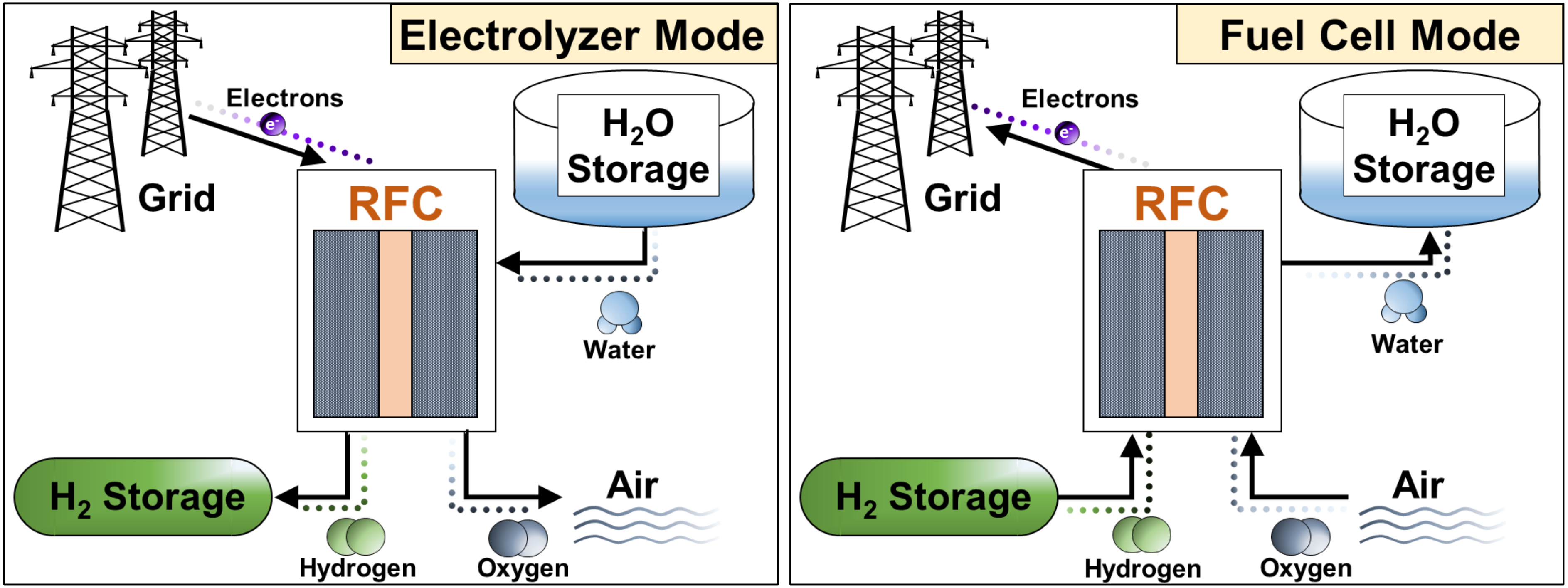
Workshop May 30 following Spring ECS in Dallas



Reversible Fuel Cell R&D

Long-Term Grid Energy Storage via Reversible Fuel Cells (RFCs)

Concept: Store grid electricity as H_2 for later conversion back to electricity



RFCs offer a broad range of versatile energy services, including energy storage, which improve the grid's reliability and resiliency

Target-Driven RFC R&D

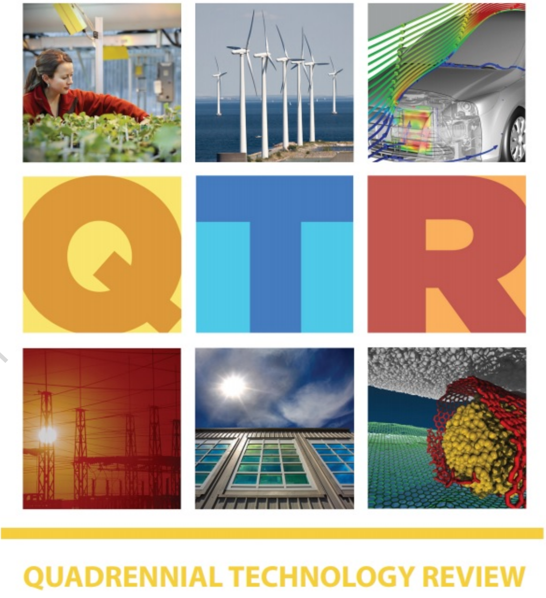
Viability and cost-competitiveness of RFCs require innovative R&D to:

- ***improve roundtrip efficiency and durability;***
- ***decrease levelized cost of electricity/storage to <10₵/kWh/cycle*;***
- ***meet long-term system capital cost targets by power and energy of less than $1250/kW and $150/kWh****

Table 3.4 Cost and Performance Targets for Electric Energy Storage Technologies

Range of baselines	**System capital cost by energy:** $805–$10,020/kWh **Levelized cost:** $0.01-$0.64/kWh/cycle **System efficiency:** 75%–92% **Cycle life:** 4,500–225,000 over life of plant **System capital cost by power:** $300–$4,600/kW
Near-term targets	**System capital cost by energy:** less than $250/kWh **Levelized cost:** less than $0.20/kWh/cycle **System efficiency:** more than 75% **Cycle life:** more than 4,000 cycles **System capital cost by power:** less than $1,750/kW
Long-term targets	**System capital cost by energy:** less than $150/kWh **Levelized cost:** less than $0.10/kWh/cycle **System efficiency:** more than 80% **Cycle life:** more than 5,000 cycles **System capital cost by power:** less than $1,250/kW

*https://www.energy.gov/sites/prod/files/2017/03/f34/quadrennial-technology-review-2015_1.pdf.
(Chapter 3, Table 3.4)

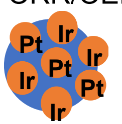


****Detailed RFC technical targets drafted; will be requesting input from stakeholders***

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

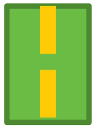
Low-T PEM Example:

WUSTL Supported Bifunctional ORR/OER catalyst



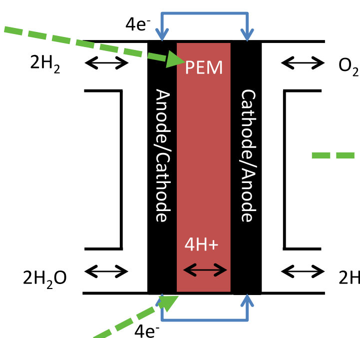
WUSTL supports:
Ru doped TiO_2 (RTO)
Nb doped TiO_2 (NTO)
Sb doped SnO_2 (ATO)

WUSTL
Advanced Membranes



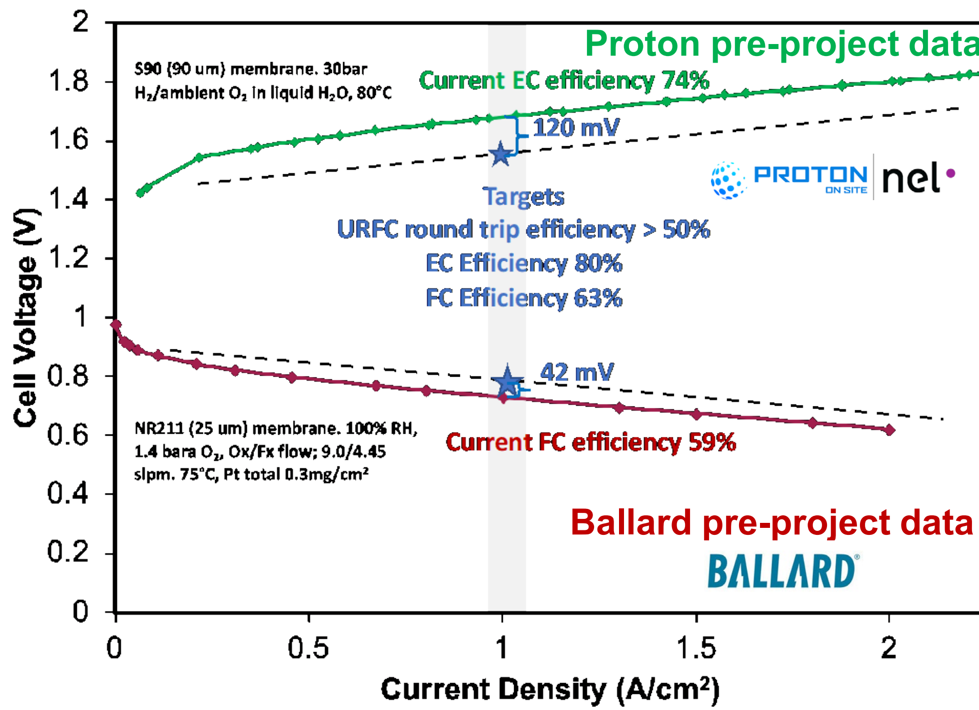
Reinforced PFSA based membrane

Traditional URFC



Ballard + Proton
50cm² performance and durability validation

LBNL + Pajarito Powders
MEA Integration and Optimization
25cm² URFC Performance and Durability

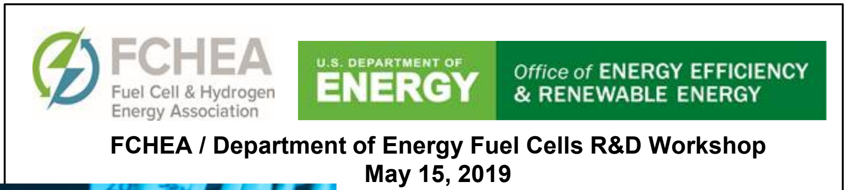


Materials/component R&D to advance both fuel cell and electrolyzer performance

FC313
N. Danilovic et al., LBNL

New Fuel Cell Applications Explored in 2019 Workshops

Bringing together leading industry representative and stakeholders to discuss current R&D needs and technology gaps



Summary of Current Activities

- **Applied Early-Stage R&D** addresses cost reduction, performance and durability enhancement of materials and stack components, including catalysts and membranes
- **ElectroCat** coordinates with newly awarded FOA projects to expedite the development of PGM-free catalysts and electrodes
- **FC-PAD**, including industry/university partners, continues to expand the knowledge base to advance fuel cell performance and durability
- **RFC R&D** to improve competitiveness with incumbent energy storage technologies

Summary of Upcoming Activities & Milestones

- **Innovative R&D projects** through FY19 FOA and FY20 Lab Call
- **Membranes Working Group** to coordinate efforts and leverage activities with other agencies
- **New focus area:** highly durable and efficient, low-PGM MEAs for medium- and heavy-duty applications
- **Technical milestones:**
  - Demonstrate **29 mA cm^{-2}** at 0.9 V (iR-corrected) in an H_2-O_2 fuel cell (**4Q 2019**)
  - Demonstrate **31 mA cm^{-2}** at 0.9 V (iR-corrected) in an H_2-O_2 fuel cell (**4Q 2020**)

Collaborative Approach to Fuel Cell R&D

Vehicle Technologies Office (VTO) Small Business Innovation Research (SBIR)

Energy Materials Network
U.S. Department of Energy

Energy Materials Network

DOE-EERE Fuel Cells Program

INDUSTRY
U.S. DRIVE Partnership: Fuel Cell Tech Team

Technology Validation

National Collaborations (inter- and intra-agency efforts)

DOE - FE	DOE - BES	DOE – ARPA-E	NSF	DOT/FTA	DOD	DOC/NIST	DOT/FRA
SOFC Program	Catalysts and Membranes	IONICS& INTEGRATE	ElectroCat	Fuel Cell Buses	DOD/DOE MOU	Neutron Imaging	H_2/FC-Rail

R&D is coordinated among a range of organizations

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Thank You

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