U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

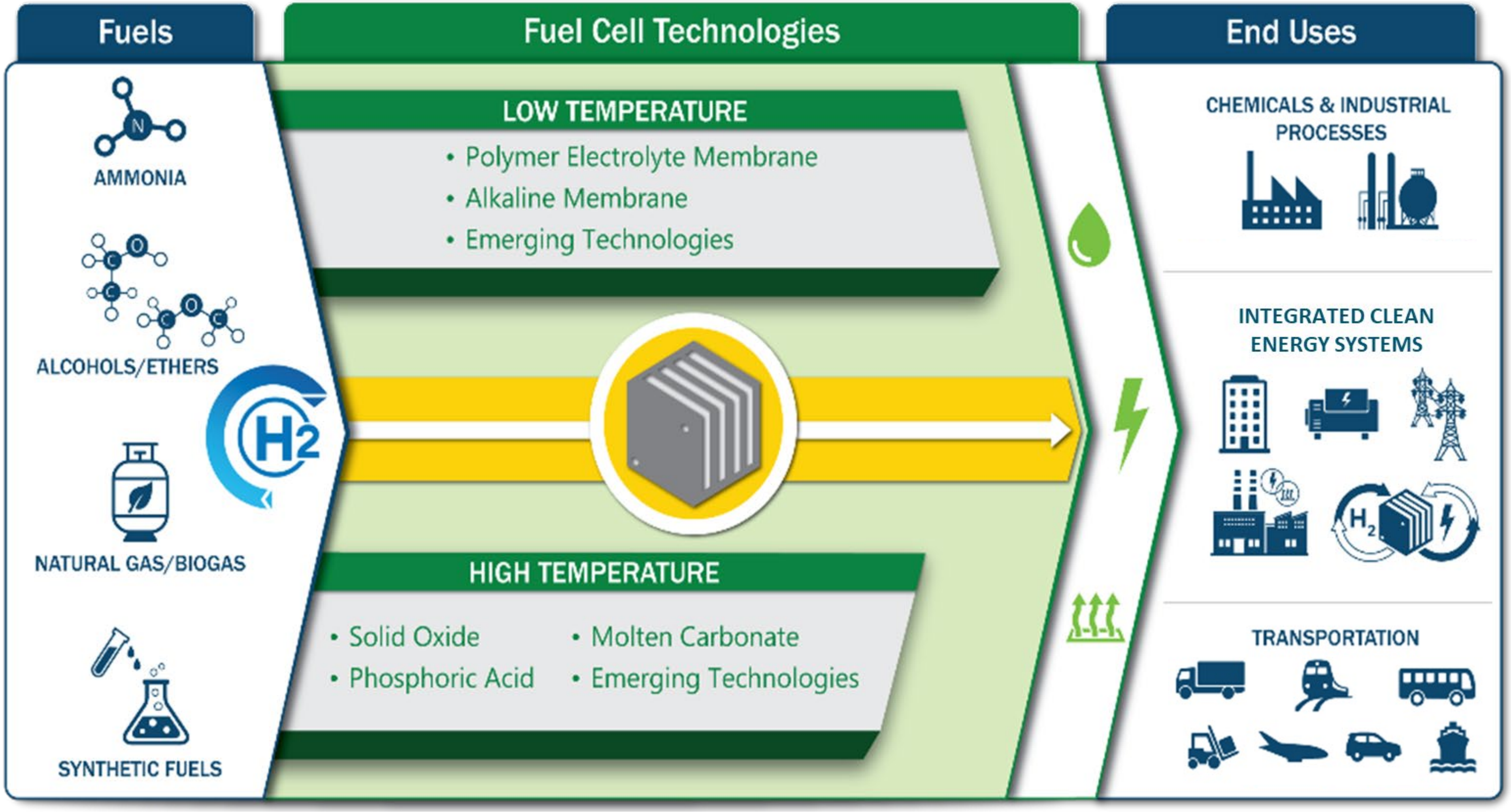
Fuel Cell Technologies Overview

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

2022 Annual Merit Review and Peer Evaluation Meeting

June 6, 2022 – Washington, DC

Fuel Cell Technologies



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 Focused on End-Use Requirements

Goal: ***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 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

- $1,000/kW fuel cell system cost
- 80,000-hour durability

REVERSIBLE FUEL CELLS FOR ENERGY STORAGE

- $1,800/kW system cost ($0.20/kWh LCOS)
- 40,000-hour durability

EXAMPLE:

A combined target (2025) for Heavy Duty (HD) Membrane Electrode Assembly (MEA) development:

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

**Total platinum group metal (PGM) loading constrained to 0.3 mg/cm^2*

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

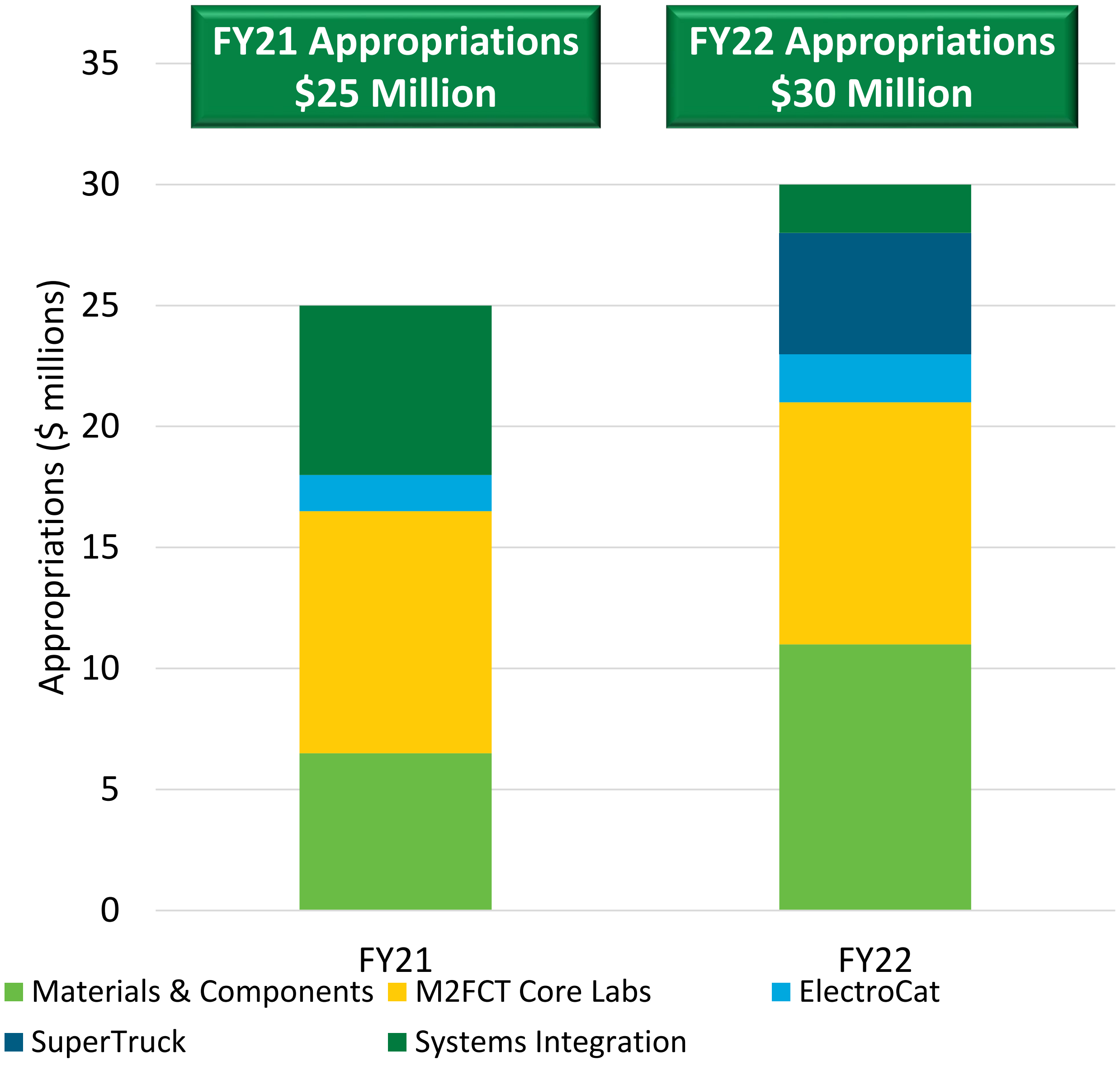
Systems and Manufacturing
- System design and operating conditions
- Standardized stacks and modular systems
- Improved manufacturing and supply chain
- Advanced BOP components and subsystems

Analysis and Modeling

Emphasis on HD Applications

- Direct-H_2 Polymer Electrolyte Membrane Fuel Cells (PEMFCs)
- Transferable benefits for medium-duty and stationary applications
- Advances in light-duty technology improvement and cost reduction a good start
- Long-term approaches considered

Fuel Cell Technologies Funding



Program Direction

Fuel cell materials, components and integration with a focus on low cost, enhanced durability and efficiency, for heavy-duty applications

- Low-PGM catalysts and MEAs
- Membranes, ionomers
- PGM-free catalysts and electrodes
- Bipolar plates, gas diffusion layers
- Balance of Plant (BOP)
- SuperTruck III
- System analysis
- Advanced manufacturing & recycling

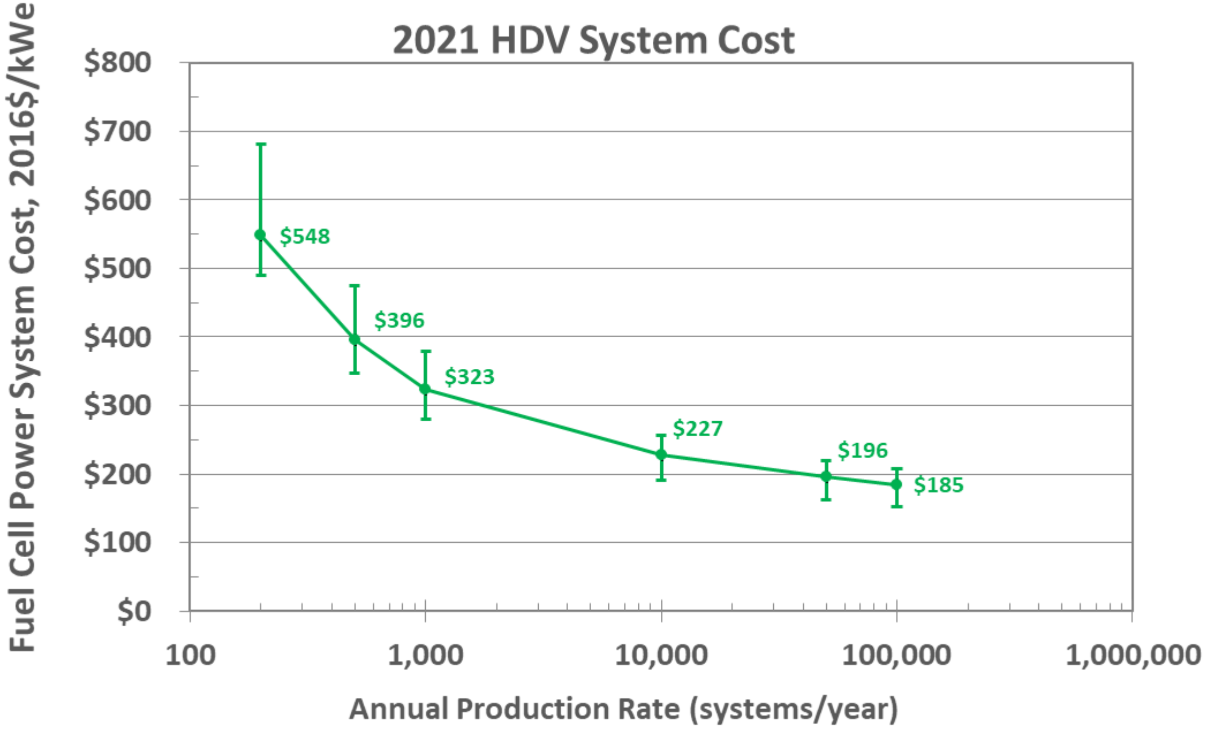
FY23 Request
$25 M

Clean H_2 Manufacturing & Recycling Program
$100 M/yr. over 5 yrs.

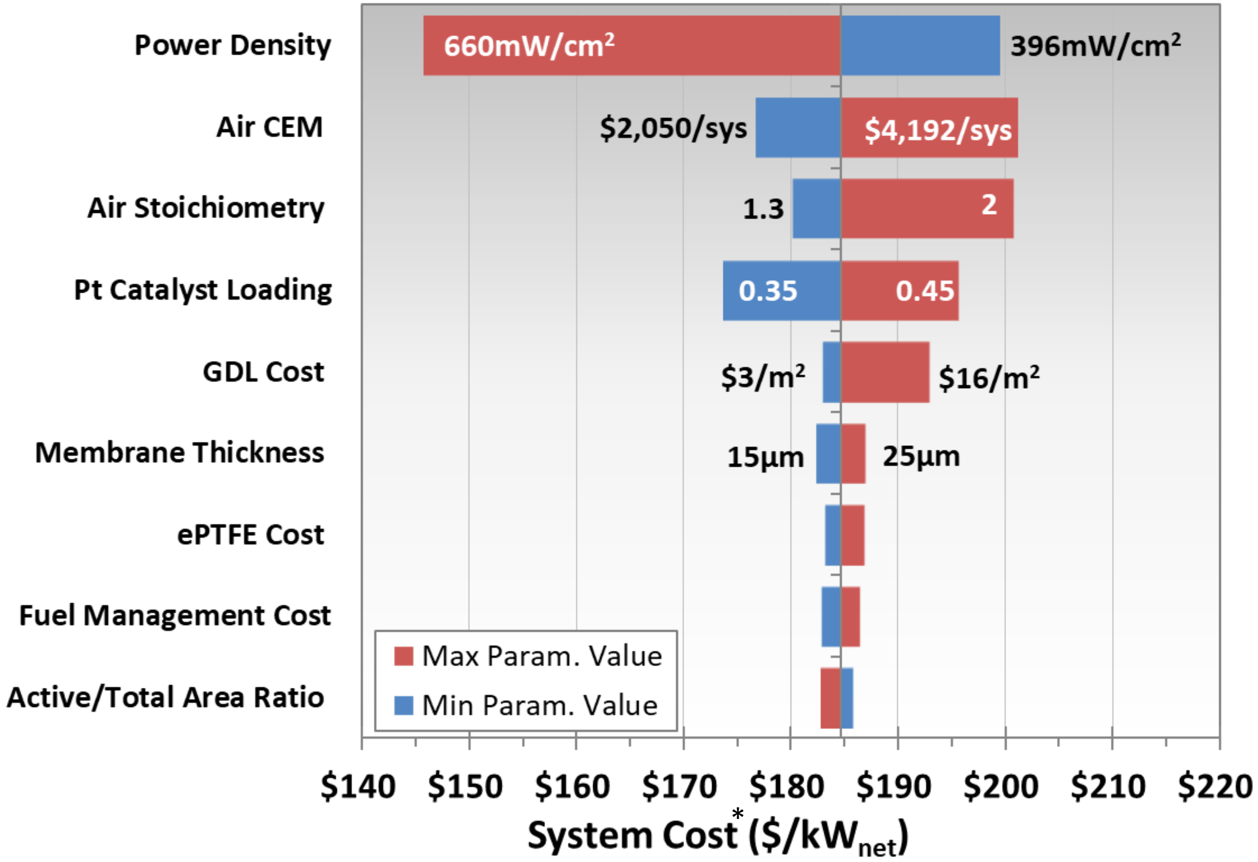
RD&D Portfolio Guided by Analysis

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

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



Sensitivity analysis identifies key cost levers



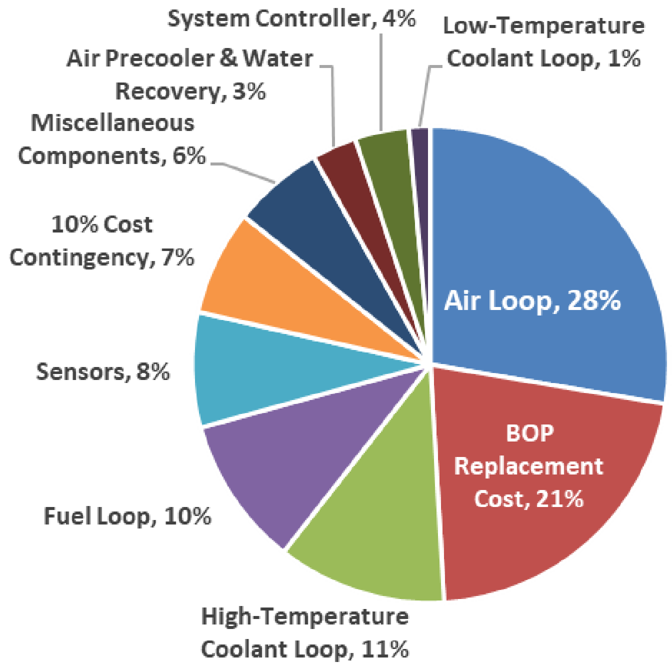
*2021 system cost at 100,000 units/year (2021)

HDV Fuel Cell Stack Cost Dominates System Cost

Stack cost breakdown at all production volumes

- Catalyst cost is projected to be the largest single component of PEMFC stack cost
- Air management drives balance of plant cost

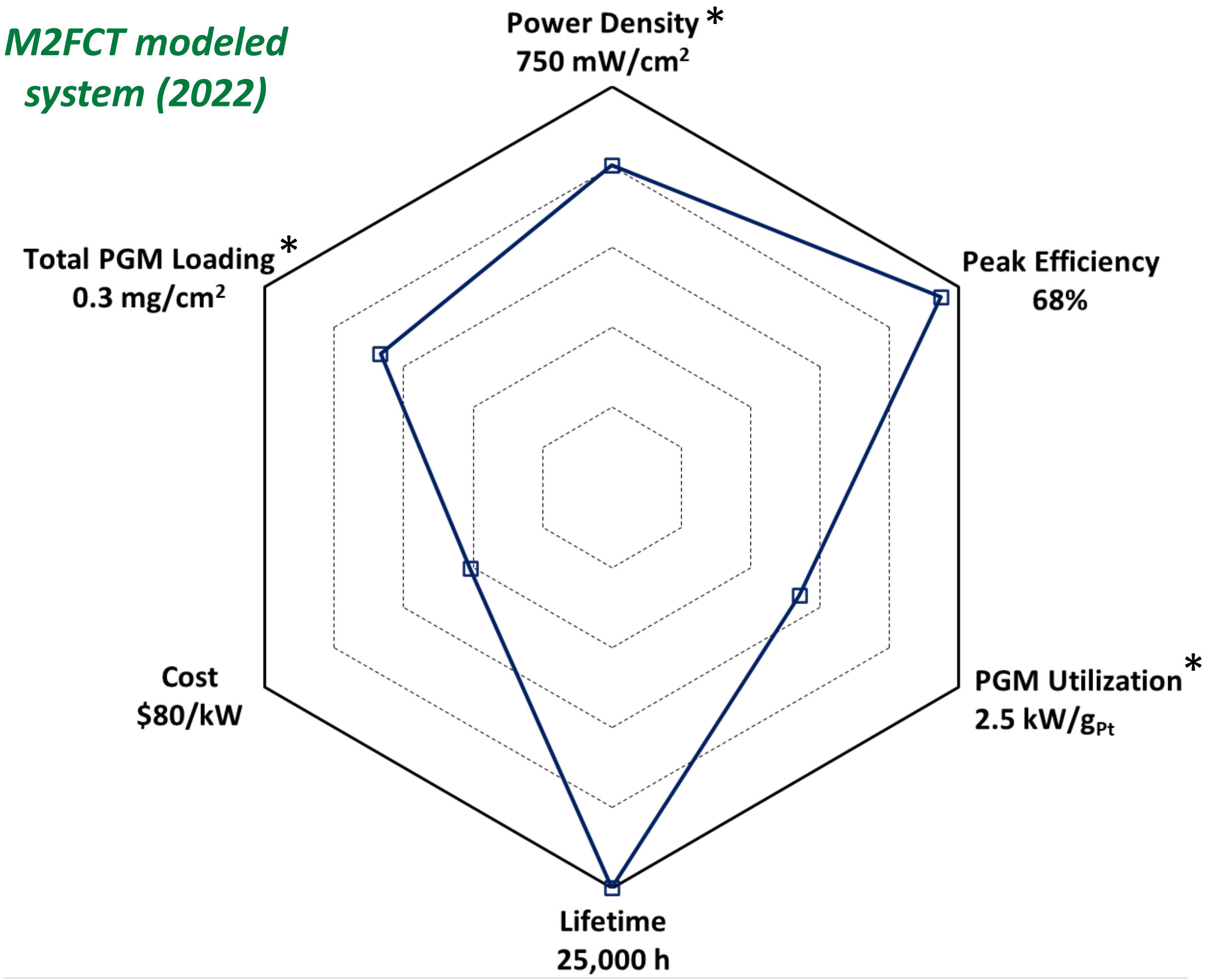
BOP cost breakdown at 100,000 units/yr



Analysis Assumptions Focus on Meeting Durability Requirements

Analysis assumes a system with 25,000-hour lifetime

M2FCT modeled system (2022)

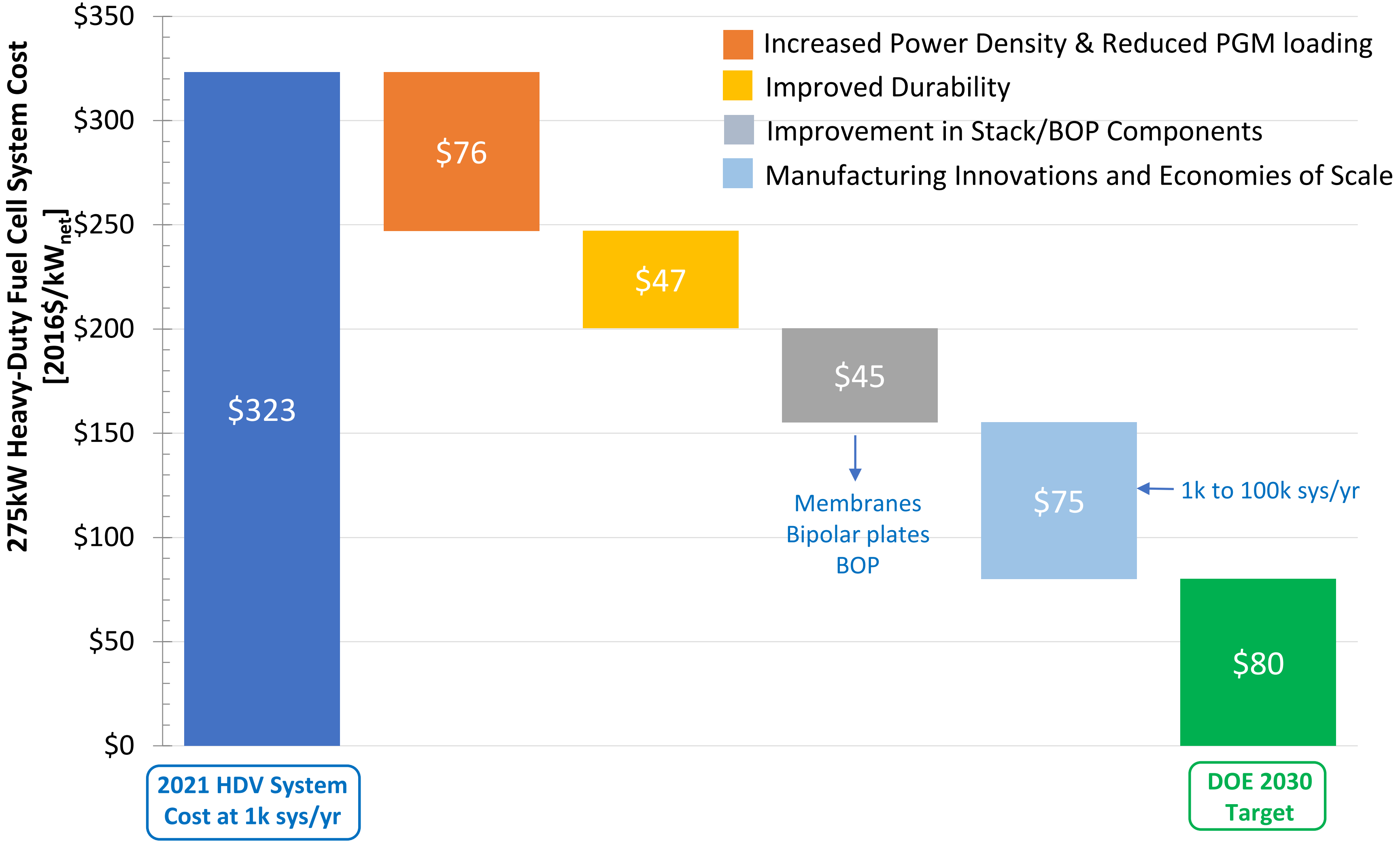


** M2FCT targets*

- Stack oversized by 100% and overloaded with PGM for 25,000-hour electrode lifetime
- Analysis addresses heat rejection requirements
- Active and stable catalysts are needed to meet 750 mW/cm^2 power density at EOL with 0.3 mg/cm^2 total PGM loading

EOL: Produce 275 kW_e at 0.7 V, 2.5 atm, 90°C coolant exit temperature, 1.5 cathode stoich.

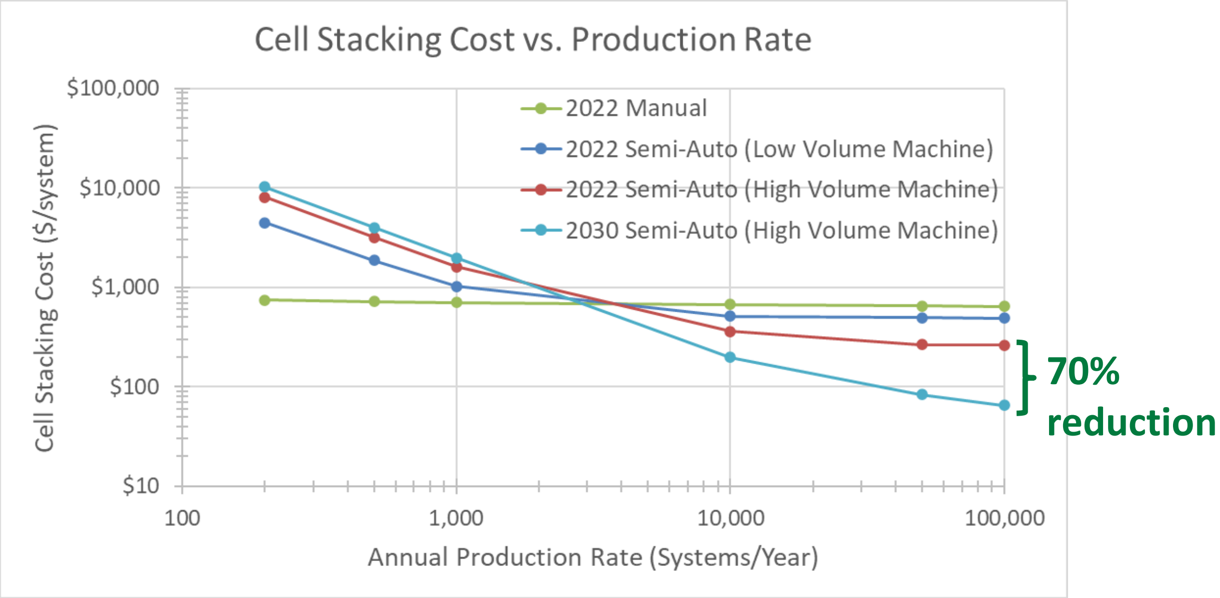
Focusing on the Four Critical RD&D Areas to Achieve Cost Target

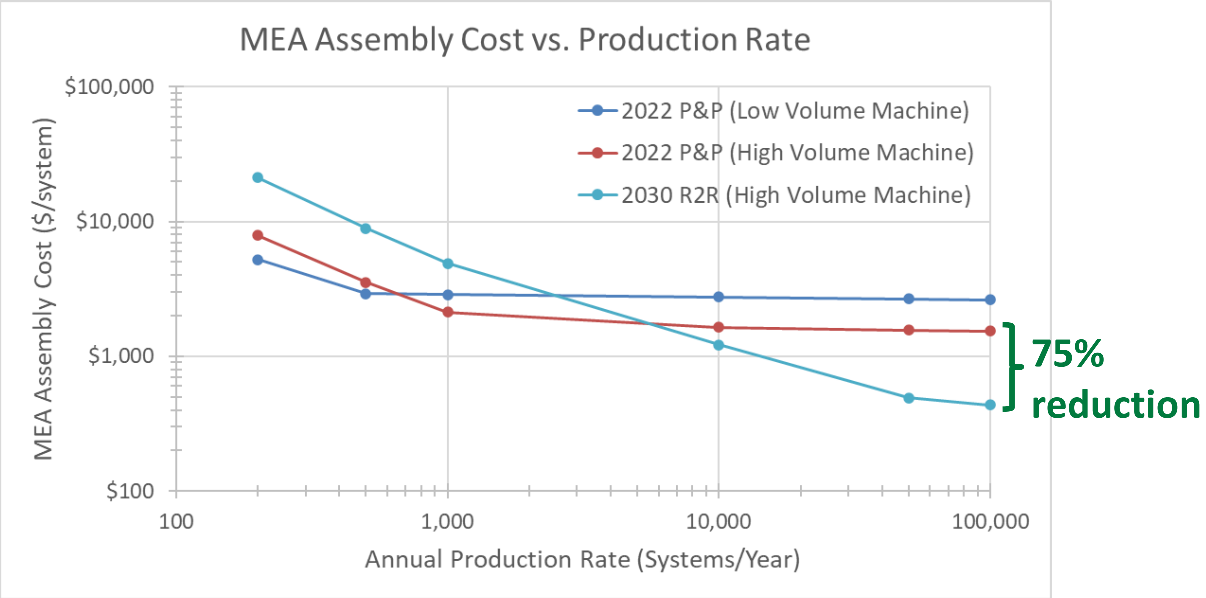


Substantial improvements needed in power density, durability, stack and BOP components, and manufacturing.

Potential for Manufacturing Innovations to Reduce Cost

Cell stacking and MEA assembly innovations include reduced cycle time; increased throughput; reduced number of parallel lines to achieve target volume; reduced high volume assembly cost





Innovations in cell stacking

Advanced synchronized robots, lightweight grippers, multiple modules for high throughput

Reduces Pick & Place (P&P) time from 6 sec to <0.5 sec per part

Innovations in MEA assembly

Switch from P&P robots to advanced Roll-to-Roll (R2R) assembly using R2R feed, timed transfer, rotary calendaring and cutters

Reduces effective MEA assembly time from 15 sec to <0.5 sec per MEA

Million Mile Fuel Cell Truck Consortium (M2FCT)

Million Mile Fuel Cell Truck Consortium (M2FCT)

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MISSION

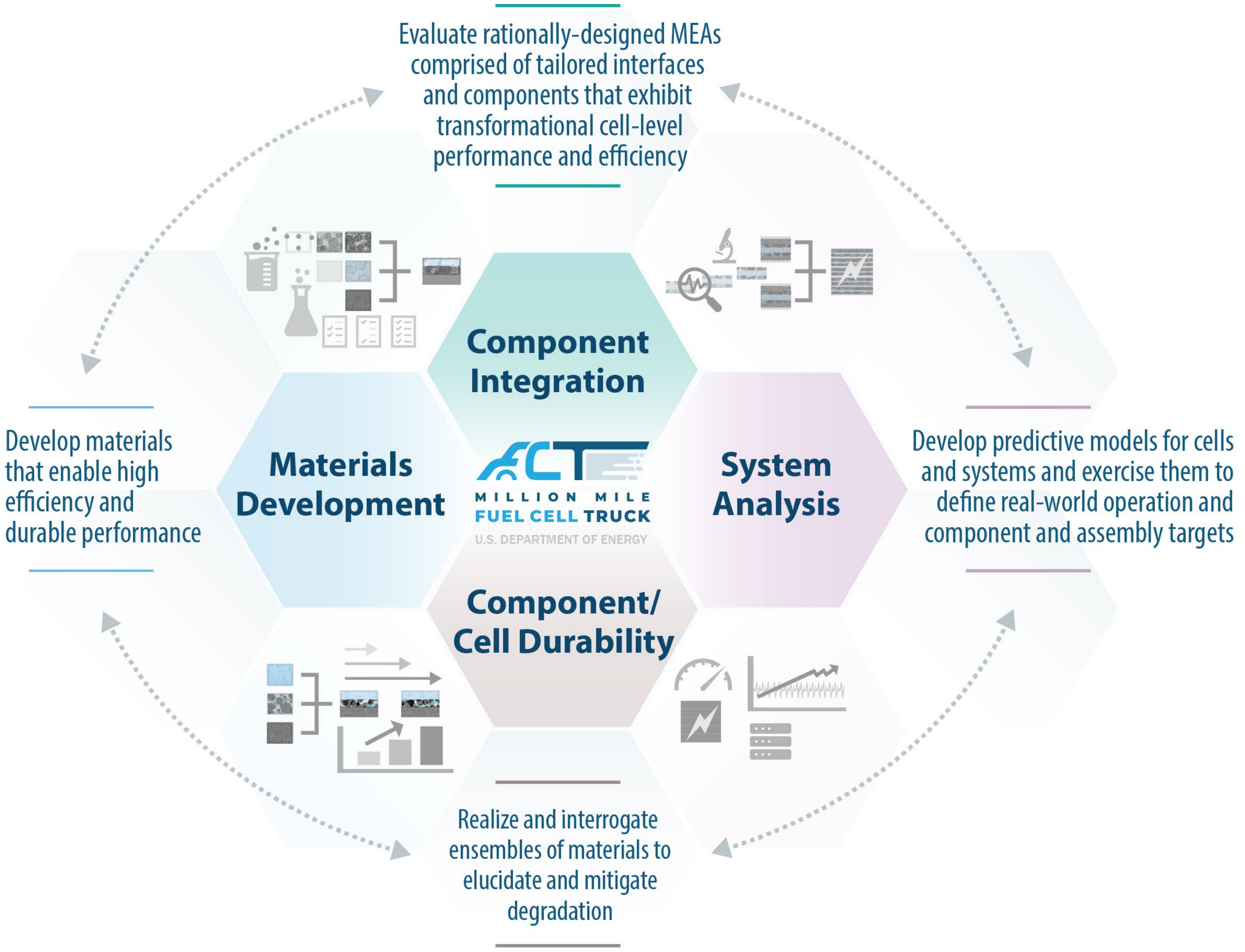
Advance efficiency and durability, and lower cost of PEMFCs for heavy-duty vehicle applications

APPROACH

Pursue a “team-of-teams” approach with teams in analysis, durability, integration, and materials development

OBJECTIVE

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



National Labs in Partnership with Universities and Industry

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MEAs

gm · Carnegie Mellon University · NIKOLA

Membranes

Lubrizol · 3M · NIKOLA

Stacks

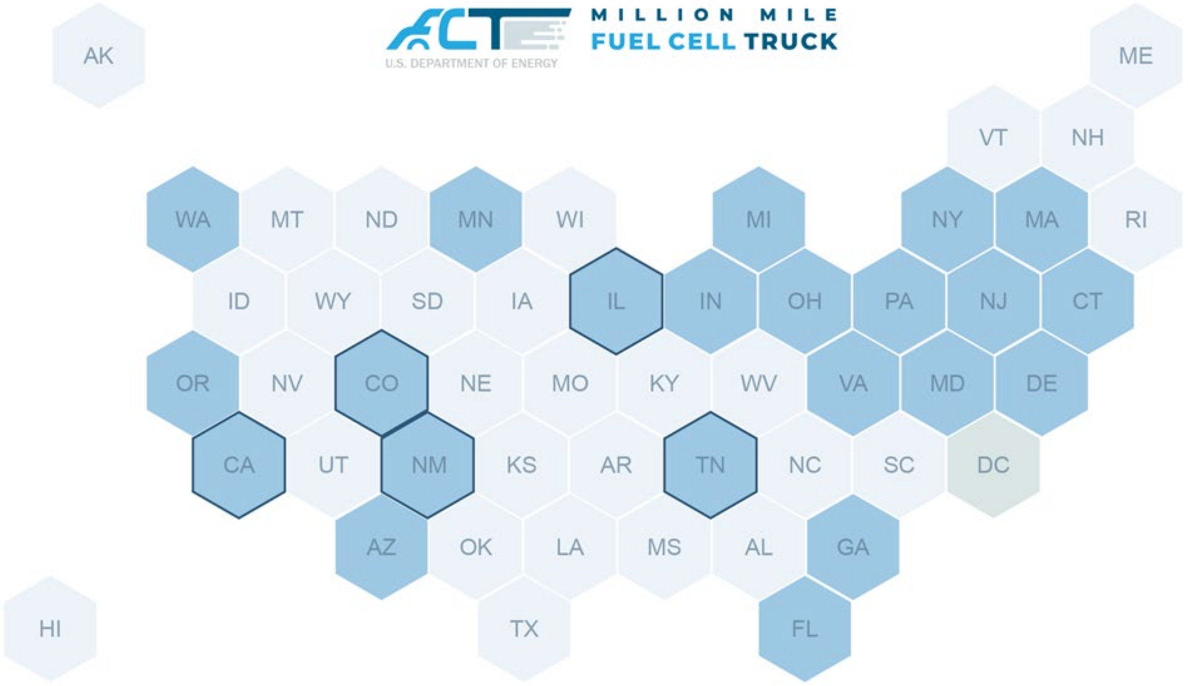
Cummins · plug

Bipolar Plates

Raytheon Technologies · NEOGRAF SOLUTIONS · TreadStone Technologies, Inc. · gm · plug

Air Management

CATERPILLAR · EATON · R&D Dynamics Corporation · MAHLE Driven by performance



LABS		ACADEMIA		INDUSTRY	
Primary Labs	LANL	Partners	Cornell	Partners	3M Company
	LBNL		Carnegie Mellon Univ.		Akron Polymer Products
	ANL		Colorado School of Mines		Ballard
	NREL		Drexel University		Chemours
	ORNL		Florida International Univ.		Cummins
Partners	PNNL		GeorgiaTech		Caterpillar
	BNL		Northeastern		Eaton
	NIST		UC Irvine		General Motors
			UC Merced		Kodak
			University at Buffalo		Lubrizol
			University of Tennessee		Mahle
					Nikola Motors
					Pajarito Powder
					Plug Power
					NeoGraf Solutions
					R&D Dynamics Corp
					Raytheon Technologies
					Strategic Analysis
					TreadStone Technologies

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

https://millionmilefuelcelltruck.org/partners

Baselining MEA Performance and Durability

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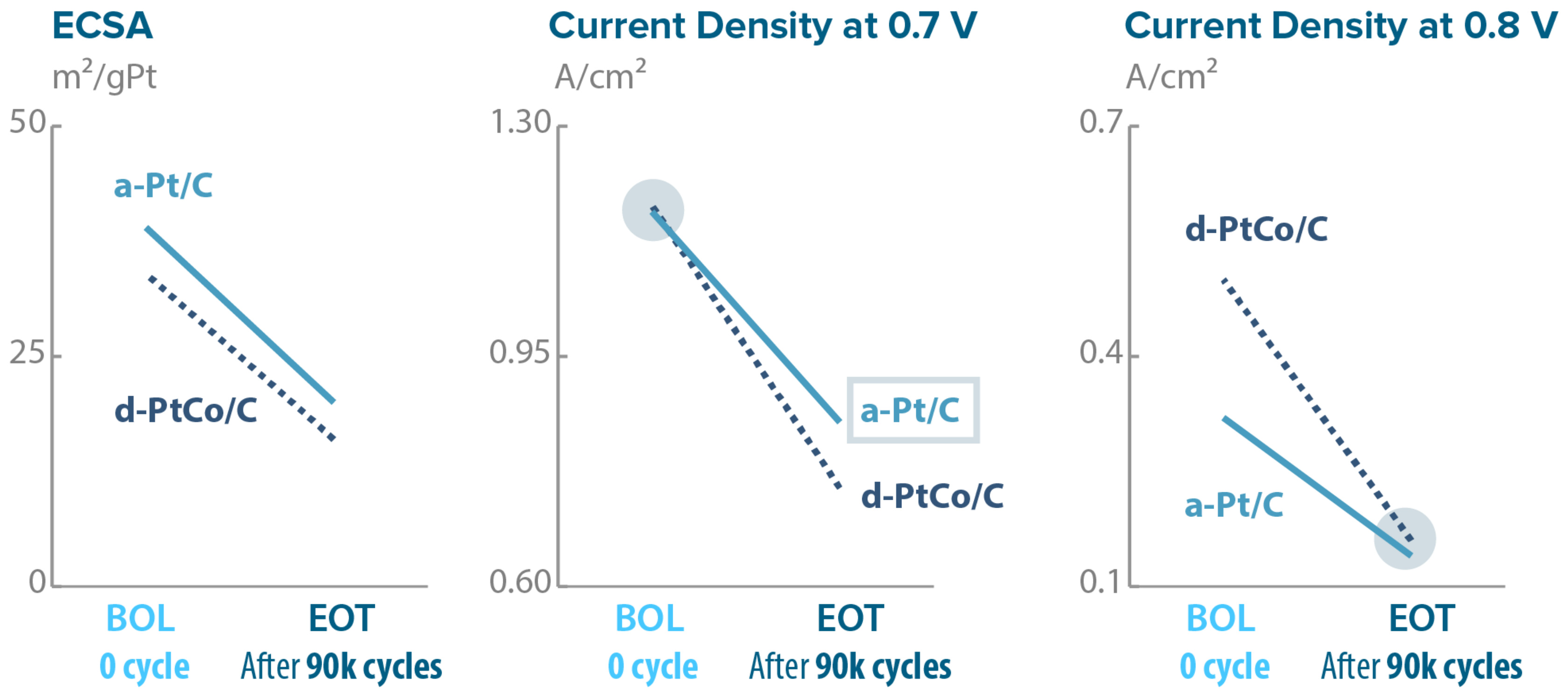
Examined catalysts with differing characteristics

Pt vs. PtCo

Supplier	Umicore	Umicore
Catalyst	Elyst Pt50 0690 (PtCo)	Elyst Pt50 0550
Carbon Support	HSA	HSA
Support BET [m^2/g]	780-800	780-800
Pt/Co ratio [mol/mol]	2.2 – 3.0	
Mean Pt Crystallite size [nm]	[a]4.4 - 5.4	[a]5.1 - 5.7
Catalyst BET [m^2/g]	240 - 280	310 – 350
ECSA [m^2/g_{Pt}]	40-45	45-50



Annealed Pt/C (a-Pt/C) chosen as the baseline to meet durability and current density requirements.

Materials Development: Catalysts

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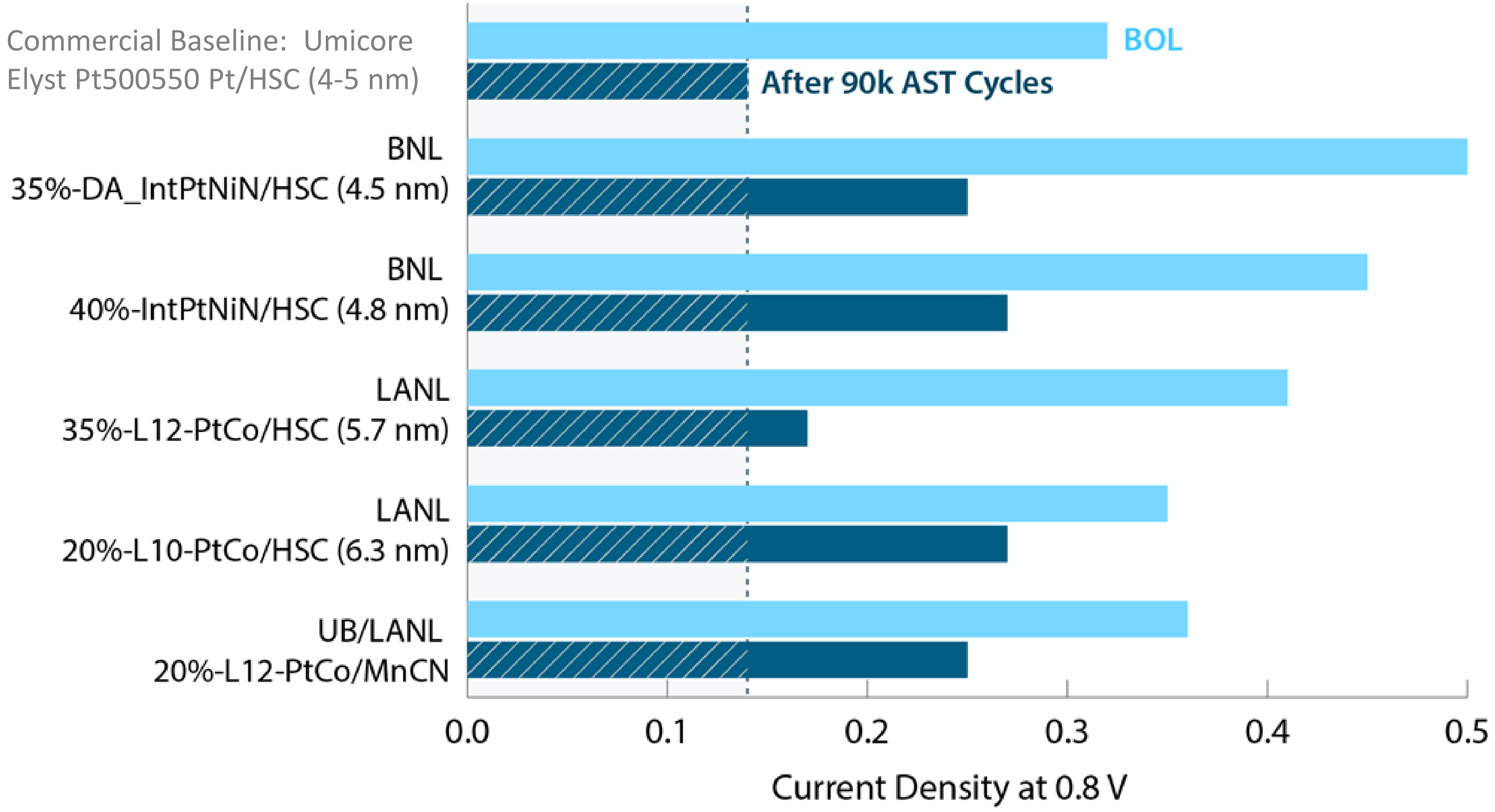
LANL and BNL catalysts outperform baseline



Baseline:
- Commercially available Pt/C

M2FCT Catalysts:
- N-doped intermetallic PtNi (BNL)
- Intermetallic PtCo on C and Mn-doped C (LANL)

Next step:
- Further development of catalysts and optimization of MEAs

Performance measured at Beginning of Life (BOL) and after 90,000 AST cycles.

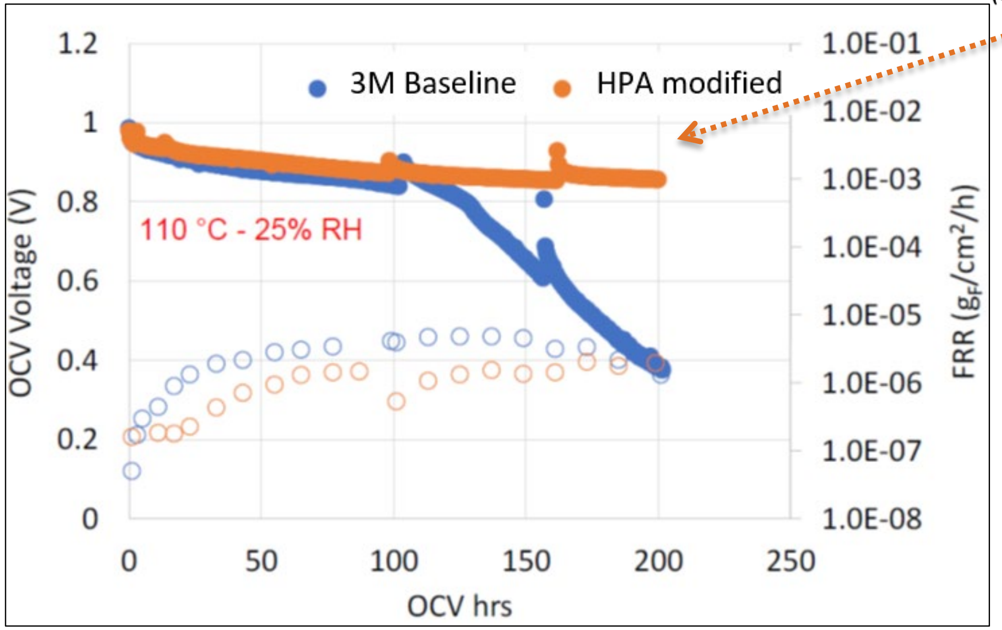
Partner Projects – General Motors

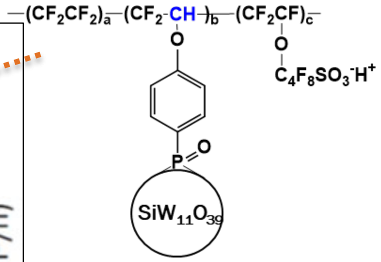
Immobilized membrane chemical stabilizers improve durability

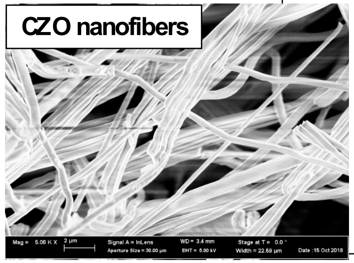
Issue: Cerium is used to improve chemical stability, but cerium salt-based additives migrate during operation

Multiple promising approaches

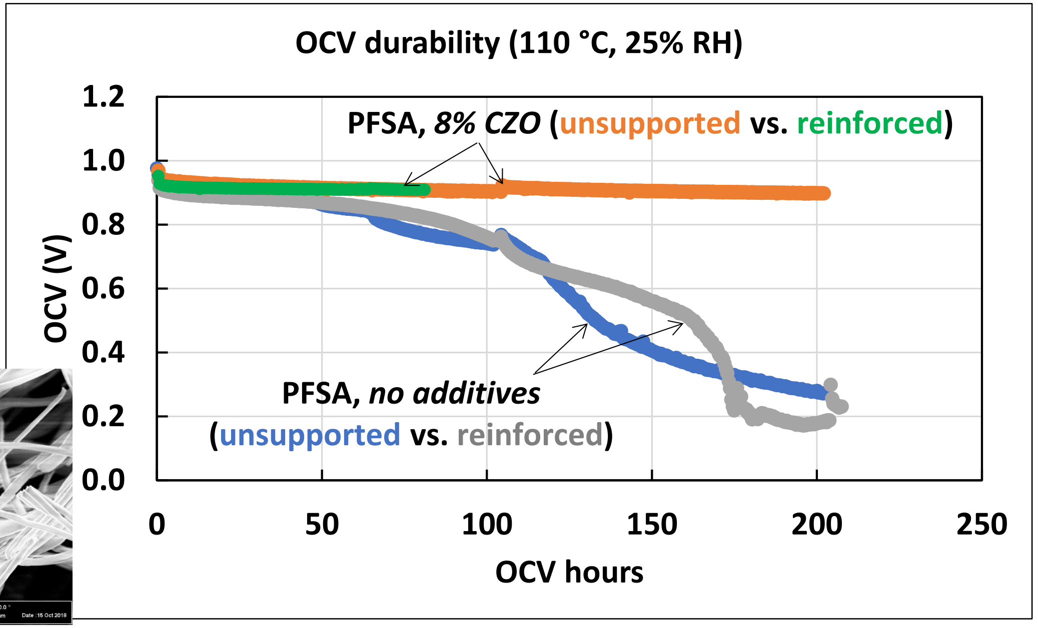
PFSA with immobilized heteropoly acid radical scavengers





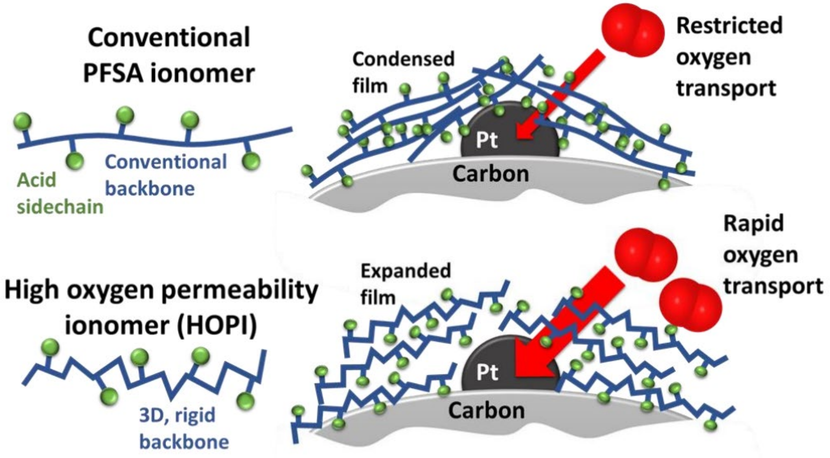


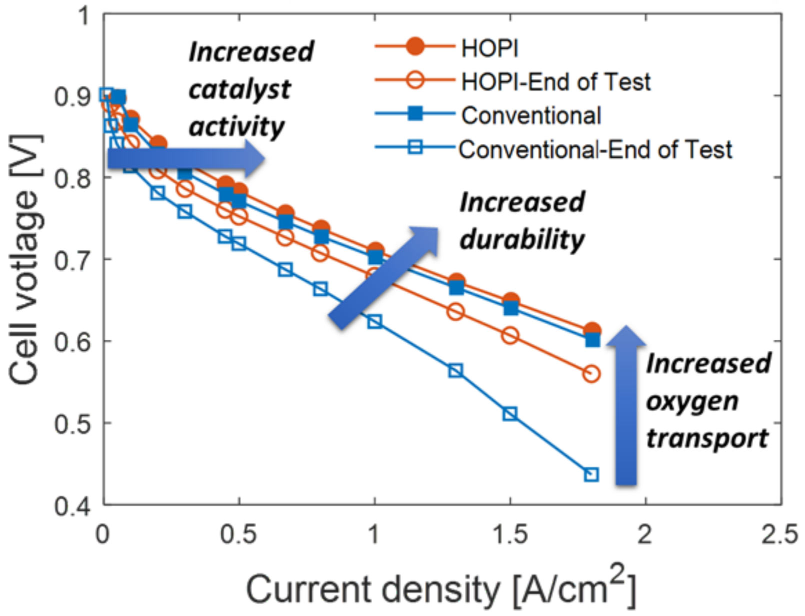
Dispersed $CeZrO_x$ (CZO) nanofibers



Partner Projects – Carnegie Mellon University

High-oxygen-permeability ionomer (HOPI) improves catalyst activity and durability





Issue:

Conventional ionomers have restricted O_2 transport that can reduce performance and durability over long heavy-duty vehicle lifetimes

Results:

- > 2X higher O_2 permeability than conventional ionomer
- > 50% increase in mass activity and noticeably better high-current-density voltage at low Pt loading
- 40% lower local O_2 transport resistance
- > 40% reduction in degradation rate

Defining the 25,000-Hour Equivalent AST

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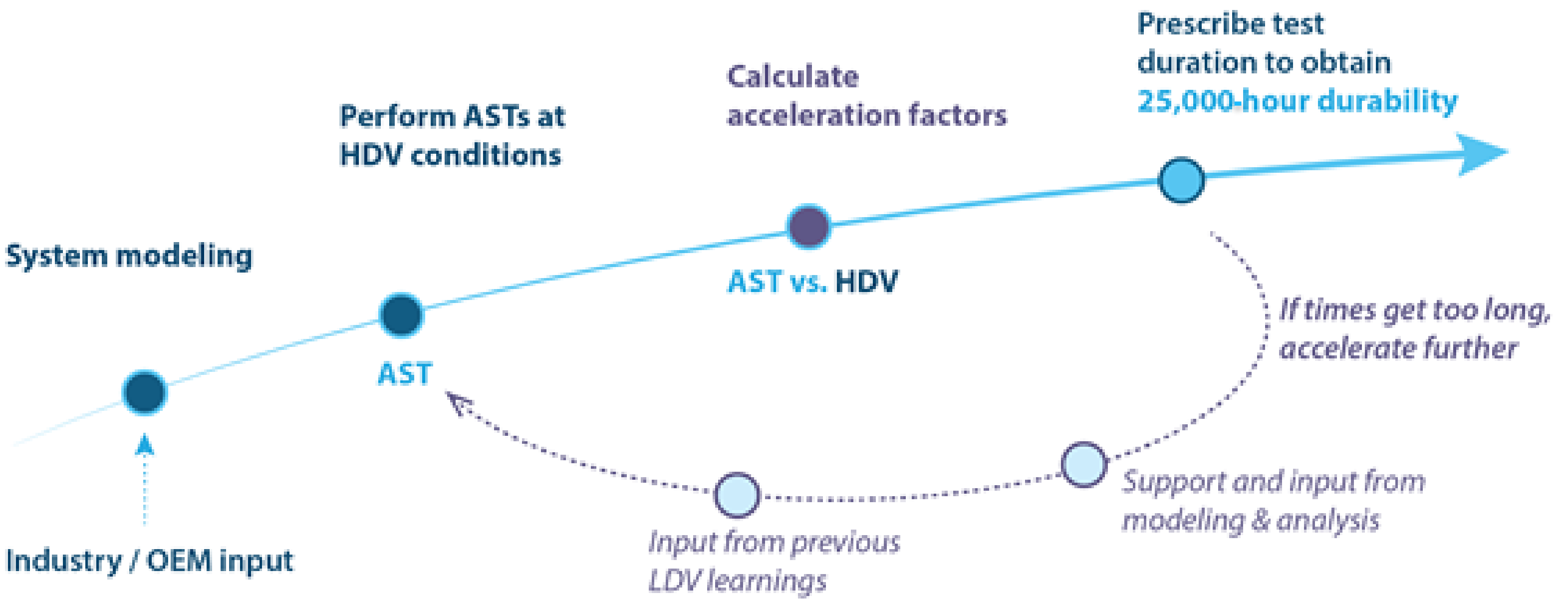
ASTs to be developed

- Catalyst
- Catalyst support
- Membrane chemical
- Membrane chemical-mechanical
- Startup/Shutdown
- Anode H_2 starvation
- MEA drive-cycle



AST WG

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

AST Development Progress

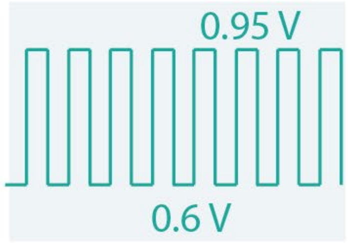
H_2/Air AST to evaluate MEAs for heavy-duty applications

AST ☑ Catalyst Degradation

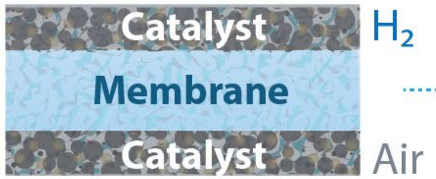
90,000 Cycles

H_2/N_2 **150 hours**

Temperature = 80°C



AST ☐ Catalyst + Membrane Degradation



Lower inlet RH to incorporate chemical-mechanical durability of membrane

30,000 Cycles — *longer duration, fewer cycles*

H_2/Air **500 hours**

Temperature = 90°C — *increase temperature from 80 to 90°C for acceleration*

lower upper potential

more representative of a HDV scenario

Single HDV AST that considers degradation of:

- ✓ catalysts
- ✓ supports
- ✓ membranes

International Coordination

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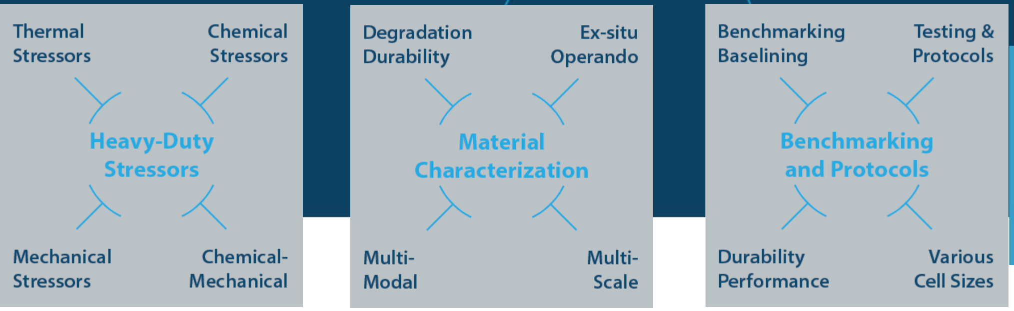
International Durability Working Group (iDWG)

8 Countries
from America, Europe, and Asia

30 Institutions
participants representing governments, universities, industry and labs

80 Researchers
facilitating data sharing, exchanging materials, promoting AST development



with representation from the US, European Union (EU), Japan, and Korea to better coordinate international efforts currently underway to help commercialize fuel cells for trucks and heavy-duty applications.

https://millionmilefuelcelltruck.org/idwg

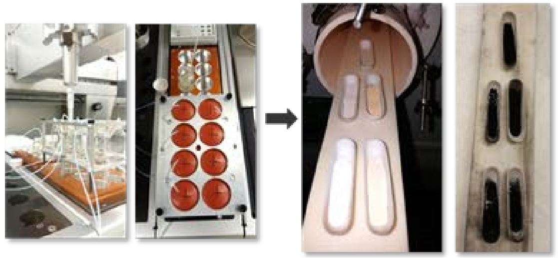
ElectroCat

World-Renowned Expertise

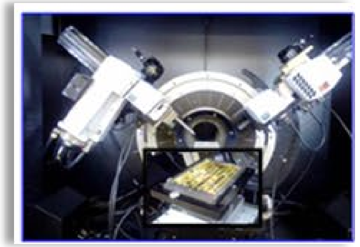
ElectroCat
Electrocatalysis Consortium

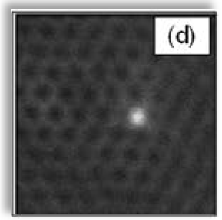
Development of durable PGM-free catalysts for PEM fuel cells and electrolyzers

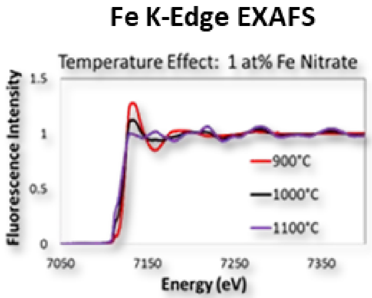
Synthesis, Processing and Manufacturing



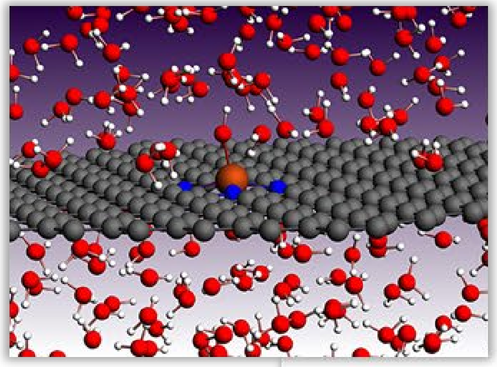
Characterization and Synthesis

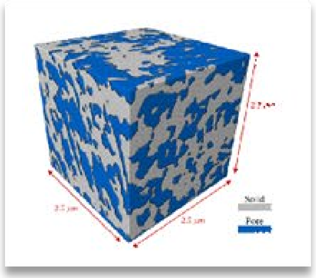


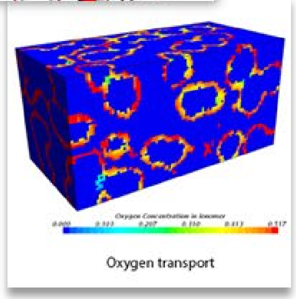




Computation, Modeling & Data Management







Argonne NATIONAL LABORATORY

Los Alamos NATIONAL LABORATORY

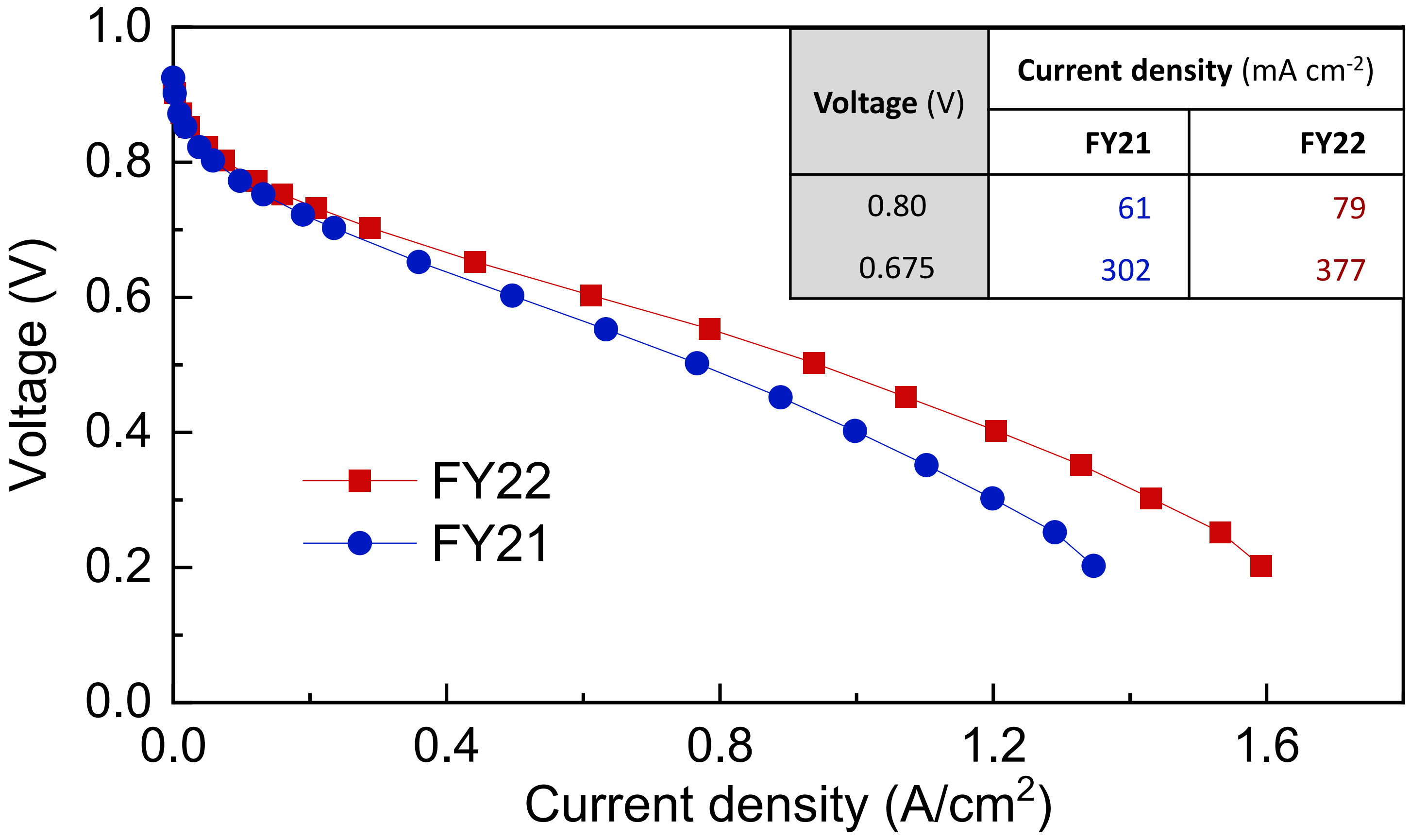
OAK RIDGE National Laboratory

NREL NATIONAL RENEWABLE ENERGY LABORATORY

PGM-Free Catalyst Performance Enhancement

ElectroCat
Electrocatalysis Consortium

Improved the performance of PGM-free catalysts by 25% over the baseline



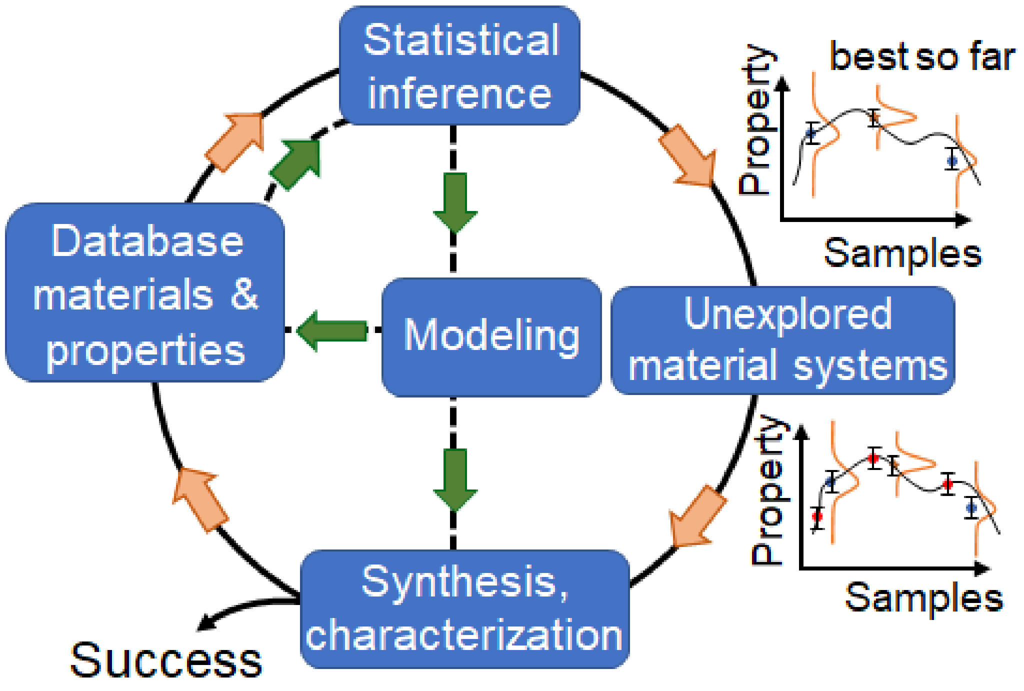
Voltage (V)	**Current density** (mA cm^{-2})	
	FY21	**FY22**
0.80	61	79
0.675	302	377

- PGM-free (Fe-N-C) cathode H_2-air initial fuel cell performance met FY22 milestone of 25% improvement versus the FY21 baseline
- Testing with published protocols validated at LANL, ANL and NREL*

H. Zhang, L. Osmieri, J. H. Park, H. T. Chung, D. A. Cullen, K. C. Neyerlin, D. J. Myers, P. Zelenay, Nat. Catal., https://doi.org/10.1038/s41929-022-00778-3.

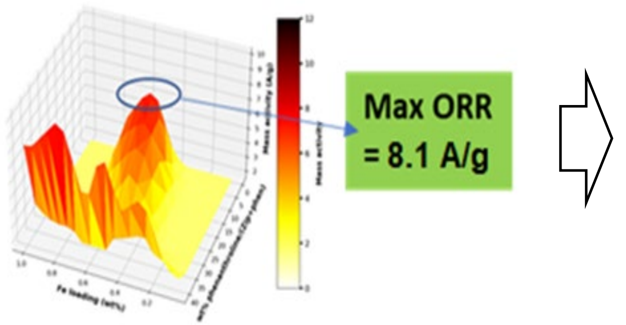
Data Science-Guided High-Throughput PGM-free Electrocatalyst Synthesis

ElectroCat
Electrocatalysis Consortium

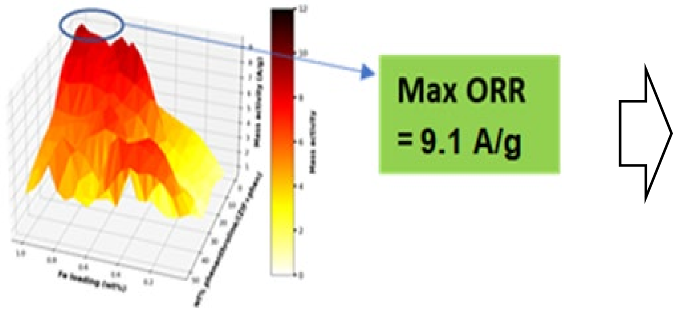


- Developed and implemented **adaptive learning design loop** with uncertainty quantification to model and guide the high-throughput catalyst synthesis
- Increased PGM-free test catalyst ORR activity by **70%** through ML-guided synthesis

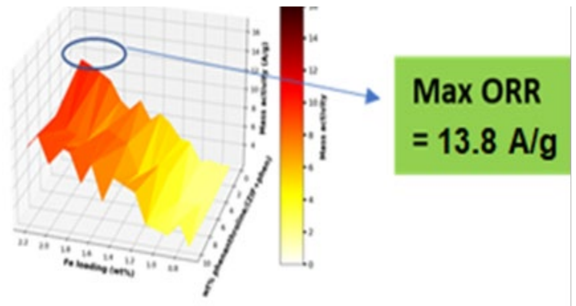
Loop 1: 16 samples



Loop 2: 32 samples



Loop 3: 36 samples



Diversity, Equity, Inclusion

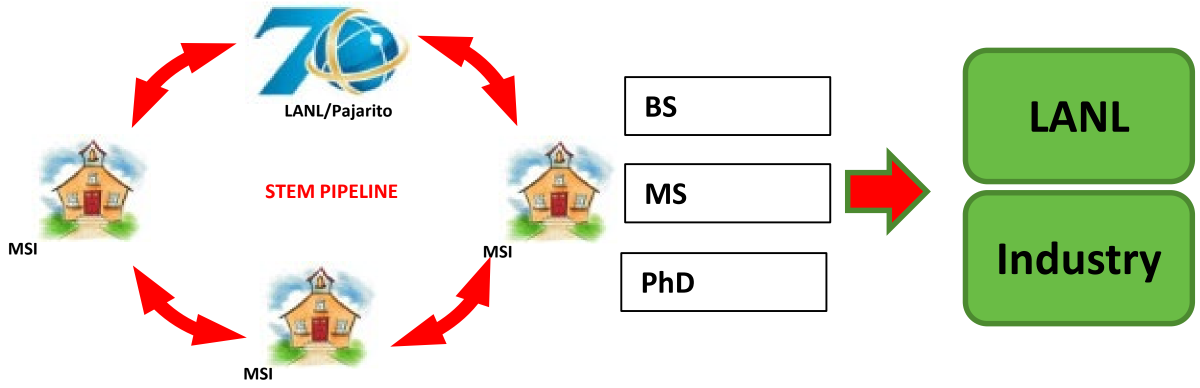
Minority Serving Institution (MSI) Partnership Program

HFTO/MSIPP/LANL/Pajarito Powder Establishes Collaboration with MSIs

Pajarito Powder & LANL host Industry

Project Goals

- Develop a mutually beneficial relationship between HFTO, LANL, industry partners, and MSIs
- Promote MSI involvement with hydrogen-related research
- Provide opportunities for MSI scholars to perform cutting-edge fuel cell research at LANL
- Encourage MSI scholars to pursue advanced degrees and enter the hydrogen and fuel cell workforce

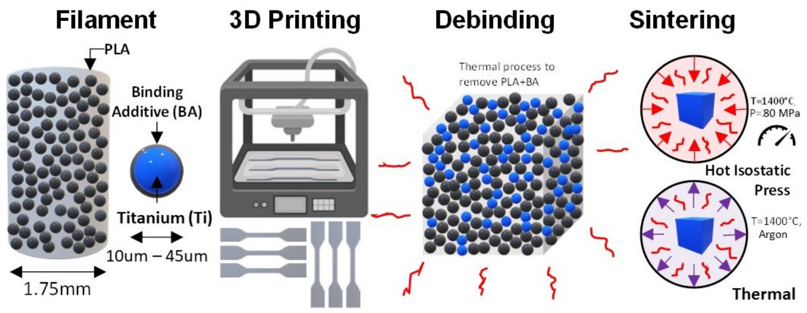


M2FCT: Inclusion, Diversity, Equity, Accountability

Outreach and Workforce Development

- Labs hosted undergraduate and graduate student interns, and DOE SCGSR Fellows to gain fuel cell and H_2 experience
- 2 new MSI students with M2FCT (summer 2022)
- 2022 summer internship programs (K12 and SULI)
- H_2 and fuel cell short courses
- **M2FCT added 3 MSI Discretionary projects:**
  - Univ Cal Irvine – AANAPISI* and HSI**
  - Univ Cal Merced– HSI
  - Florida International University– HSI

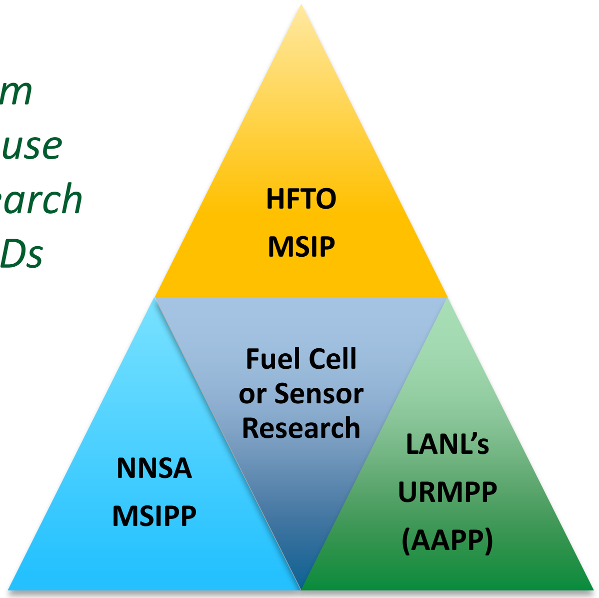
Dr. David Alexander
Ph.D Thesis: April 2022
HBCU – Undergrad
HSI - graduate
New LANL staff scientist



Bound metal deposition for fuel cell bipolar plates

M2FCT working with Minority Serving Institution Partnership Program

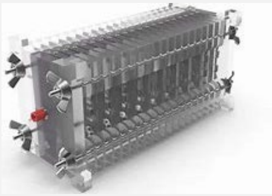
Students from HBCUs/HSIs use fuel cell research to obtain PhDs and launch careers



*AANAPISI: Asian American Native American Pacific Islander-Serving Institution **HSI: Hispanic-Serving Institution

Sec. 40314 (EPACT Sec 815) Clean Hydrogen Manufacturing & Recycling

Sec. 40314, EPACT Sec. 815 and Related IIJA Provisions



"Clean H_2 Electrolysis Program": BIL Includes RDD&D across multiple electrolysis technologies, compression, storage, drying, integrated systems, etc. - directly supports Hydrogen Shot

Sec. 40314 (EPACT Sec 816): Clean Hydrogen Electrolysis Program; **$1 Billion over 5 years. Goal $2/kg by 2026**

"Clean Hydrogen Manufacturing and Recycling"

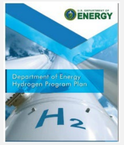
Raw Materials → **Processed Materials** → **Subcomponents** → **End Product**

Focus on manufacturing and end of life/recycling RD&D

Sec. 40314 (EPACT Sec 815): Clean Hydrogen Manufacturing & Recycling **$0.5 Billion over 5 years**

Regional Clean H_2 Hubs: At least 4 Hubs, geographic diversity, includes renewables, fossil + CCS, nuclear, for clean hydrogen production, multiple end use applications.

Sec. 40314 (EPACT Sec 813): Regional Clean Hydrogen Hubs; **$8 Billion over 5 years**



National Hydrogen Strategy and Roadmap: Includes working with EPA to develop an initial clean hydrogen production standard per Sec. 822 $\leq$ 2 kg CO_2e/kg H_2

Sec. 40314 (EPACT Sec 814: Strategy & Roadmap and **Sec. 40315 (EPACT Sec 822)**: Clean Hydrogen Production Qualifications)

Section 815a: Clean Hydrogen Manufacturing Initiative

Research, development and demonstration projects to advance new clean H_2 delivery, storage and use equipment **manufacturing technologies and techniques**.

The Secretary, to the maximum extent practicable, shall give priority to clean hydrogen equipment manufacturing projects that —

A. Increase efficiency and cost-effectiveness in —

   i. the **manufacturing process**; and
   ii. the use of resources, **including existing energy infrastructure**.

B. Support **domestic supply chains** for materials and components.
C. Identify and incorporate nonhazardous **alternative materials** for components and devices.
D. Operate in partnership with tribal energy development organizations, **Indian Tribes, Tribal orgs., Native Hawaiian community**-based organizations, **or territories or freely associated States**; or
E. Are in **economically distressed areas** of the major natural gas-producing regions of the US.

Section 815b: Clean H_2 Technologies Recycling RD&D Program

Multiyear grants will be awarded for RD&D projects **to create innovative and practical approaches to increase the reuse and recycling** of clean H_2 technologies.

Including by —

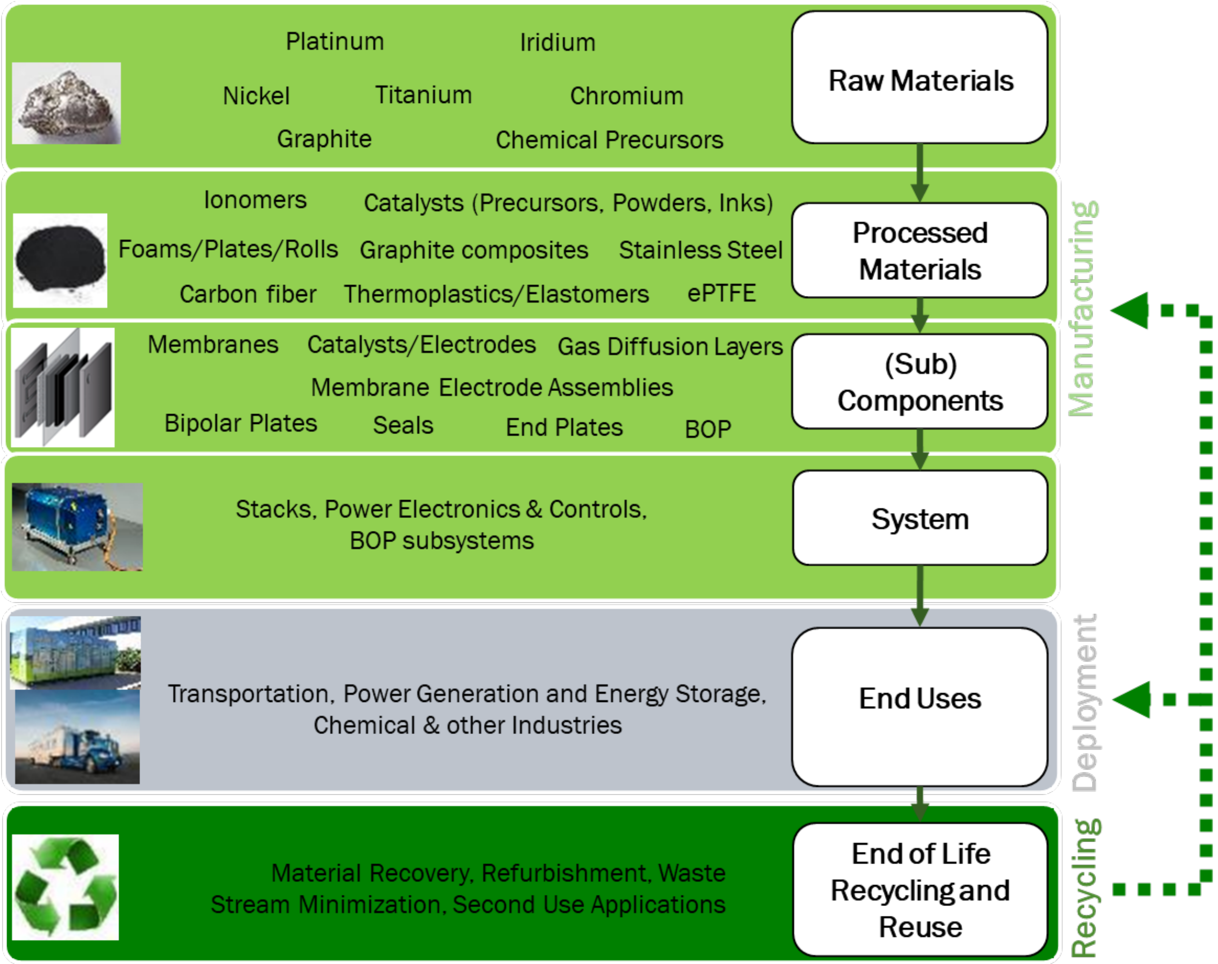
A. Increasing the efficiency and **cost-effectiveness of the recovery of raw materials** from clean hydrogen technology components and systems, including enabling technologies such as electrolyzers and fuel cells.
B. **Minimizing environmental impacts** from the recovery and disposal processes.
C. Addressing any barriers to the research, development, demonstration, and commercialization **of technologies and processes for the disassembly and recycling of devices** used for clean hydrogen production, processing, delivery, storage, and use.
D. Developing **alternative materials, designs, manufacturing processes,** and other aspects of clean H_2 technologies.
E. Developing alternative **disassembly and resource recovery** processes that enable efficient, cost-effective, and environmentally responsible disassembly of, and resource recovery from, clean hydrogen technologies.
F. Developing strategies to increase consumer acceptance of, and participation in, **the recycling of fuel cells**.

Independent review of project progress no later than 3 years after IIJA is enacted, and at least every 4 years after that.

Addressing Supply Chain Challenges

Growth required across domestic clean H_2 supply chains*

Example: PEM fuel cell & electrolyzer supply chain



Key Manufacturing & Recycling Program Opportunities:

- Cost reduction and increased commercialization of clean H_2 technologies
- Development of domestic material supplies – including recycling and alternative non-hazardous materials
- Development of manufacturing capacity to meet projected H_2 demand
- Leadership on energy and environmental justice issues for a new industry

*www.energy.gov/eere/fuelcells/water-electrolyzers-and-fuel-cells-supply-chain-deep-dive-assessment

Stakeholder Engagement

Nov. 15, 2021: IIJA Enacted

Dec. 2-3, 2021: Workshop #1, Power Electronics for H_2 (including Manufacturing & Recycling discussion)

Feb. 15 2022: RFI Issued for Manufacturing and Recycling

Mar. 15, 2022: Listening Session #1, Tribal and Alaska Native Corporation Leaders

Mar. 17, 2022: Listening Session #2, EEJ & Tribal Organizations

Mar. 29, 2022: RFI responses received from stakeholders

Apr. 7, 2022: Listening Session #3, EEJ & Tribal Organizations

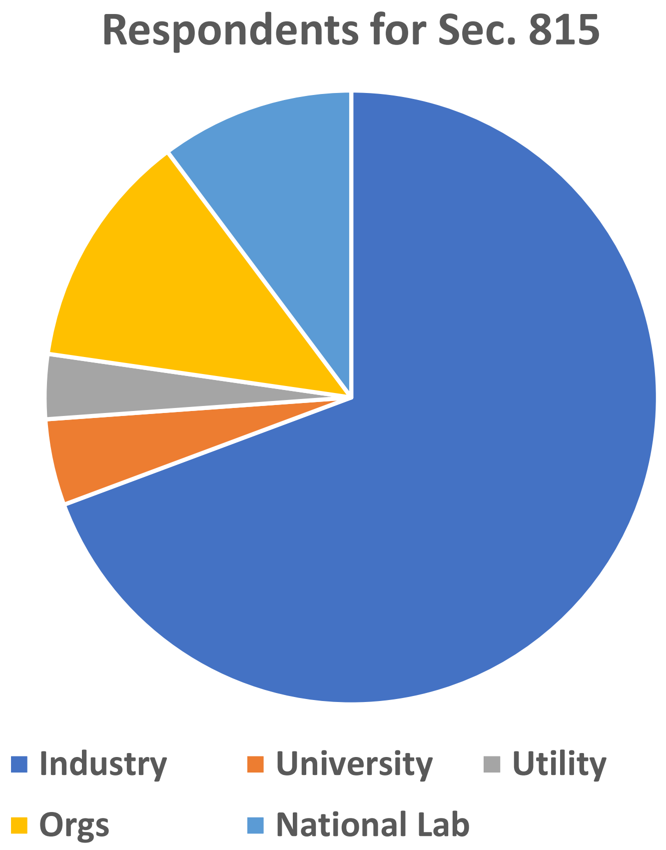
Apr. 14, 2022: Listening Session #4, EEJ & Tribal Organizations

Apr. 19 2022: Workshop #2, Advanced Component Development of Gas Diffusion Layers

May 24-26, 2022: Workshop #3, Manufacturing Automation and Recycling for Clean H_2 Technologies

FY22, Q1 | **FY22, Q2** | **FY22, Q3**

Request for Information on Clean H_2 Manufacturing and Recycling



Responses included >1000 pages from ~90 stakeholders

Stakeholders from industry, academia, national labs, utilities, and organizations:

- Confirmed the necessity for a clean H_2 technology recycling consortium to advance the state of the art.
- Identified RD&D needs for automation and scaling of cell, stack, and system manufacturing.
- Identified gaps in the domestic component and critical material supply chains.
- Suggested a strategic PGM reserve and approximate needs.

Collaborations, Milestones, Team

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-H_2: ElectroCat	FC-SDI: HD Transportation (SuperTruck)	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	Energy Storage Grand Challenge
HPC	EMN	Space-related
IIJA Provisions		

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 Benchmarking

Highlights and Milestones

FY2021	FY2022	FY2023
MEA durability ASTs incorporating relevant degradation mechanisms for catalyst, support, electrodes and membrane in a single AST; defined MEA baseline	*Improved MEA FY21 baseline performance at a PGM loading of 0.3 mg_{PGM}/cm^2*	*Improve MEA performance at a PGM loading of 0.3 mg_{PGM}/cm^2*
Improved PGM-free catalyst activity to 38 mA/cm^2	*Improved PGM-free cathode H_2-air initial fuel cell performance by 25% compared to FY21 baseline*	*Improve PGM-free catalyst ORR activity compared to FY22 baseline*
Selected M2FCT FOA projects (bipolar plates, BOP)	*Solicit M2FCT FOA projects*	*Select M2FCT FOA projects*
Established durability adjusted HDV cost of $196/kW at 50,000 systems/year	*Meet durability adjusted HDV cost of $185/kW at 50,000 systems/year*	*Meet durability adjusted HDV cost of $170/kW at 50,000 systems/year*
Completed RFC and H_2 stationary MW-scale PEMFC analysis	*Establish targets for MW-scale H_2-PEM for stationary and long-duration energy storage applications*	*Select Sec. 815 Manufacturing and Recycling projects*

The Team

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Thank You

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