U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

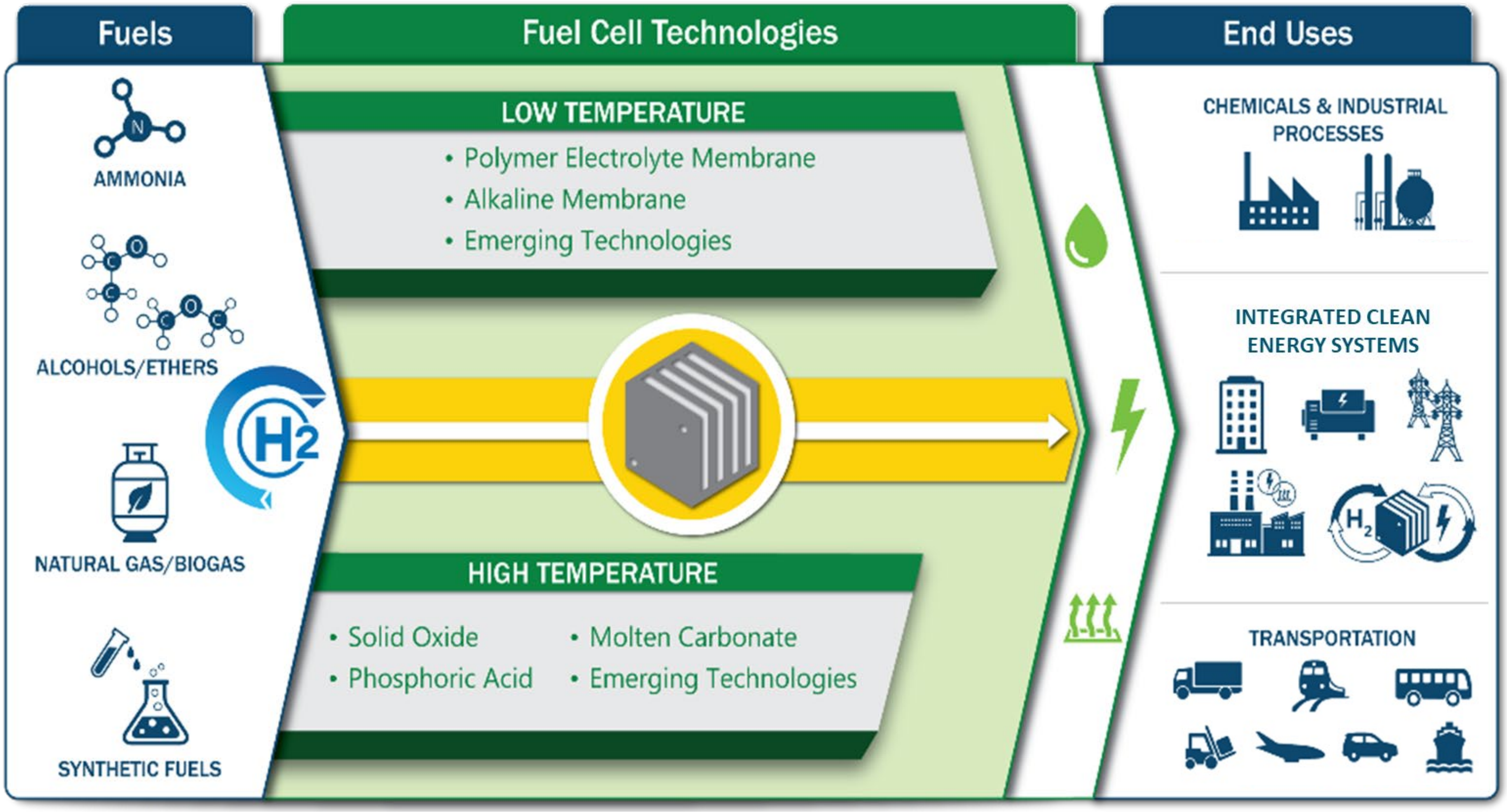
Fuel Cell Technologies Overview

Dr. Dimitrios Papageorgopoulos, HFTO – Fuel Cell Technologies Program Manager

2021 Annual Merit Review and Peer Evaluation Meeting

June 7, 2021 – Washington, DC

Fuel Cell Technologies: Building an Affordable, Resilient, and Clean Energy Economy



Fuel cells use a wide range of fuels and feedstocks; deliver power for applications across multiple sectors; provide long-duration energy storage for the grid in reversible systems

Innovative RD&D Considers End Use Requirements

<u>Goal:</u> Fuel cells that are competitive with incumbent and emerging technologies across applications

Application-Driven Targets

System-level targets to achieve competitiveness with incumbent and emerging technologies

Supported by guideline component and stack level targets/milestones

EXAMPLE 2030 TARGETS

FUEL CELLS FOR LONG-HAUL TRUCKS

- $80/kW fuel cell system cost
- 25,000-hour durability

FUEL CELLS FOR STATIONARY POWER

- $1000/kW fuel cell system cost
- 80,000-hour durability

REVERSIBLE FUEL CELLS FOR ENERGY STORAGE

- $1800/kW system cost ($0.20/kWh LCOS)
- 40,000-hour durability

EXAMPLE:

A combined target for HD MEA development:
Improve power at appropriate voltage measured *after* durability test.

2025 target:
Achieve 2.5 kW/g_{PGM} power
(1.07 A/cm^2 current density)* at 0.7 V after 25,000 hour-equivalent accelerated durability test**

**Total PGM loading constrained to 0.3 mg/cm^2.*
***Heavy duty AST.*

Revised targets and milestones being updated in Program Plan

RD&D Strategies Address Fuel Cell Challenges

Cross-cutting fuel cell challenges

- Cost
- Durability
- Efficiency
- Power Density

Are strategically addressed through...

Materials and Components

- Low-PGM and PGM-free catalysts and electrodes
- Innovative membranes and ionomers
- Durable high performance MEAs
- Advanced bipolar plates and coatings

Systems and Manufacturing

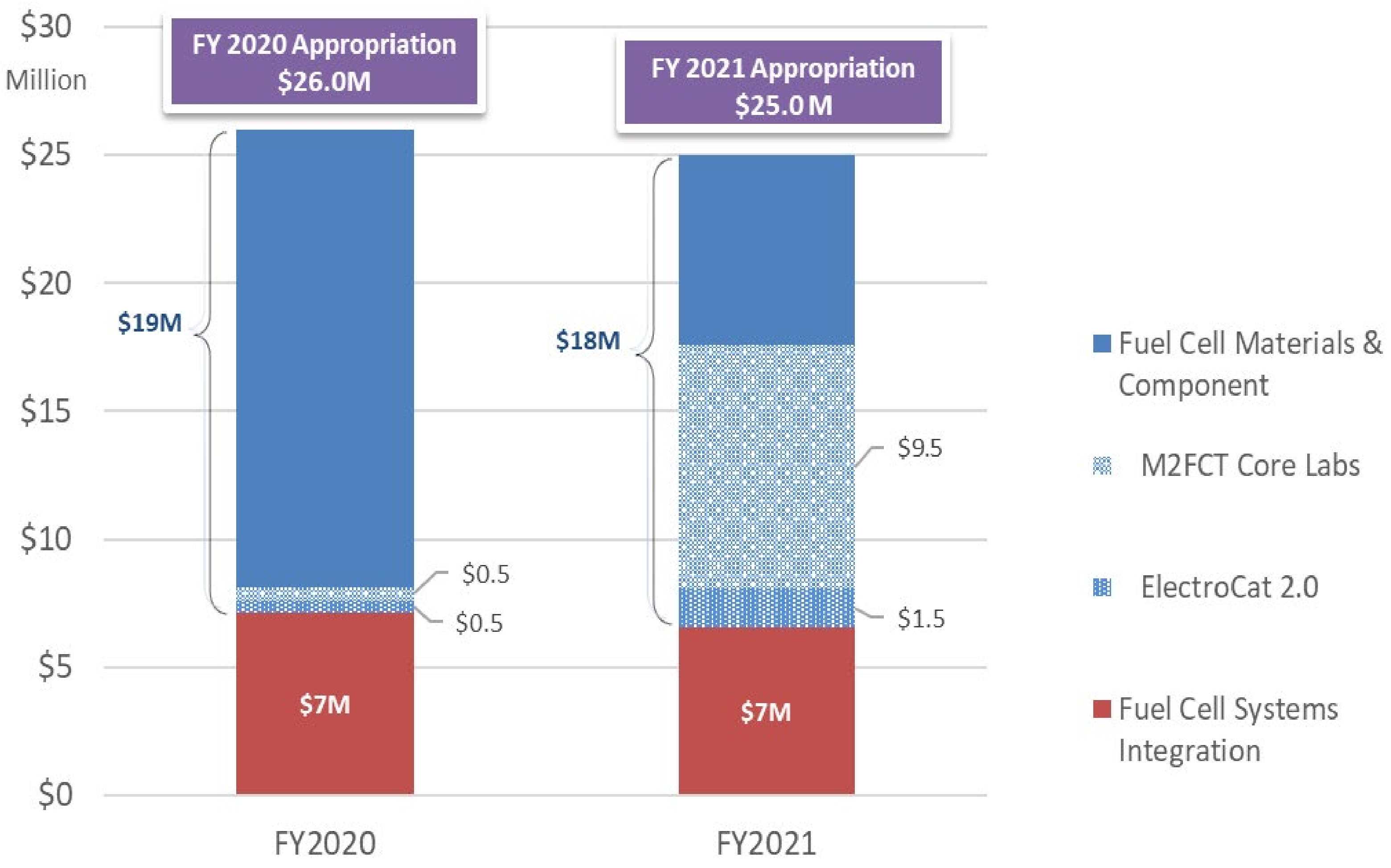
- System design and operating conditions
- Standardized stacks and modular systems
- Improved manufacturing and supply chain
- Advanced BOP components and subsystems

Analysis and Modeling

With emphasis on HD applications…….

- Heavy duty efforts prioritize efficiency and durability to achieve cost and lifetime targets
- Transferable benefits for medium duty and stationary applications
- Leverages previous light duty efforts in technology improvement and cost reductions

Fuel Cell Technologies Funding



Program Direction

Fuel Cell Materials & Components

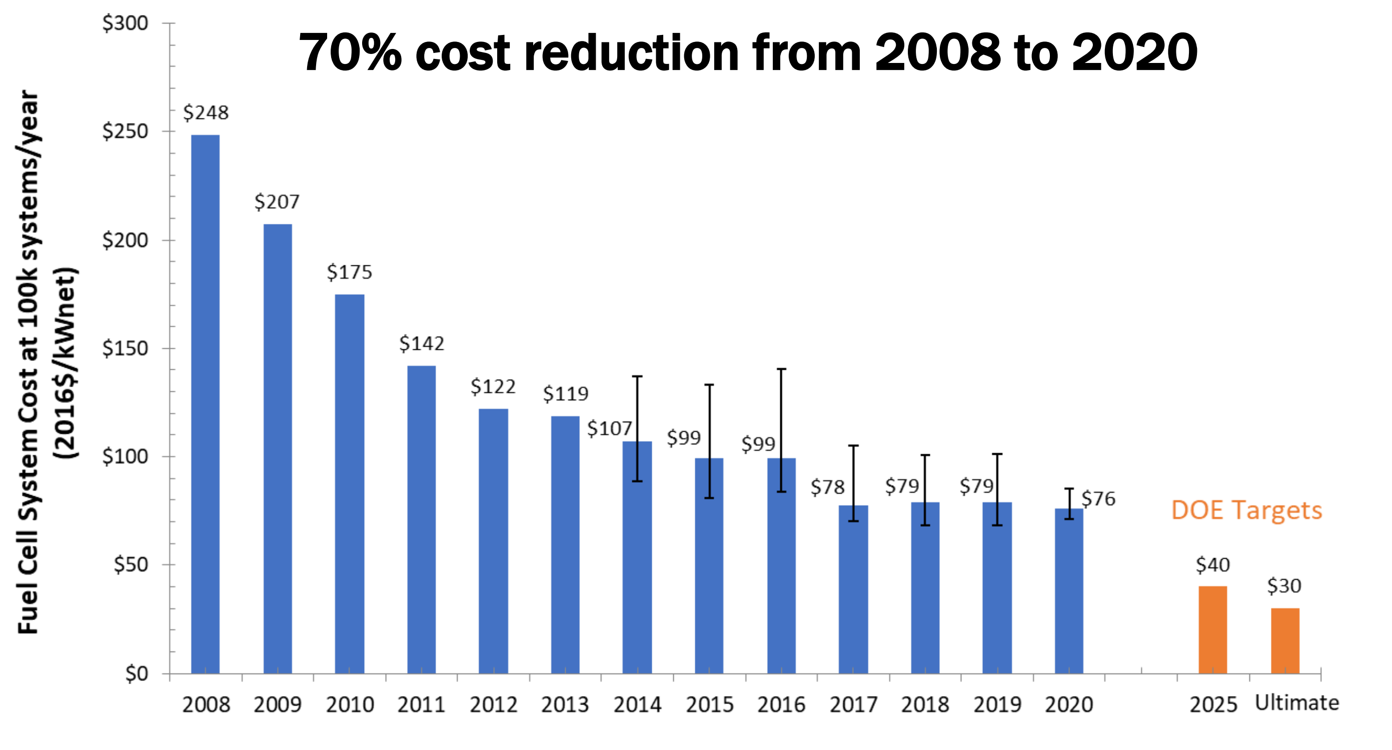
- Low-PGM MEAs and MEA components with enhanced durability
- PGM-free catalysts/electrodes
- Bipolar plates, Gas diffusion layers
- Advanced manufacturing & sustainability

Fuel Cell Systems Integration

- Stacks
- BOP components including power electronics
- SuperTruck III
- System analysis
- Advanced manufacturing & sustainability

RD&D Portfolio Guided by Analysis

Historic Reduction in LDV Hydrogen Fuel Cell Cost

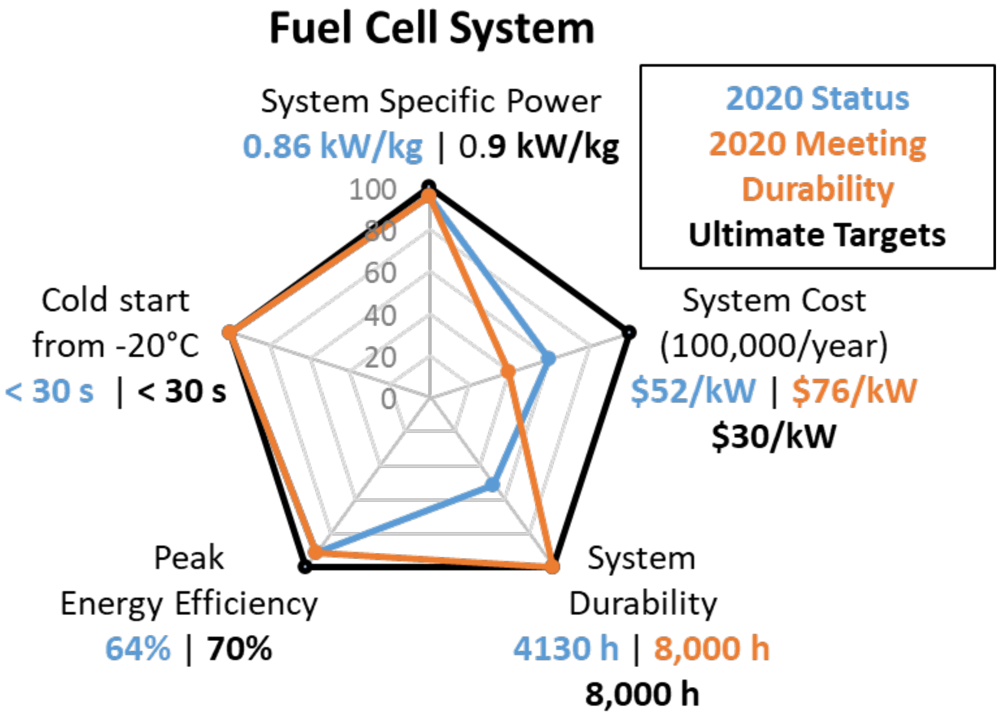


*2020 estimated cost of an 80-kW$_{net}$ automotive PEMFC system is projected to be **\$76/kW$_{net}$** when manufactured at 100,000 units/year and adjusted to meet **8,000 hours** of durability*

https://www.hydrogen.energy.gov/pdfs/21001-durability-adjusted-fcs-cost.pdf

Cost Reductions Achieved Through:

- Reduced Pt catalyst loading (30% since 2008)
- Increased cell power density (>70% since 2008), allowing for smaller stacks
- Optimized BOP components and system design
- Innovative manufacturing processes for BOP and stack components

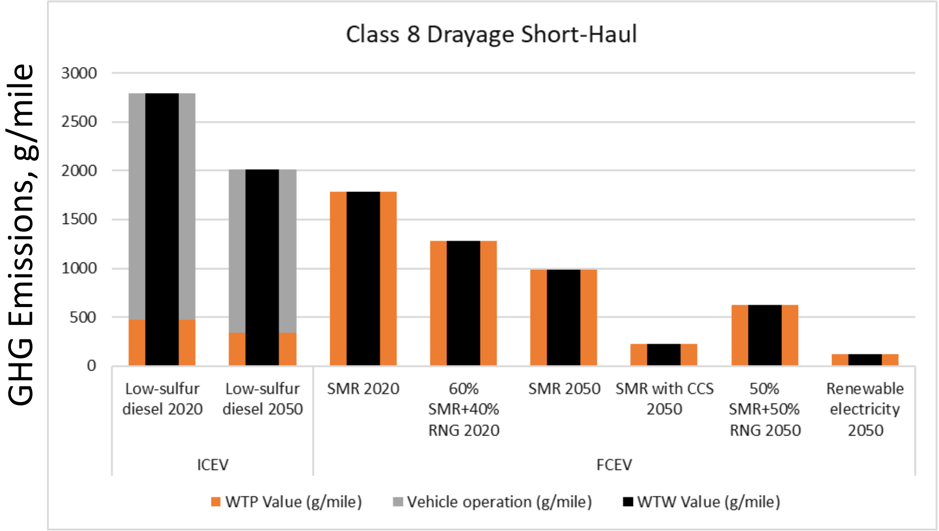


Fuel Cells are Attractive for Medium- and Heavy-Duty Vehicles

H_2 fuel cells can offer several advantages over incumbent technologies including higher efficiency, zero-emissions, higher torque, fast-fueling, no noise pollution, while addressing longer range demands

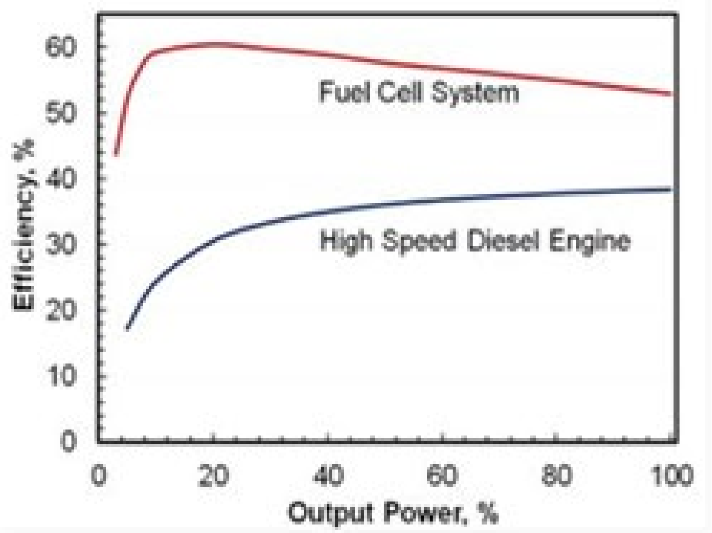
Examples:

HD Trucks: Fuel cell trucks have zero vehicle emissions and can reduce the well-to-wheels GHG emissions by >95% compared to conventional trucks (Preliminary Analysis)

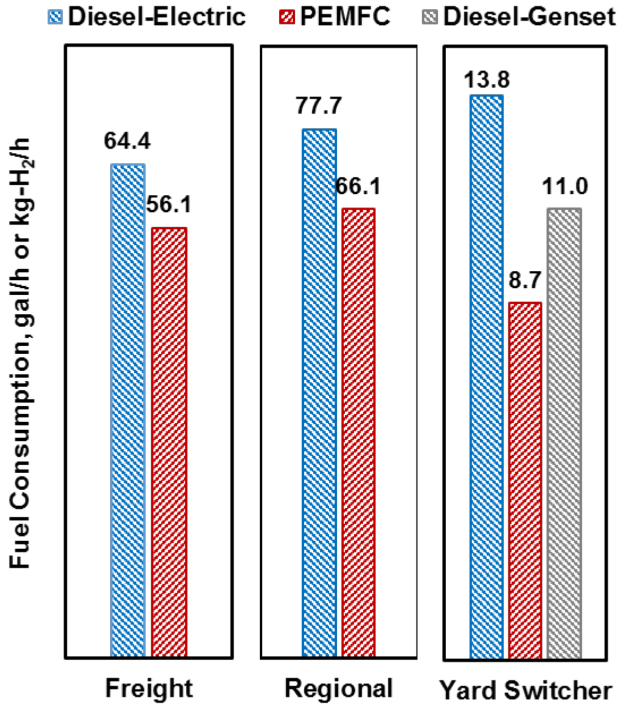


Fuel cell trucks introduce significant social benefits improving air quality of communities around freight facilities

Maritime: Largest benefits for applications spending substantial time operating at less than full load (ferries and towboats)



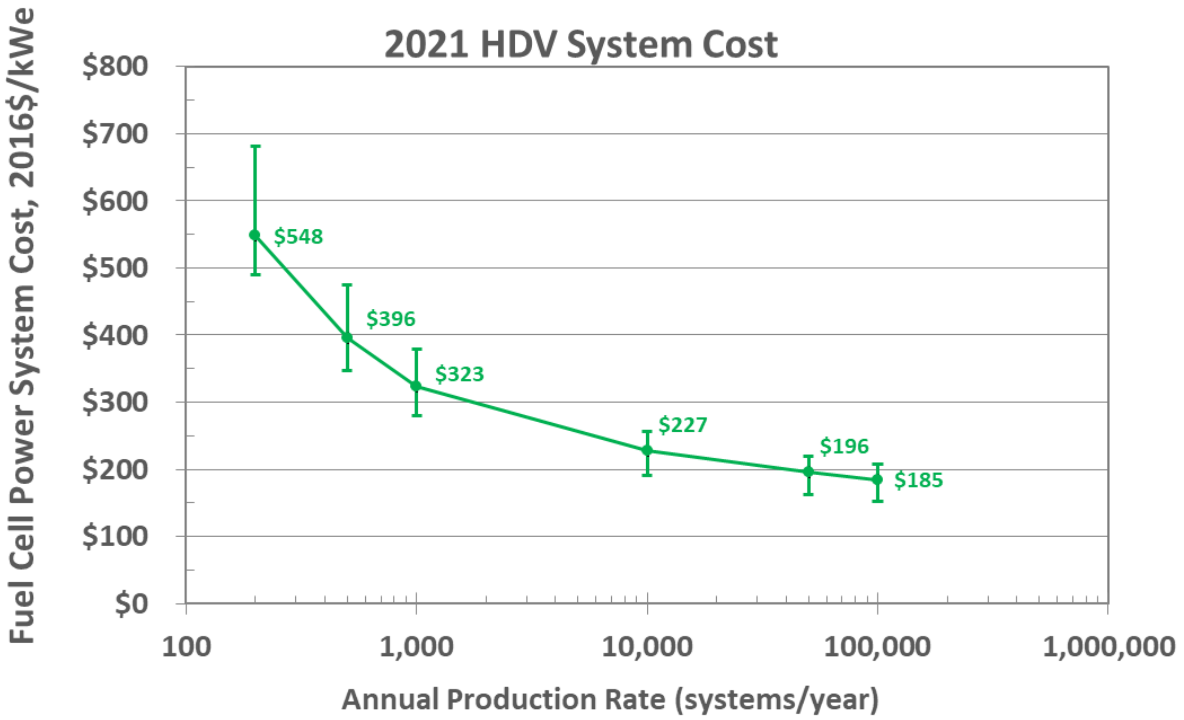
Rail: Fuel cells have lower fuel consumption over the duty cycle vs. diesel locomotives



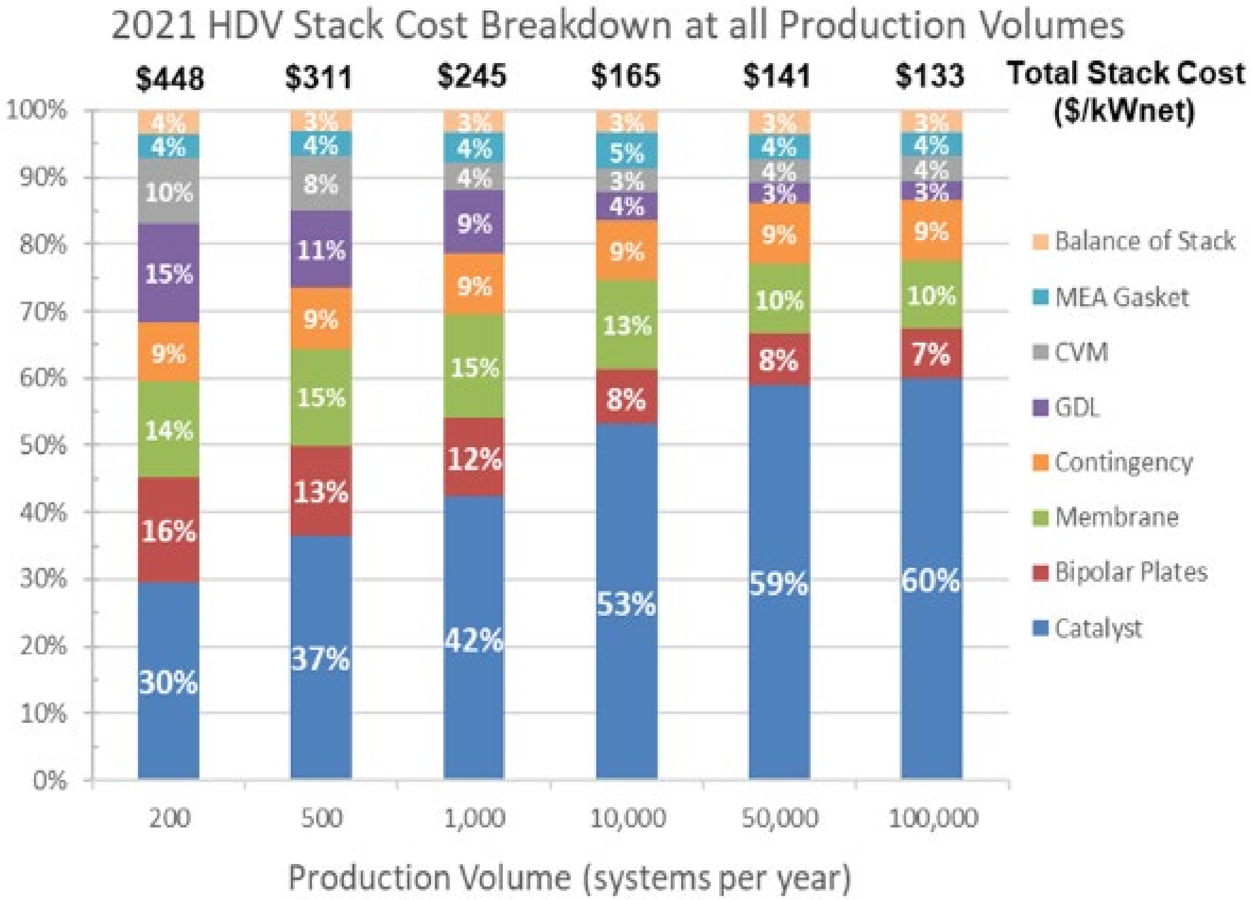
Source: Argonne

HDV Fuel Cell Durability-Adjusted Costs (for 25,000 hours lifetimes)

- **$323/kW$_{net}$** for 1,000 units/year
- **$196/kW$_{net}$** for 50,000 units/year
- **$185/kW$_{net}$** for 100,000 units/year

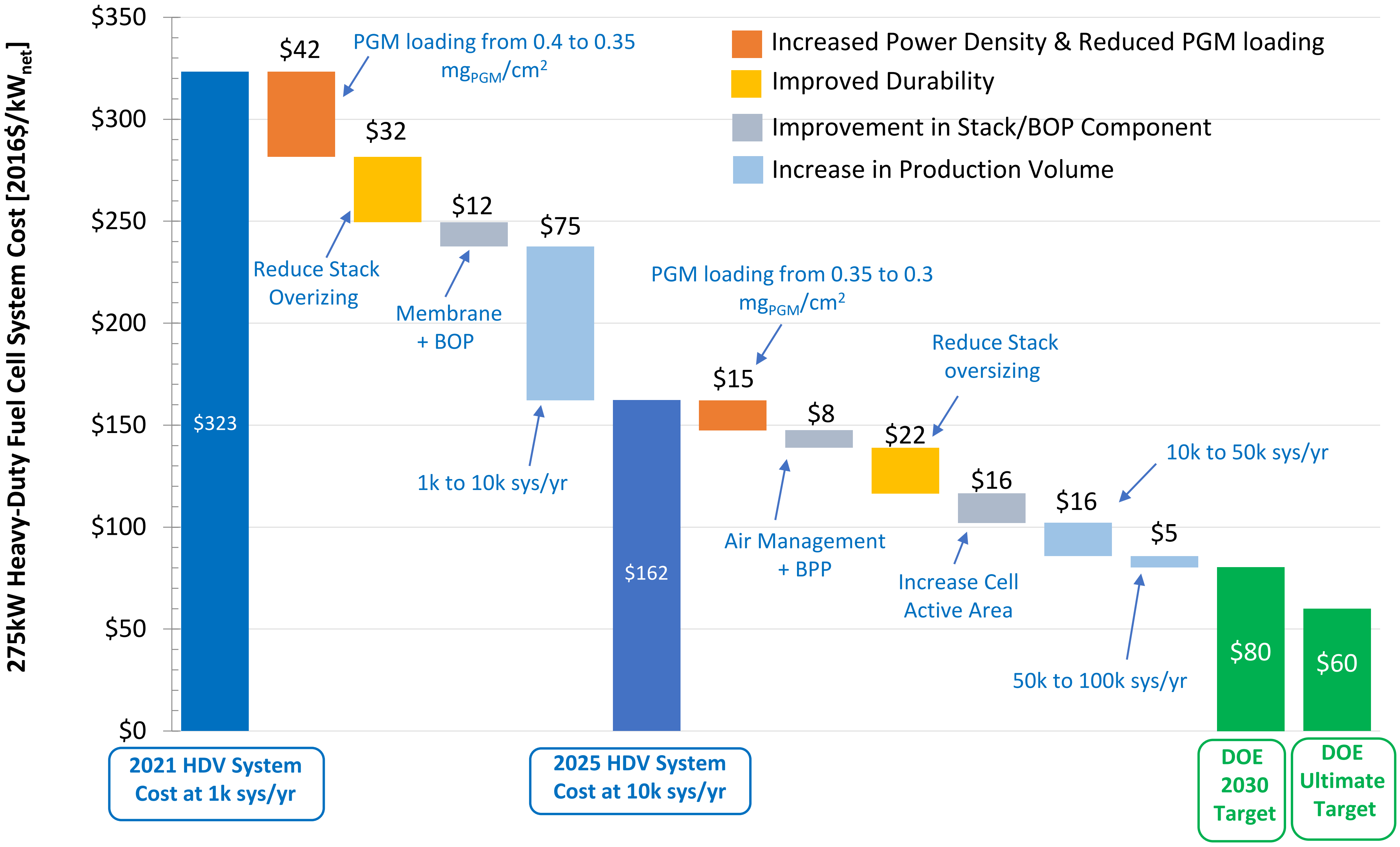


Stack cost dominates system cost



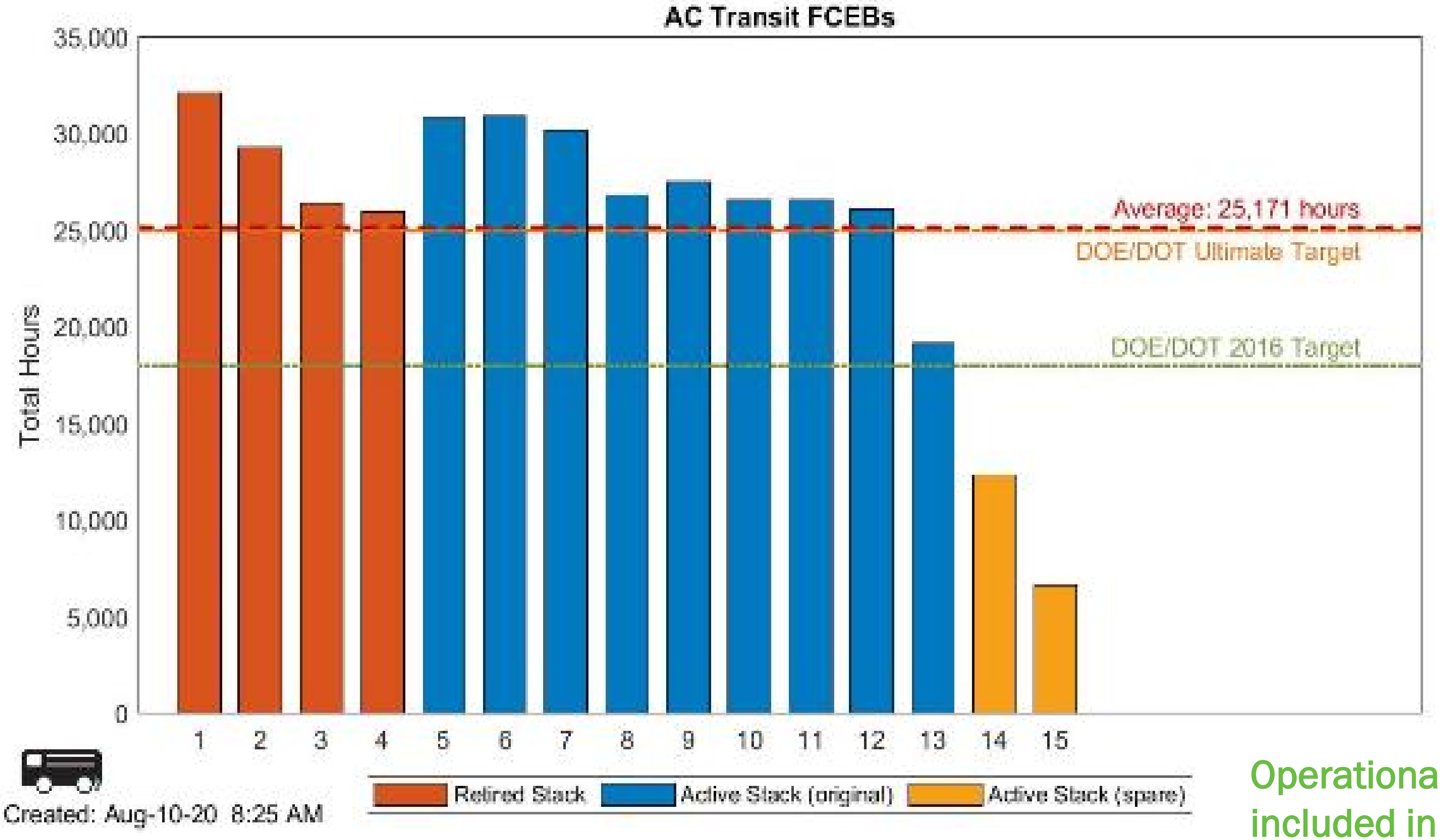
Catalyst cost is projected to be the largest single component of PEMFC stack cost

Meeting HD Fuel Cell Cost Targets - Viable Pathway



On-Road Transit Fuel Cell Bus Milestone

Fuel cell electric buses (FCEBs) demonstrated over 25,000 hours operating time



Twelve systems have surpassed 25,000 hours, <u>including one with > 32,000 hours</u>

Operational hours accumulated by 15 FCEBs included in a fleet operated by Alameda-Contra Costa Transit District (AC Transit)

https://www.hydrogen.energy.gov/pdfs/20008-fuel-cell-bus-durability.pdf

On-Road Transit Fuel Cell Bus Durability Assessment

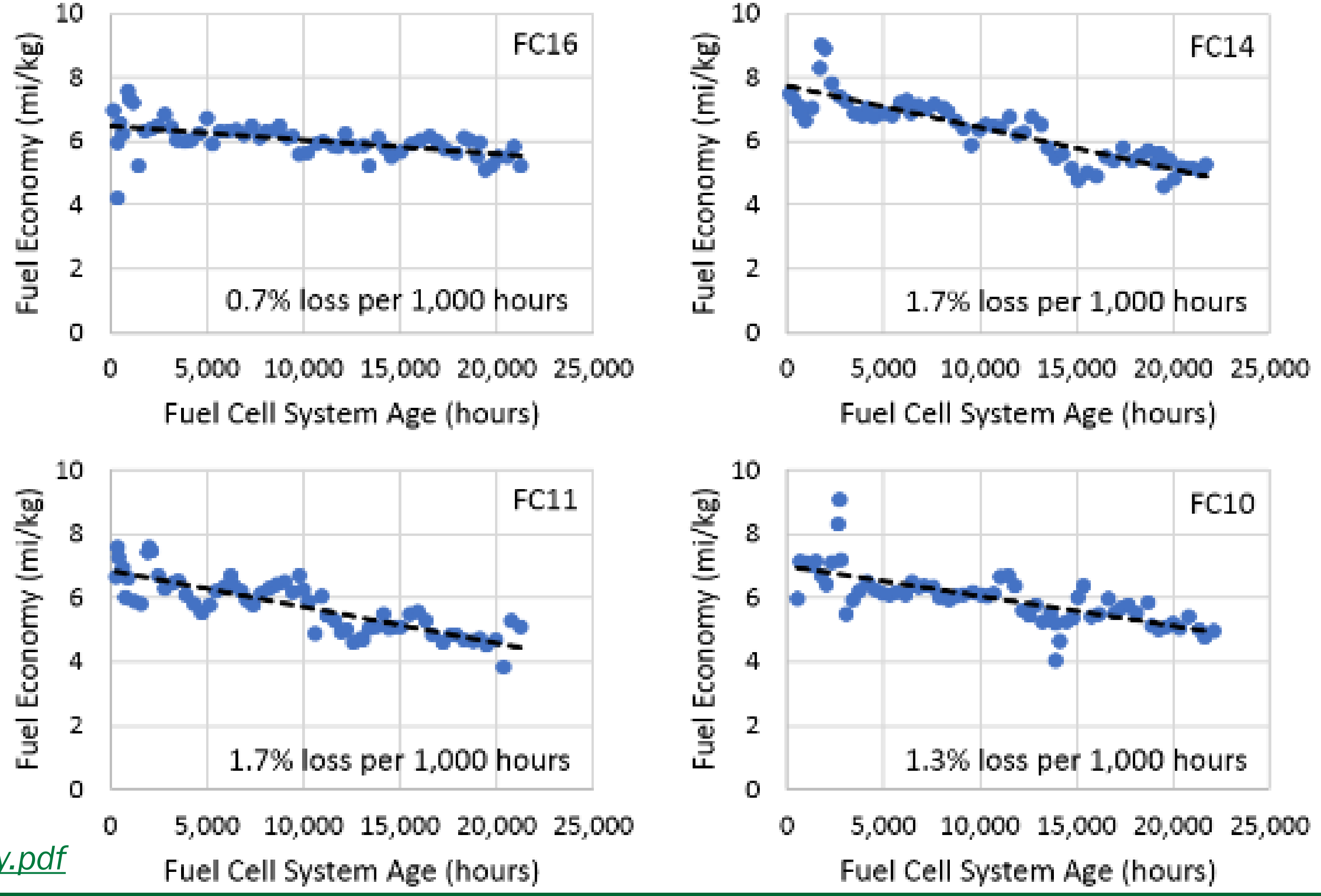
FCEB durability was determined to be 17,000 hours with less than 20% degradation (8,500 hours with less than 10% degradation)

- Relative degradation in fuel economy is a useful approximation for voltage degradation at rated power

- <u>Targeted 20% degradation at 25,000 hours</u> enables the FCEB to maintain relatively high performance and fuel efficiency across its operational lifetime *(not necessarily reflecting FCEB end-of-life)*

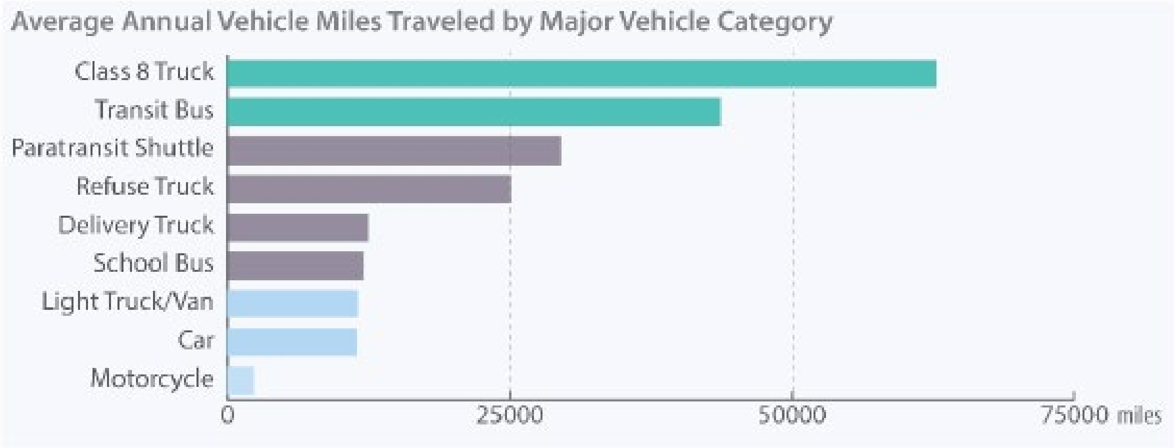
Status is based on real-world FCEB data collected between 2011 and 2017

Recorded fuel economy of four representative FCEBs, with linear fits used to determine the average rate of fuel economy loss



https://www.hydrogen.energy.gov/pdfs/20008-fuel-cell-bus-durability.pdf

Total Cost of Ownership and Durability are Key Drivers for HD Applications



D. Cullen et. al. Nature Energy, 2021

High fuel cell system durability is essential for heavy-duty applications. Long-haul trucks require a lifetime of over 1 million miles and 25,000 operation hours

Technical System Targets: Class 8 Long-Haul Tractor-Trailers

Characteristic	Units	Targets for Class 8 Tractors-Trailers	
		Interim (2030)	Ultimate
Fuel Cell System Lifetime	[hours]	**25,000**	**30,000**
Fuel Cell System Cost	[$/kW]	**80**	**60**
Fuel Cell Efficiency (peak)	[%]	**68**	**72**

DOE Hydrogen and Fuel Cells Program Record 19006: Hydrogen Class 8 Long Haul Truck Targets (energy.gov);
Targets are under development for marine, rail, mining and aviation applications

Increased fuel cell efficiency is a key parameter to reduce H_2 fuel cost for economic viability. At the same time, fuel cell components and systems need to be cost-competitive with incumbent and advanced alternative powertrains

Million Mile Fuel Cell Truck Consortium

(M2FCT)

Million Mile Fuel Cell Truck Consortium (M2FCT)

MISSION

To advance efficiency and durability, and lower cost of PEMFCs to enable their commercialization for heavy-duty vehicle applications.

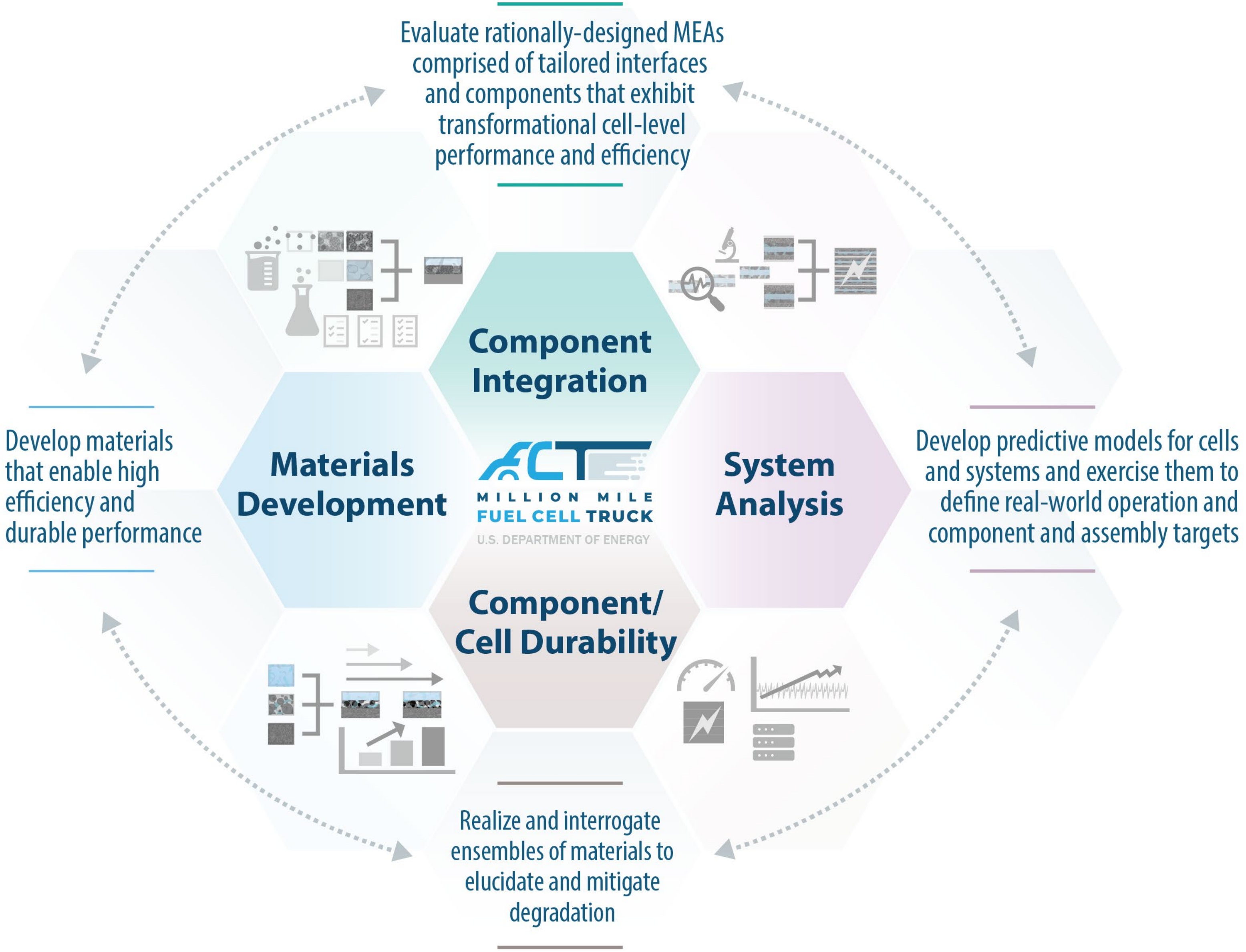
APPROACH

Pursue a "team-of-teams" approach featuring main teams in analysis, durability, integration, and materials development.

OBJECTIVE

Achieve MEA target that combines efficiency, durability, power density, and implicitly, cost in a single metric:

2.5 kW/g_{PGM} power (1.07 A/cm^2 current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test



M2FCT: National Labs in Partnership with Universities and Industry

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HD MEA Projects

gm

Carnegie Mellon University

NIKOLA™

HD Membrane Projects

Lubrizol

3M

NIKOLA™

HD Stack Projects

Cummins

PLUG POWER

To add FOA bipolar plate and air management projects in FY21

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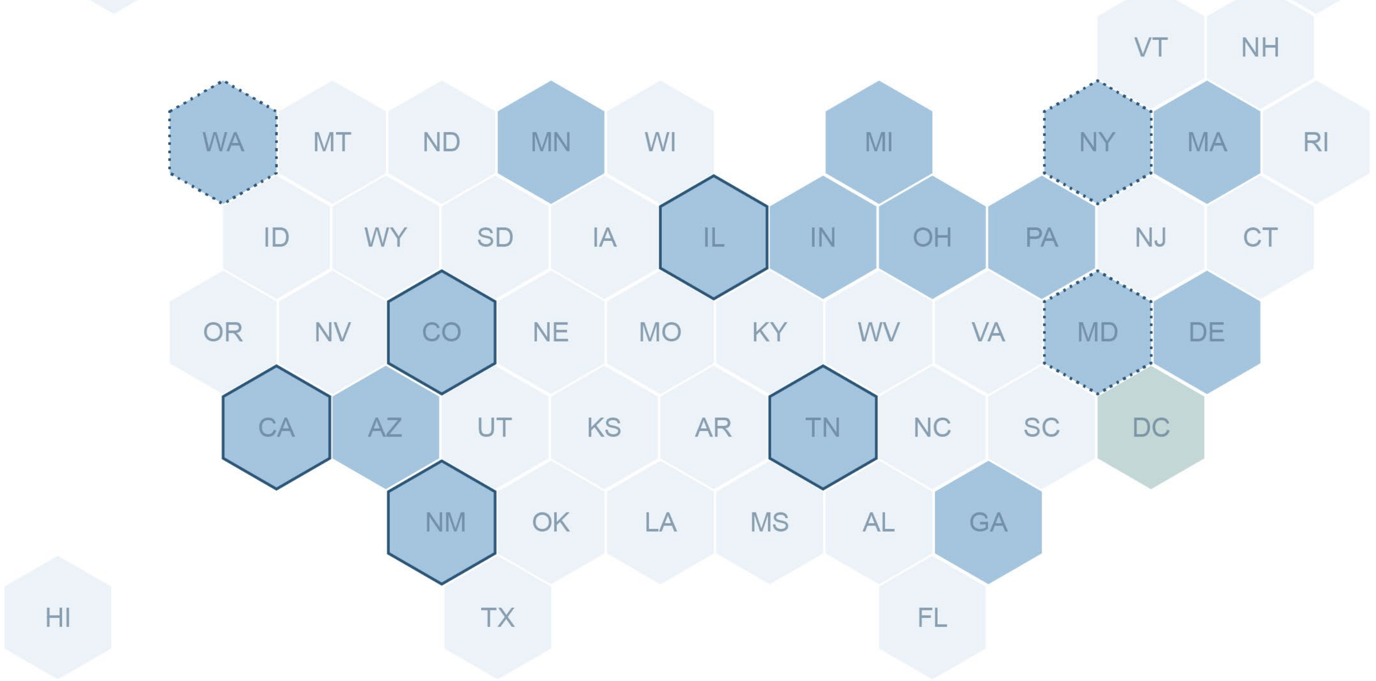

Primary Labs	Partners Labs	Partners Academia	Partners Industry	
LBNL	PNNL	Cornell	3M Company	Kodak
LANL	BNL	Carneige Mellon Univ.	Akron Polymer Products	Lubrizol
ANL	NIST	Colorado School of Mines	Ballard	Nikola Motors
NREL		GeorgiaTech	Chemours	Pajarito Powder
ORNL		Northeastern	Cummins	Plug Power
		University of Tennessee	General Motors	

Main Laboratories

Los Alamos NATIONAL LABORATORY

BERKELEY LAB

OAK RIDGE National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Argonne NATIONAL LABORATORY

Affiliate Laboratories

Pacific Northwest NATIONAL LABORATORY

BROOKHAVEN NATIONAL LABORATORY

NIST National Institute of Standards and Technology

M2FCT Core-Lab RD&D: Efficient and Durable Materials Systems

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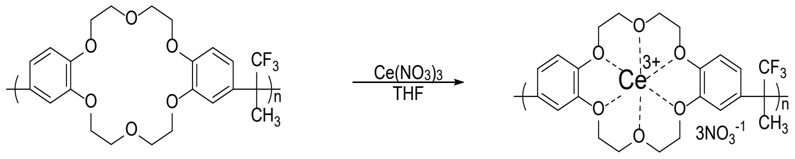
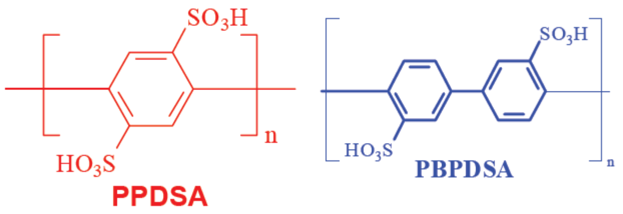
Ionomers/Membranes

- Functionalization of perfluorosulfonic acids with Ce^{3+}
- Use of reinforcement strategies and characterization of PF materials
- Low molecular-weight oligomers

Crown Ether Functionalized PFSA



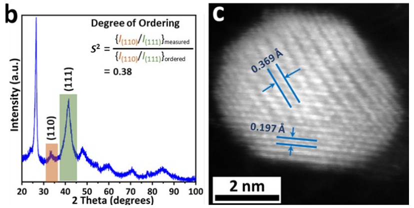
Low EW Sulfonated Oligomers



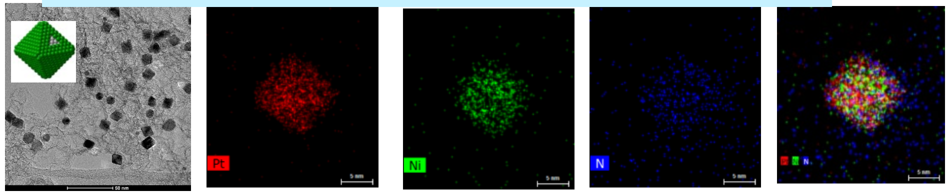
Catalysts/Supports

- Pt intermetallics on nitrogen-doped graphitic supports
- Nitriding of Pt intermetallics
- Addition of metal oxide (AOx) adjacent to Pt and PtM NPs on carbon
- Control of particle shape, intraparticle composition, and structure to inhibit metal dissolution
- Control particle-ionomer interface

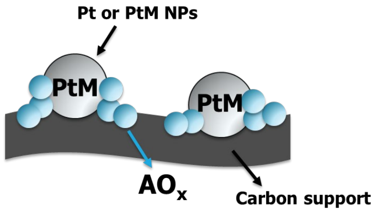
Ordered PtCo Intermetallic



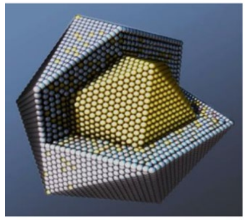
N-doped Octahedral PtNiN/C



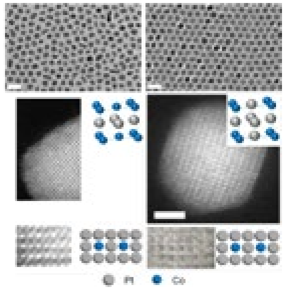
Metal oxide Additive



PtAu Structured Particle



Ordered PtCo Intermetallic



Incorporation and testing in MEAs for performance and durability

M2FCT Core-Lab R&D: Integration, Baselining, & Manufacturing

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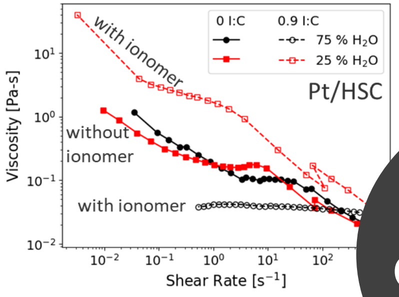
U.S. DEPARTMENT OF ENERGY

Fundamental information pertinent to the integration of known and novel materials

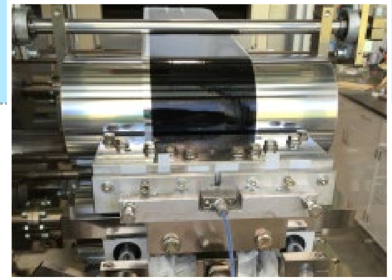


Film and Ink Characterization

- Rheology
- Ionomer aggregation
- Intrinsic interactions and binding

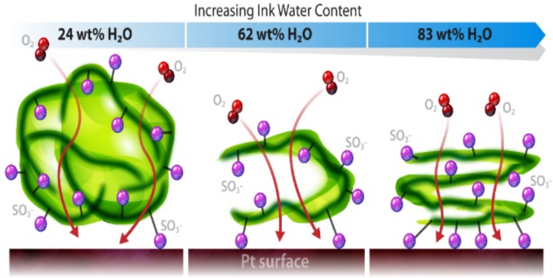
Electrode Formation and Design

- Time evolution of formation of ionomer and electrodes
- Additives and pore formers
- Manufacturing



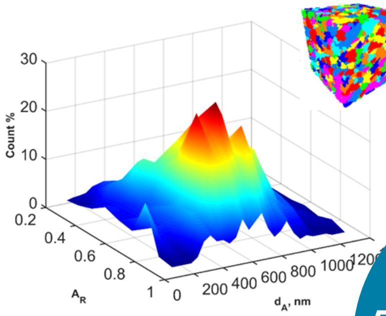
Cell Performance and *In situ* Diagnostics

- Baseline and standardization
- Limiting current
- Ionomer adsorption
- Interfaces



Optimization and Understanding

- Multiphysics modeling
- MEAs with novel materials



***Ex situ* Component Characterization**

- Ionomer
- GDL/MPL
- Electrode structure

Accelerated Stress Test Working Group (ASTWG)

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Define the 25,000-hour equivalent AST in the M2FCT 2025 Target

- Recommend protocols and targets related to heavy duty application of fuel cells
- ASTs for use in M2FCT for evaluations with reference to lifetime targets
- Accelerated Stress Tests (ASTs) being developed for
  - Catalyst
  - Catalyst support
  - Membrane chemical degradation
  - Membrane combined chemical-mechanical degradation
  - Shutdown/Startup
  - Anode H_2 starvation
  - MEA operating drive-cycle

ASTWG meets every other month
Currently establishing International group with representation from US, EU, Japan, and Korea

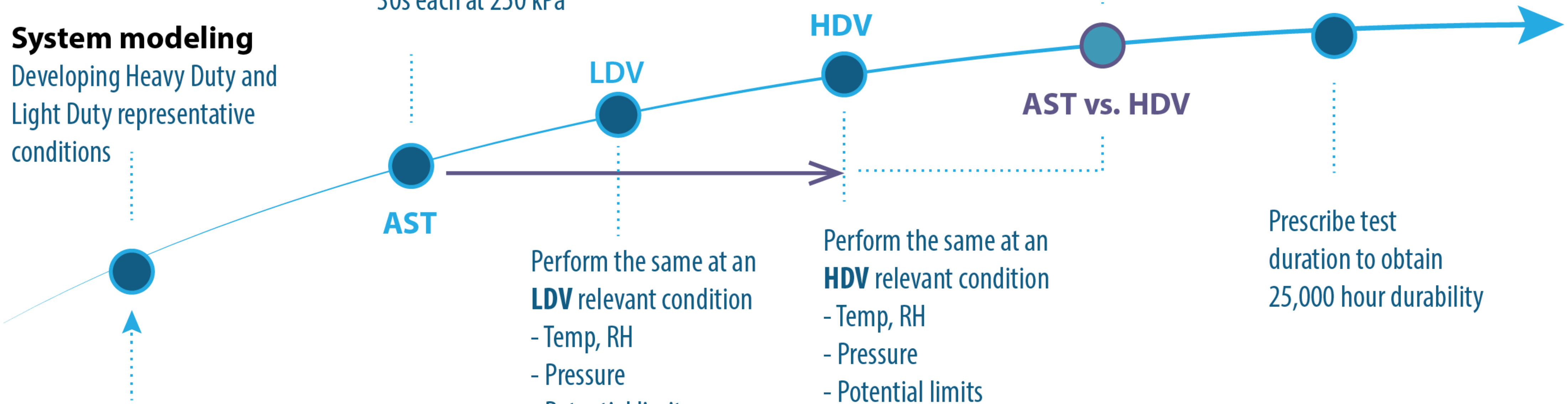
Participants
3M
ANL
Ballard
Carnegie Mellon
Chemours
Cummins
DOE
GM
LANL
LBNL
Nikola
NREL
ORNL
Plug Power
W.L. Gore

Defining the 25,000-Hour Equivalent AST

Calculate Aceleration factors
From 90ºC 100% / 90%RH test to HDV

Perform ASTs
H_2/Air on integral cell @ 90ºC 100% and 90%RH square wave cycling from 675 mV to 925 mV 30s each at 250 kPa

System modeling
Developing Heavy Duty and Light Duty representative conditions



Perform the same at an **LDV** relevant condition
- Temp, RH
- Pressure
- Potential limits

Perform the same at an **HDV** relevant condition
- Temp, RH
- Pressure
- Potential limits

Prescribe test duration to obtain 25,000 hour durability

Input from 21st century truck (real drive cycles and representative stressors)

2.5 kW/g_{PGM} power (1.07 A/cm^2 current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test

M2FCT Core Values: Inclusion, Diversity, Equity, Accountability

- **Work with disadvantaged communities and HBCUs, HSIs, community colleges**
  - Have various internships for students and targeted discretionary funding
  - Existing collaboration with NNSA to enhance STEM background & education
    - Including set-up of electrochemistry systems at HBCU's
    - Training, access to cutting-edge research, use of state-of-the-art facilities

Hands-on research

Short Courses/Trainings

On-site support

- **Disadvantaged neighborhoods will be favorably impacted with improvements to long-haul trucking corridors and heavy-duty centers (*e.g.*, ports) ***
  - Greening of the transportation will greatly improve their local emissions and air and noise pollution

** References: Preble et al. Environ. Sci. Technol. 2019, 53, 24, 14568–14576; Dallman et al. Environ. Sci. Technol. 2013, 47, 23, 13873–13881*

ElectroCat 2.0

ElectroCat: Building on Success and World-Class Capabilities

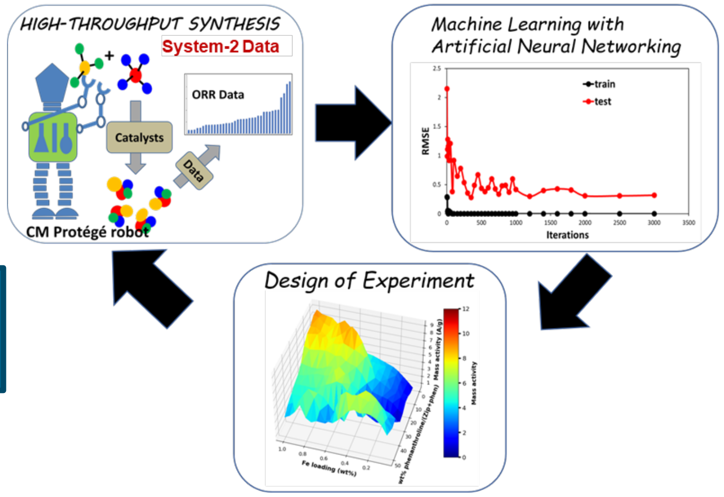
ElectroCat
Electrocatalysis Consortium

Development of durable PGM-free catalysts for PEMFCs and for low-temperature electrolyzers, as low-cost alternative to PGM catalysts, addressing critical mineral challenges

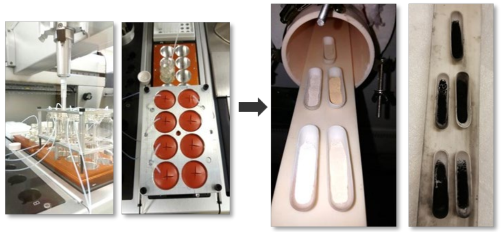
➢ *Comprising 30 world-class capabilities and expertise in:*

- Catalyst synthesis, characterization, processing, & manufacturing
- High-throughput, combinatorial techniques
- Advanced computational tools

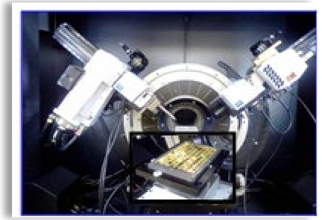
Active Learning Loop for Material Discovery

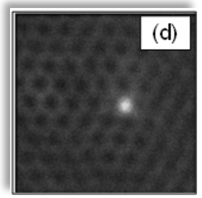


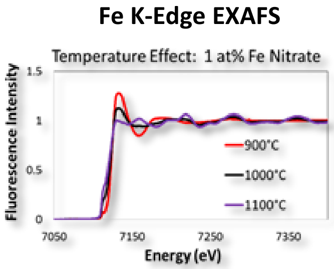
Synthesis, Processing and Manufacturing



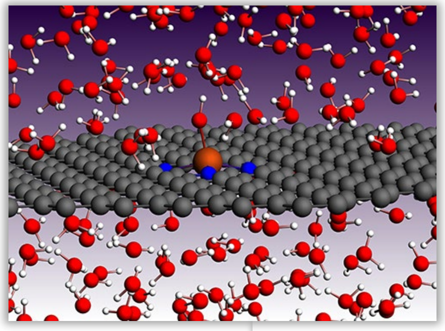
Characterization and Synthesis

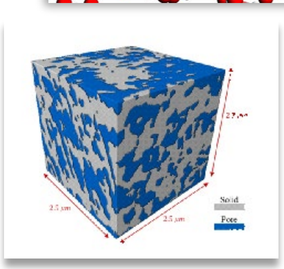


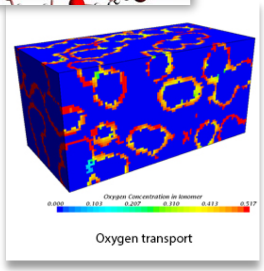




Computation, Modeling & Data Management







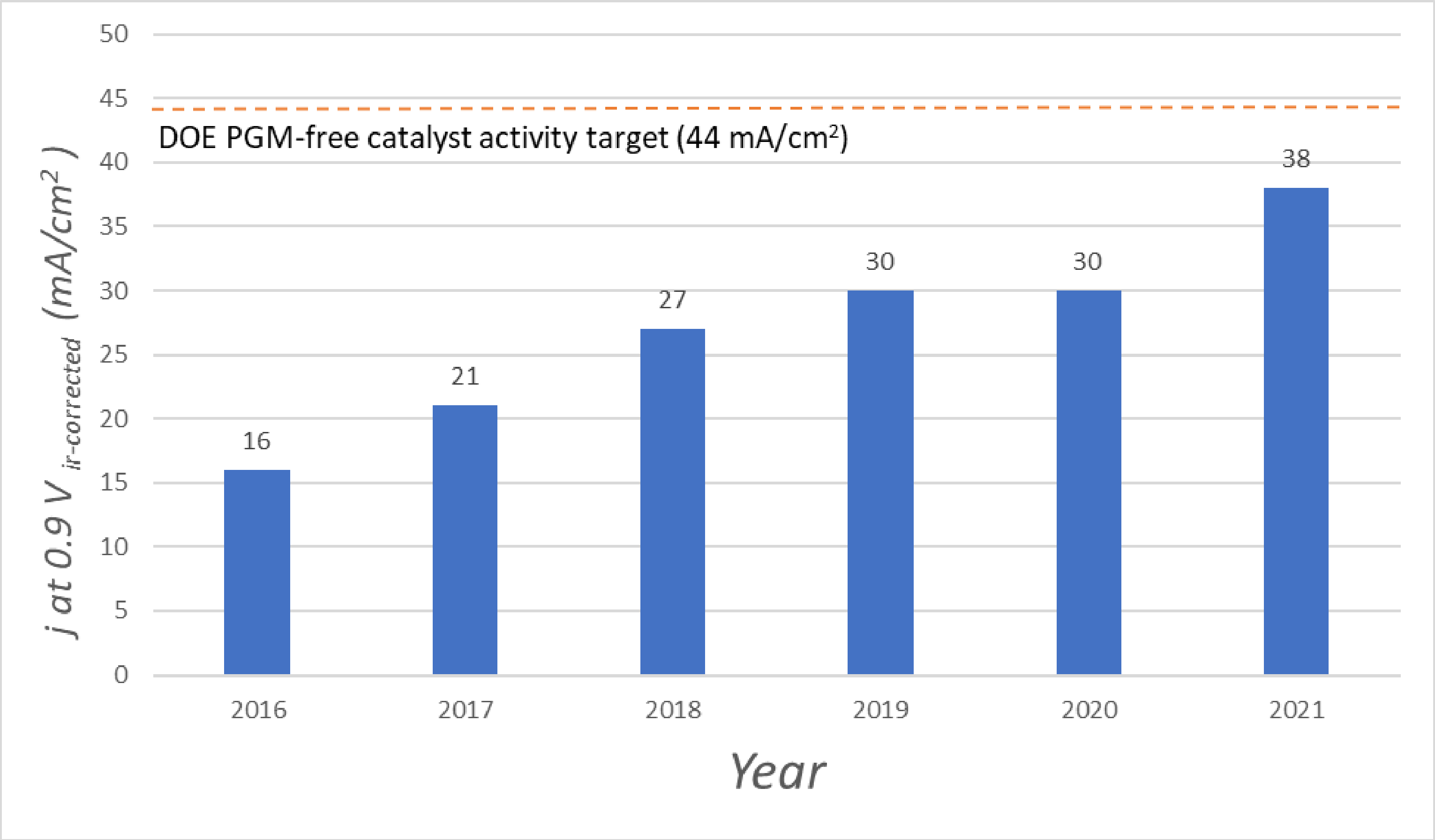
Core Labs

Los Alamos National Laboratory
Argonne National Laboratory
Oak Ridge National Laboratory
NREL

PGM-Free Catalyst Activity Accomplishment

ElectroCat
Electrocatalysis Consortium

Improved the activity of PGM-free catalysts by over 2x compared to the 2016 baseline (16 mA/cm^2)

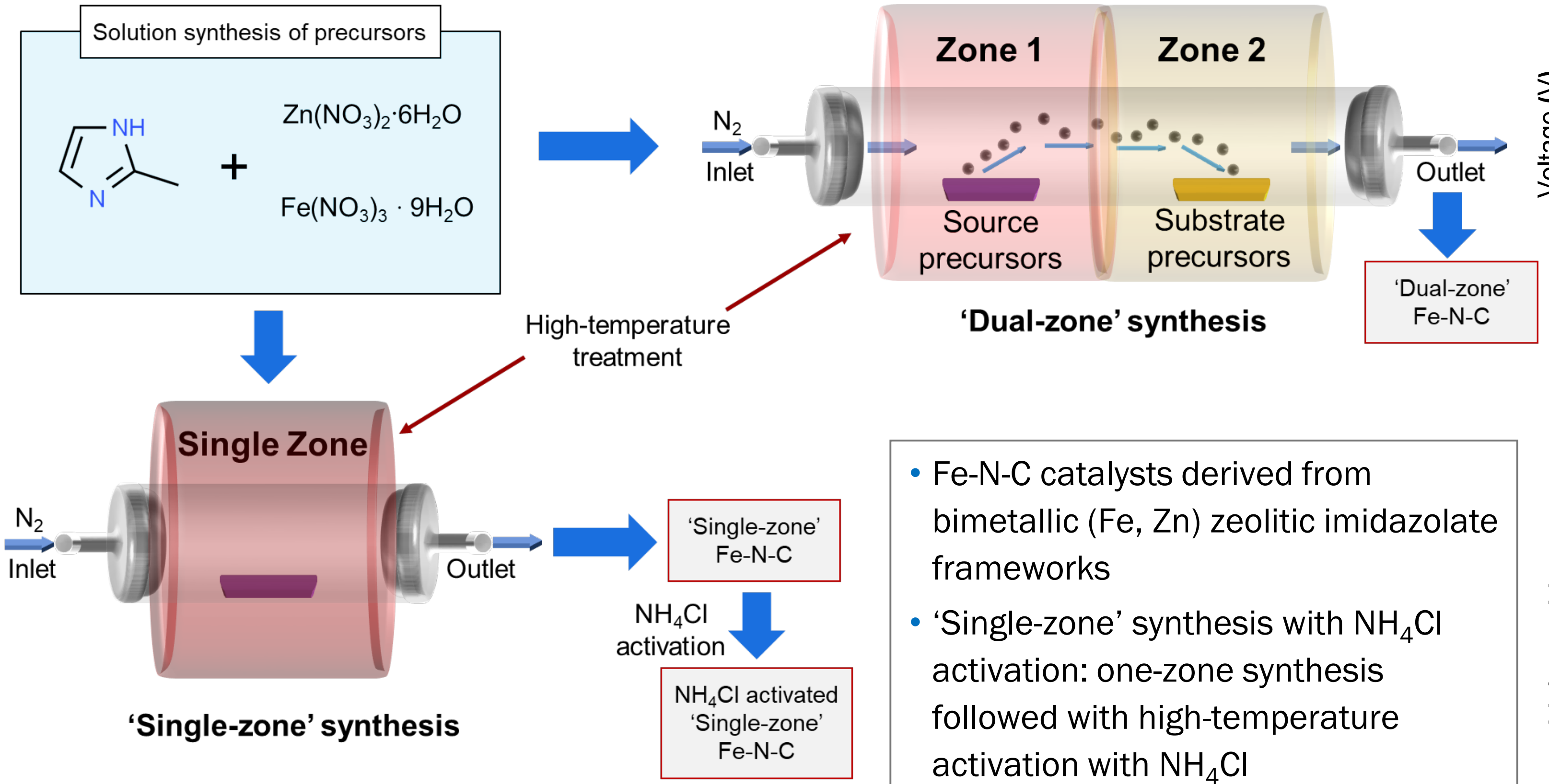


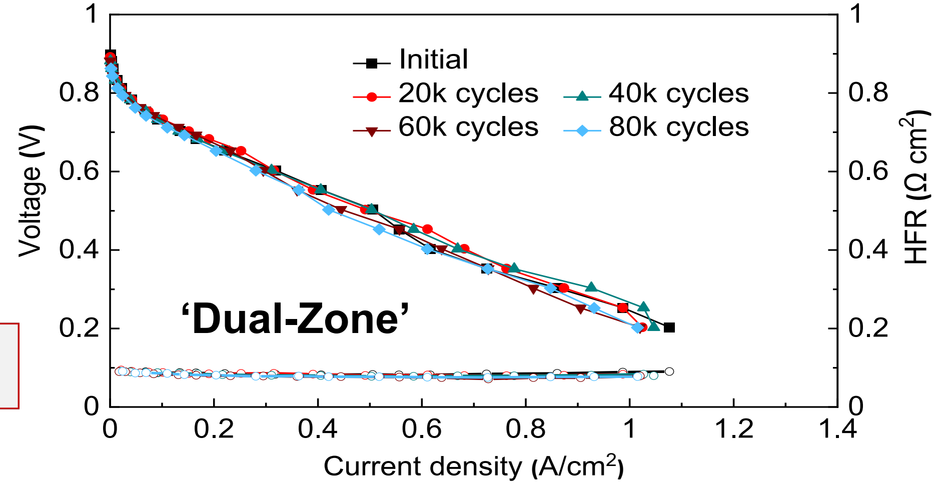
- Performance exceeded the **FY21 catalyst activity target:** 38 mA/cm^2 *vs.* 35 mA/cm^2
- Achieved with NH_4Cl-treated 'single-zone' Fe-C-N catalyst
- Efforts focusing on durability improvements

PGM-Free Catalyst Durability Accomplishment

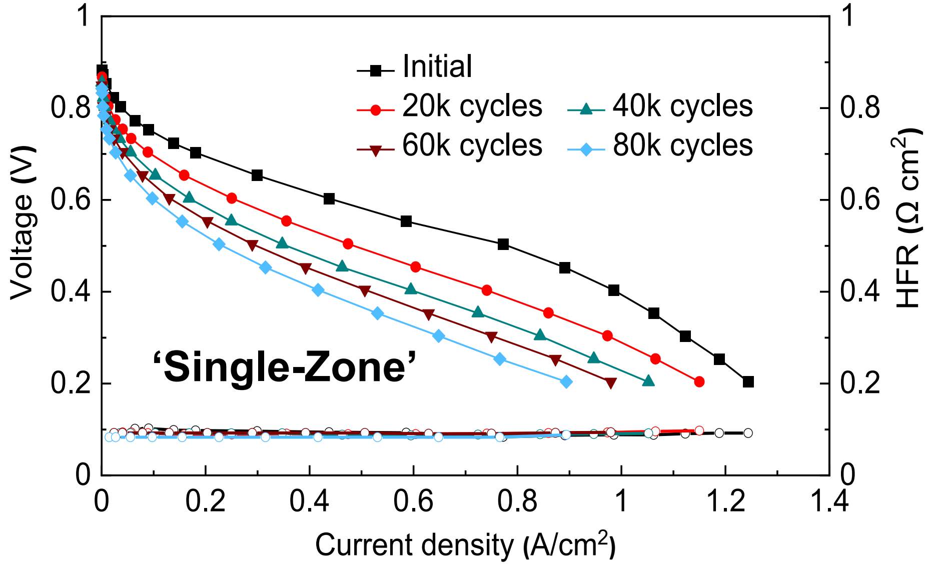
ElectroCat Electrocatalysis Consortium

Catalyst synthesis development leads to excellent durability after 80,000 cycles



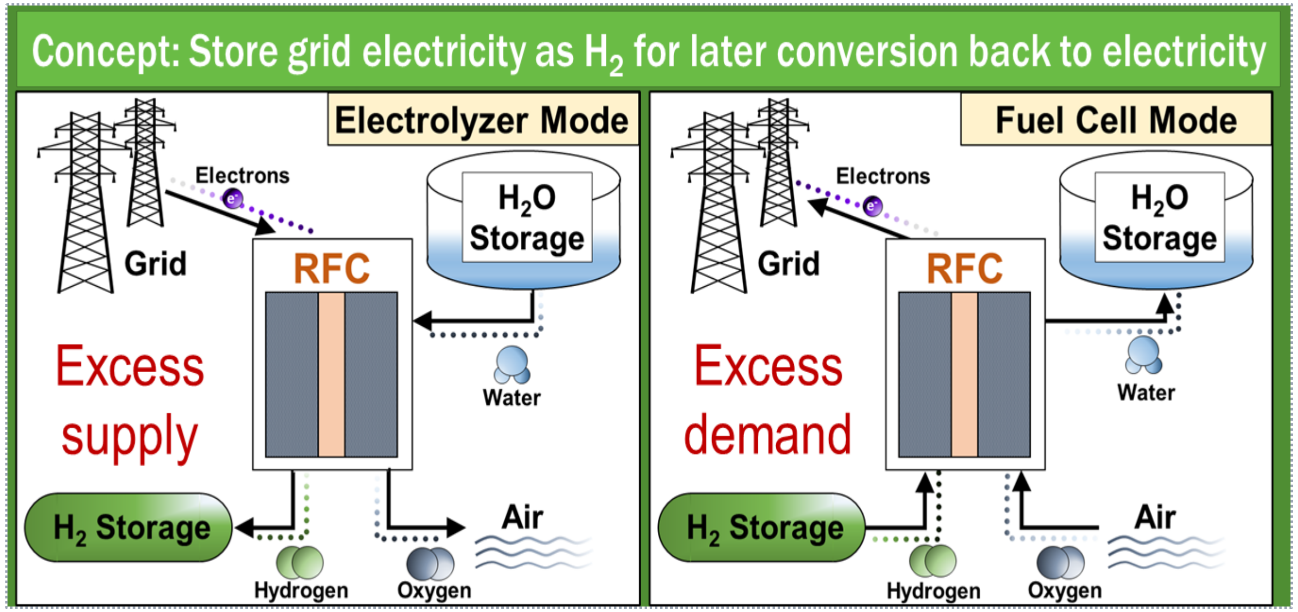


- Fe-N-C catalysts derived from bimetallic (Fe, Zn) zeolitic imidazolate frameworks
- 'Single-zone' synthesis with NH_4Cl activation: one-zone synthesis followed with high-temperature activation with NH_4Cl
- 'Dual-zone' synthesis: synthesis involving deposition from zone 1 to zone 2 with independently-controlled temperatures



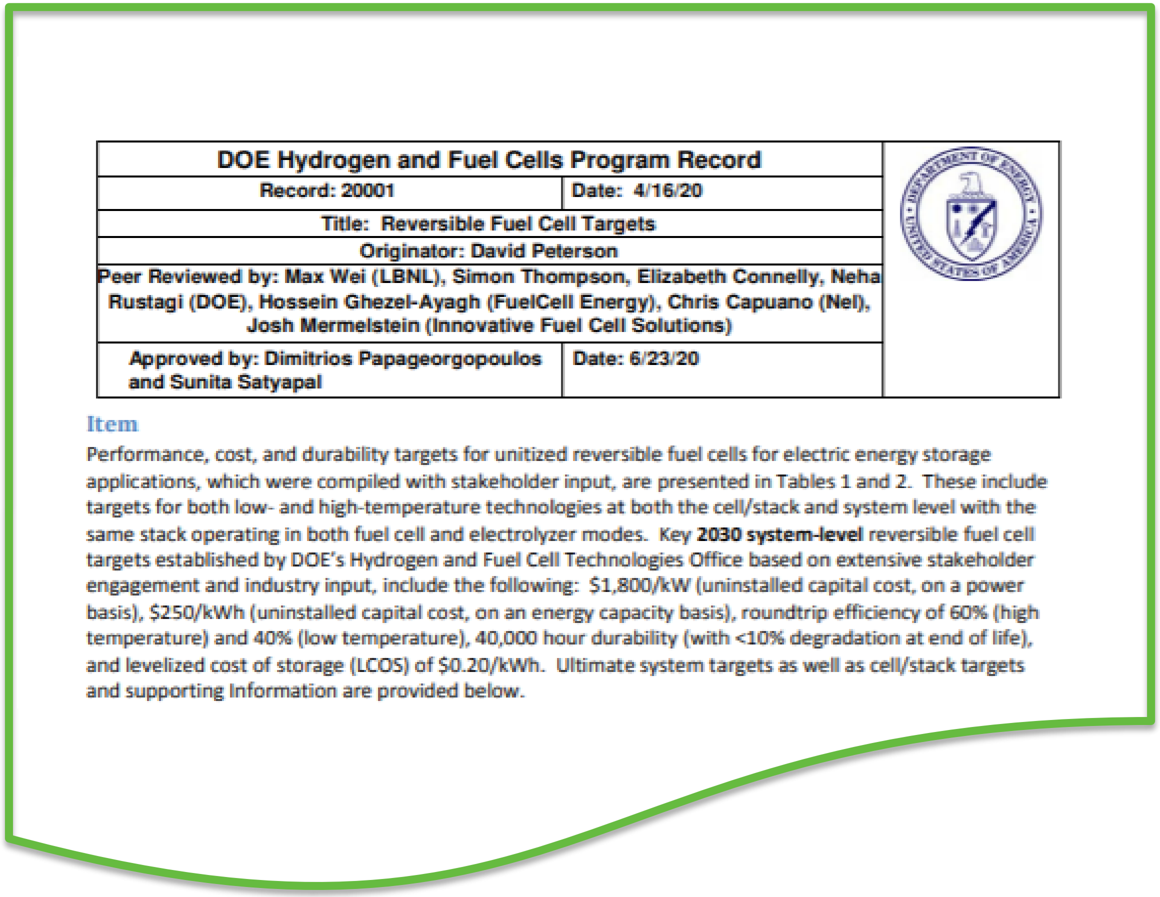
Reversible Fuel Cells for Energy Storage

HFTO Establishment of Reversible Fuel Cell (RFC) Targets



Detailed unitized RFC technical targets published to guide RD&D efforts. **Viability** and **cost-competitiveness** require innovative RD&D to:

- improve roundtrip efficiency and durability;
- decrease levelized cost of electricity/storage to <10₵/kWh;
- meet long-term system capital cost targets by power and energy of less than $1300/kW and $150/kWh



DOE Hydrogen and Fuel Cells Program Record	
Record: 20001	Date: 4/16/20
Title: Reversible Fuel Cell Targets	
Originator: David Peterson	
Peer Reviewed by: Max Wei (LBNL), Simon Thompson, Elizabeth Connelly, Neha Rustagi (DOE), Hossein Ghezel-Ayagh (FuelCell Energy), Chris Capuano (Nel), Josh Mermelstein (Innovative Fuel Cell Solutions)	
Approved by: Dimitrios Papageorgopoulos and Sunita Satyapal	Date: 6/23/20

Item

Performance, cost, and durability targets for unitized reversible fuel cells for electric energy storage applications, which were compiled with stakeholder input, are presented in Tables 1 and 2. These include targets for both low- and high-temperature technologies at both the cell/stack and system level with the same stack operating in both fuel cell and electrolyzer modes. Key **2030 system-level** reversible fuel cell targets established by DOE's Hydrogen and Fuel Cell Technologies Office based on extensive stakeholder engagement and industry input, include the following: $1,800/kW (uninstalled capital cost, on a power basis), $250/kWh (uninstalled capital cost, on an energy capacity basis), roundtrip efficiency of 60% (high temperature) and 40% (low temperature), 40,000 hour durability (with <10% degradation at end of life), and levelized cost of storage (LCOS) of $0.20/kWh. Ultimate system targets as well as cell/stack targets and supporting Information are provided below.

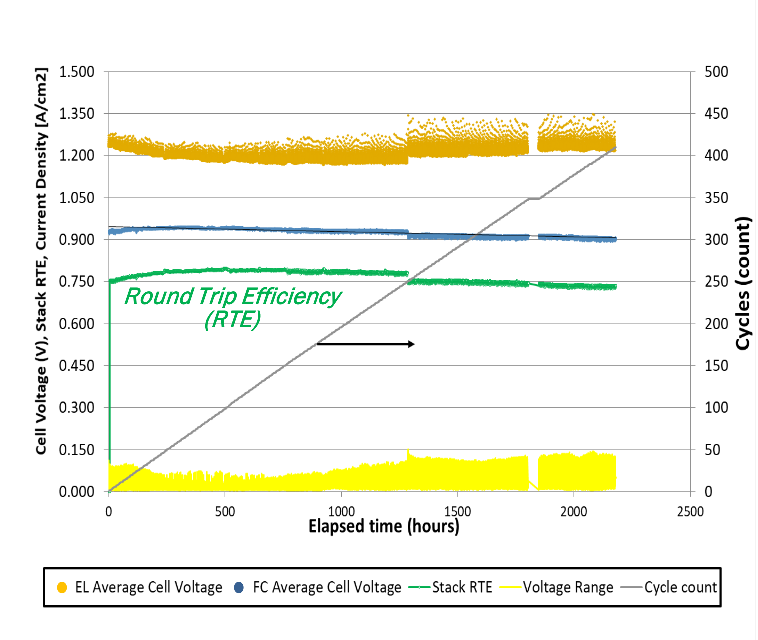
DOE Hydrogen and Fuel Cells Program Record: https://www.hydrogen.energy.gov/pdfs/20001-reversible-fuel-cell-targets.pdf

HFTO Reversible Fuel Cell Activities

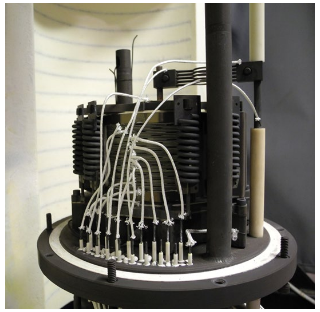
Overall Goal: Develop stable, robust, high-performance materials and devices to enable durable, efficient, low-cost unitized RFCs.

	Low Temperature	High Temperature
Materials and Components	**Lawrence Berkeley National Lab** PEM novel bifunctional electrocatalysts, supports and membranes. **Giner, Inc.** Alkaline membrane RFCs emphasizing PGM-free catalysts. **Plug Power** PEM RFC stacks focused on optimizing water management with non-flow through fuel cell design.	**Northwestern Univ.** Oxide conducting materials development and novel cell designs targeting high roundtrip efficiency and stable operation **Georgia Tech.** Proton conducting materials development improving durability and lowering temperature operation
Systems Integration	**Proton Energy Systems** PEM RFC system with improved membrane and water management. Cooperation with utilities.	**FuelCell Energy, Inc.** Solid-oxide RFC system with improved efficiency and thermal management. Industry end-user advisory panel.

Example Accomplishment



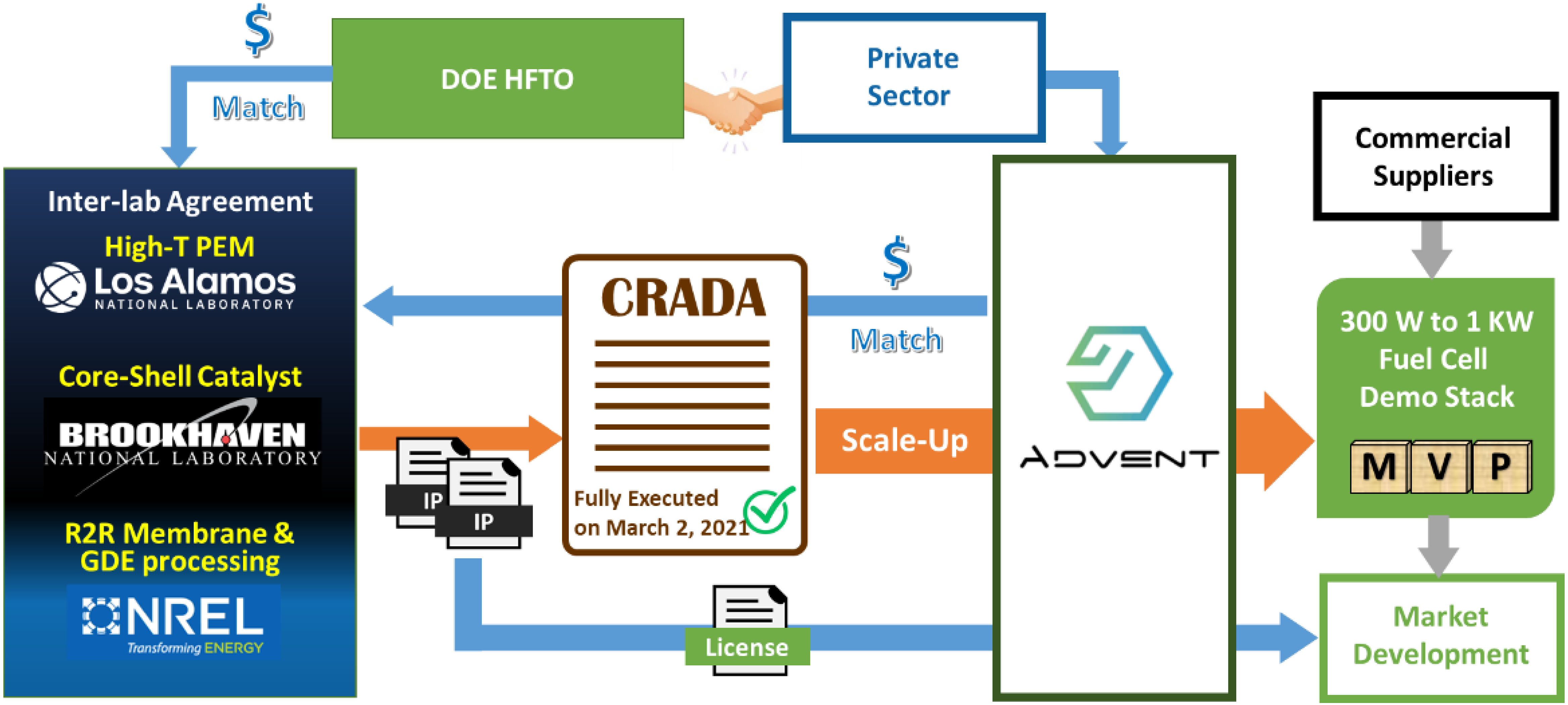
Using a 50-cell stack completed 410 cycles in >2180 hr with RTE~75% and <5%/1000 cycle degradation



Tech to Market: L’Innovator

L'Innovator: CRADA Moving Fuel Cell Technology Closer to Commercialization

Pilot bundles unique, state-of-the-art lab IP (LANL&BNL), utilizes lab manufacturing expertise (NREL), and leverages industrial's partner commercialization experience (Advent)



Collaborations, Milestones, Team

Fuel Cell Technologies Program: Collaboration Network

Fostering technical excellence, economic growth and environmental justice

Industry Engagement

- US DRIVE Partnership: Fuel Cell Tech Team
- 21st Century Truck Partnership
- M2FCT
- ElectroCat
- Workshops/RFIs
- FCHEA

HFTO Internal Synergies

FC-H2: ElectroCat	FC-TA: HD Application Target-Setting and Real-World Data	FC-TA: Systems Analysis

DOE H_2 Program Collaborations

EERE/VTO: SuperTruck	ARPA-E: Advanced Fuel Cell Concepts	FE: SOFCs/RFCs	BES: SBIR-STTR

DOE Cross-Cutting Initiatives

Critical Minerals	Advanced Manufacturing	Advanced Energy Storage
HPC	EMN	Space

Cross-Agency Collaborations

- DOC/NIST Fuel Cell Neutron Imaging
- DOT/FTA (Fuel Cell Buses)

International Collaborations

IEA Technology Collaboration Programme on Advanced Fuel Cells	M2FCT AST Working Group	ElectroCat Test Protocols

Fuel Cell Technologies Program: Highlights and Milestones

FY2019

- *Established fuel cell system targets for long-haul trucks*
- *Selected HD MEA R&D FOA projects*
- *Developed low-PGM intermetallic catalysts meeting durability targets*
- *Achieved an 85% improvement in PGM-free catalyst activity over the 2016 baseline*
- *Selected system-level RFC RD&D FOA projects*
- *Expanded analysis efforts to define HD fuel cell system designs*

FY2020

- *Launched M2FCT*
- *Launched ElectroCat 2.0*
- *Selected M2FCT FOA projects (membrane, stacks)*
- *Established durability adjusted LDV cost ($76/kW at 100,000 systems/year)*
- *Released RFC targets*
- *L'Innovator: CRADA drafted between Advent and labs (LANL,BNL,NREL)*

FY2021

- *MEA durability ASTs incorporating relevant degradation mechanisms for catalyst, support, electrodes and membrane in a single AST; define MEA baseline*
- *Improved PGM-free catalyst activity to 38 mA/cm^2*
- *Select M2FCT FOA projects (bipolar plates, BOP)*
- *Established durability adjusted HDV cost ($196/kW at 50,000 systems/year)*
- *Complete RFC and H_2 stationary MW-scale PEMFC analysis*
- *L'Innovator: CRADA fully executed between Advent and labs (LANL,BNL,NREL)*

FY2022

- *Improve MEA FY21 baseline performance at a PGM loading of 0.3 mg$_{PGM}$/cm^2*
- *Improve PGM-free cathode H_2-air initial fuel cell performance by 25% compared to FY21 baseline*
- *Select M2FCT FOA projects*
- *Meet durability adjusted HDV cost of $185/kW at 50,000 systems/year*
- *Establish targets for MW-scale direct H_2-PEM for stationary and long-duration energy storage applications*
- *L' Innovator: Pilot scale up of membranes/MEAs*

Exciting Fellowship Opportunities…

for DOE's Office of Energy Efficiency and Renewable Energy (EERE)
Hydrogen and Fuel Cell Technologies Office (HFTO)
in Washington, D.C. or Golden, CO
(currently via telework from home)

ORISE Fellows will participate in technology management within HFTO's Fuel Cell Technologies Program.
Candidates should have experience in fuel cell materials, components, stacks and systems. **The Program currently focuses primarily on polymer electrolyte membrane fuel cells (PEMFCs) for transportation applications**, but also supports long-term technologies including anion exchange membrane fuel cells (AEMFC) and reversible fuel cells (RFCs) for power generation and energy storage applications.

- A degree in the physical sciences or engineering, such as chemistry, physics, materials science, chemical engineering, or a related area is required.
- Candidates with graduate, post-doctoral, or industrial experience in fuel cells will be given preference.
- Good written and oral communication skills are important.

Fuel Cell Technologies is currently seeking two candidates

HFTO Contacts:
Gregory.Kleen@ee.doe.gov
Donna.Ho@ee.doe.gov

To apply: https://www.zintellect.com/Opportunity/Details/DOE-EERE-STP-HFTO-2021-1800

Fuel Cell Technologies Program Contacts

Dimitrios Papageorgopoulos
Fuel Cells Technologies Program Manager
202-586-5463
dimitrios.papageorgopoulos@ee.doe.gov

David Peterson
720-356-1747
david.peterson@ee.doe.gov

Donna Lee Ho
202-586-8000
donna.ho@ee.doe.gov

Greg Kleen
720-356-1672
gregory.kleen@ee.doe.gov

William Gibbons
720-356-1747
william.gibbons@ee.doe.gov

John Kopasz
Argonne National Laboratory

Eric Parker
Contractor – Keylogic-Systems

Thank You

Dr. Dimitrios Papageorgopoulos

Program Manager, Fuel Cell Technologies, HFTO

Dimitrios.Papageorgopoulos@ee.doe.gov

hydrogenandfuelcells.energy.gov