Fuel Cell Technologies Overview

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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

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 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/cm² current density)* at 0.7 V after 25,000 hour-equivalent accelerated durability test**

*Total PGM loading constrained to 0.3 mg/cm².
**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...

- Low-PGM and PGM-free catalysts and electrodes
- Innovative membranes and ionomers
- Durable high performance MEAs
- Advanced bipolar plates and coatings
- System design and operating conditions
- Standardized stacks and modular systems
- Improved manufacturing and supply chain
- Advanced BOP components and subsystems

Materials and Components

Systems and Manufacturing

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

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

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.

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

H₂ 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).

**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.

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

Catalyst cost is projected to be the largest single component of PEMFC stack cost
Meeting HD Fuel Cell Cost Targets - Viable Pathway

- **Increased Power Density & Reduced PGM loading**
- **Improved Durability**
- **Improvement in Stack/BOP Component**
- **Increase in Production Volume**

**2021 HDV System Cost at 1k sys/yr**

- $323
- PGM loading from 0.4 to 0.35 mg$_{PGM}$/cm$^2$
- Reduce Stack Overizing
- Membrane + BOP
- $32$
- $12$
- $75$

**2025 HDV System Cost at 10k sys/yr**

- $162$
- PGM loading from 0.35 to 0.3 mg$_{PGM}$/cm$^2$
- Air Management + BPP
- $15$
- $8$
- $22$

**DOE 2030 Target**

- $80$

**DOE Ultimate Target**

- $60$

**10k to 50k sys/yr**

- $16$
- $5$

**50k to 100k sys/yr**

- $80$
- $60$
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, including one with > 32,000 hours

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

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

- Targeted 20% degradation at 25,000 hours 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

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

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Units</th>
<th>Interim (2030)</th>
<th>Ultimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Cell System Lifetime</td>
<td>[hours]</td>
<td>25,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Fuel Cell System Cost</td>
<td>[$/kW]</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>Fuel Cell Efficiency (peak)</td>
<td>[%]</td>
<td>68</td>
<td>72</td>
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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/cm² current density) at 0.7 V after 25,000 hour-equivalent accelerated durability test
M2FCT: National Labs in Partnership with Universities and Industry

HD MEA Projects
- gm
- Carnegie Mellon University
- Nikola™

HD Membrane Projects
- T
- Lubrizol
- 3M
- Nikola™

HD Stack Projects
- Plug Power

To add FOA bipolar plate and air management projects in FY21

Main Laboratories
- Los Alamos National Laboratory
- Berkeley Lab
- Oak Ridge National Laboratory
- Argonne National Laboratory
- Pacific Northwest National Laboratory
- Brookhaven National Laboratory
- NIST

Affiliate Laboratories
- Kodak
- Lubrizol
- Nikola Motors
- Pajarito Powder
- Plug Power

Primary Labs
- LBNL
- LANL
- ANL
- NREL
- ORNL

Partners Labs
- PNNL
- BNL
- NIST

Partners Academia
- Cornell
- Carnegie Mellon Univ.
- Colorado School of Mines
- GeorgiaTech
- Northeastern
- University of Tennessee

Partners Industry
- 3M Company
- Akron Polymer Products
- Ballard
- Chemours
- Cummins
- General Motors
M2FCT Core-Lab RD&D: Efficient and Durable Materials Systems

**Ionomers/Membranes**
- Functionalization of perfluorosulfonic acids with Ce$^{3+}$
- Use of reinforcement strategies and characterization of PF materials
- Low molecular-weight 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**

**Low EW Sulfonated Oligomers**

**Crown Ether Functionalized PFSA**

**Metal oxide Additive**

**PtAu Structured Particle**

**Incorporation and testing in MEAs for performance and durability**
**M2FCT Core-Lab R&D: Integration, Baselining, & Manufacturing**

**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

- **Optimization and Understanding**
  - Multiphysics modeling
  - MEAs with novel materials

- **Cell Performance and In situ Diagnostics**
  - Baseline and standardization
  - Limiting current
  - Ionomer adsorption
  - Interfaces

**Ex situ Component Characterization**
- Ionomer
- GDL/MPL
- Electrode structure
Accelerated Stress Test Working Group (ASTWG)

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 H₂ 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

**Perform ASTs**

- **H₂/Air on integral cell @ 90°C 100% and 90%RH**
- square wave cycling from 675 mV to 925 mV
- 30s each at 250 kPa

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**System modeling**

Developing Heavy Duty and Light Duty representative conditions

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

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**Calculate Acceleration factors**

- From 90°C 100% / 90%RH test to HDV

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**Perform the same at an LDV relevant condition**

- Temp, RH
- Pressure
- Potential limits

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**Perform the same at an HDV relevant condition**

- Temp, RH
- Pressure
- Potential limits

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**Prescribe test duration to obtain 25,000 hour durability**

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**2.5 kW/g PGM power (1.07 A/cm² 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

• 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

ElectroCat 2.0
ElectroCat: Building on Success and World-Class Capabilities

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
PGM-Free Catalyst Activity Accomplishment

- Performance exceeded the FY21 catalyst activity target: 38 mA/cm² vs. 35 mA/cm²
- Achieved with NH₄Cl-treated ‘single-zone’ Fe-C-N catalyst
- Efforts focusing on durability improvements

Improved the activity of PGM-free catalysts by over 2x compared to the 2016 baseline (16 mA/cm²)
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 NH₄Cl activation: one-zone synthesis followed with high-temperature activation with NH₄Cl
- ‘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

Concept: Store grid electricity as H₂ for later conversion back to electricity

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

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

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.

High Temperature

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.

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

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<td>US DRIVE Partnership: Fuel Cell Tech Team</td>
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<td>21st Century Truck Partnership</td>
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<td>M2FCT</td>
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<td>ElectroCat</td>
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<td>Workshops/RFIs</td>
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<td>FCHEA</td>
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## DOE H₂ Program Collaborations

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<tr>
<td>EERE/VTO: SuperTruck</td>
<td>ARPA-E: Advanced Fuel Cell Concepts</td>
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<tr>
<td>FC-H2: ElectroCat</td>
<td>FC-TA: HD Application Target-Setting and Real-World Data</td>
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<td>FC-TA: Systems Analysis</td>
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## DOE Cross-Cutting Initiatives

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<td>Critical Minerals</td>
<td>Advanced Manufacturing</td>
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<td>Advanced Energy Storage</td>
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<td>HPC</td>
<td>EMN</td>
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<td>Space</td>
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## International Collaborations

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<tr>
<td>IEA Technology Collaboration Programme on Advanced Fuel Cells</td>
<td>M2FCT AST Working Group</td>
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<td>ElectroCat Test Protocols</td>
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## Cross-Agency Collaborations

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<tr>
<td>DOC/NIST Fuel Cell Neutron Imaging</td>
<td>DOT/FTA (Fuel Cell Buses)</td>
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# Fuel Cell Technologies Program: Highlights and Milestones

<table>
<thead>
<tr>
<th>FY2019</th>
<th>FY2020</th>
<th>FY2021</th>
<th>FY2022</th>
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<tbody>
<tr>
<td>Established fuel cell system targets for long-haul trucks</td>
<td>Launched M2FCT</td>
<td>MEA durability ASTs incorporating relevant degradation mechanisms for catalyst, support, electrodes and membrane in a single AST; define MEA baseline</td>
<td>Improve MEA FY21 baseline performance at a PGM loading of 0.3 mg\textsubscript{PGM}/cm\textsuperscript{2}</td>
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<tr>
<td>Selected HD MEA R&amp;D FOA projects</td>
<td>Launched ElectroCat 2.0</td>
<td>Improved PGM-free catalyst activity to 38 mA/cm\textsuperscript{2}</td>
<td>Improve PGM-free cathode H\textsubscript{2}-air initial fuel cell performance by 25% compared to FY21 baseline</td>
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<tr>
<td>Developed low-PGM intermetallic catalysts meeting durability targets</td>
<td>Selected M2FCT FOA projects (membrane, stacks)</td>
<td>Established durability adjusted LDV cost ($76/kW at 100,000 systems/year)</td>
<td>Select M2FCT FOA projects</td>
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<tr>
<td>Achieved an 85% improvement in PGM-free catalyst activity over the 2016 baseline</td>
<td>Established durability adjusted HDV cost ($196/kW at 50,000 systems/year)</td>
<td>Select M2FCT FOA projects (bipolar plates, BOP)</td>
<td>Meet durability adjusted HDV cost of $185/kW at 50,000 systems/year</td>
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<tr>
<td>Selected system-level RFC RD&amp;D FOA projects</td>
<td>Released RFC targets</td>
<td>Established durability adjusted HDV cost ($196/kW at 50,000 systems/year)</td>
<td>Establish targets for MW-scale direct H\textsubscript{2}-PEM for stationary and long-duration energy storage applications</td>
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<td>Expanded analysis efforts to define HD fuel cell system designs</td>
<td>L’Innovator: CRADA drafted between Advent and labs (LANL, BNL, NREL)</td>
<td>Complete RFC and H\textsubscript{2}, stationary MW-scale PEMFC analysis</td>
<td>L’Innovator: Pilot scale up of membranes/MEAs</td>
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U.S. DEPARTMENT OF ENERGY  OFFICE OF ENERGY EFFICIENCY & RENEWABLE ENERGY  HYDROGEN AND FUEL CELL TECHNOLOGIES OFFICE
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

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Thank You

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