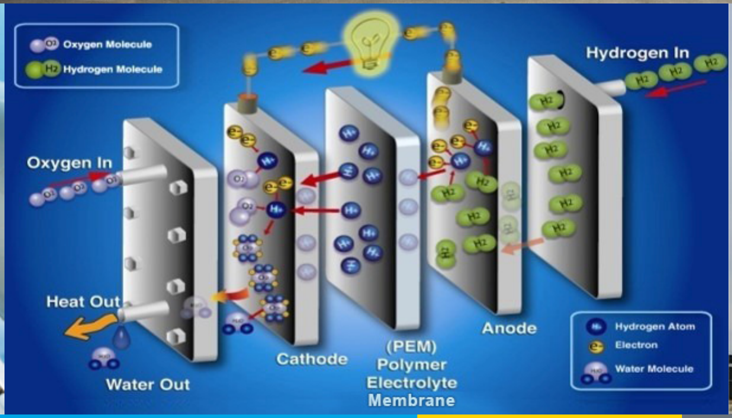
U.S. Department of Energy
Fuel Cell Technologies Office

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy



Overview of Fuel Cell Activities with a focus on AEMFC R&D

Phoenix, AZ

April 1, 2016

Dimitrios Papageorgopoulos

Program Manager, Fuel Cells

Fuel Cell Technologies Office
U.S. Department of Energy

Key Driver- Paris Agreement at COP 21

"Let that be the common purpose here in Paris. A world that is worthy of our children. A world that is marked not by conflict, but **by cooperation**; and not by human suffering, but by human progress. A world that's safer, and more prosperous, and more secure, and more free than the one that we inherited. **Let's get to work**."

- President Barack Obama at the launch of COP21

PARIS2015
UN CLIMATE CHANGE CONFERENCE
COP21·CMP11

Major Administration Energy Goals

Reduce GHG emissions by 17% by 2020, 26-28% by 2025 and 83% by 2050 from 2005 baseline Climate Action Plan

By 2035, generate 80% of electricity from a diverse set of clean energy resources Blueprint Secure Energy Future

Double energy productivity by 2030 Department of Energy

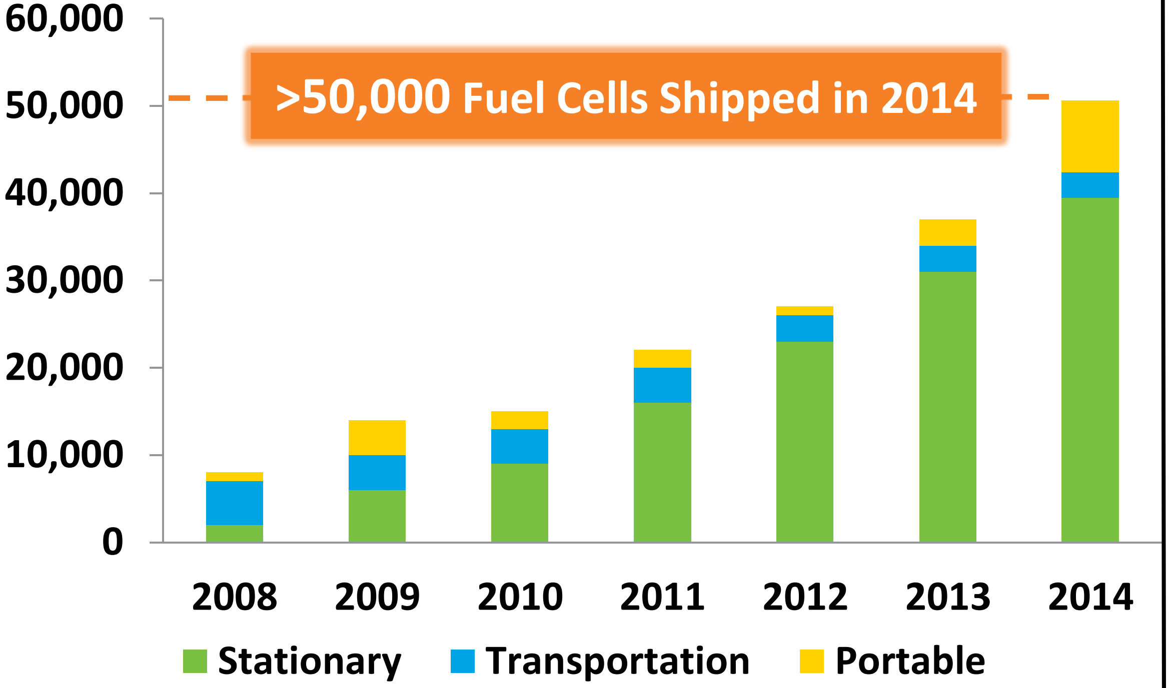
Reduce net oil imports by half by 2020 from a 2008 baseline Blueprint Secure

Reduce CO_2 emissions by **3 billion metric tons** cumulatively by 2030 through efficiency standards set between 2009 and 2016

CAP Progress Report

Fuel Cells Going Strong

Fuel Cell Systems Shipped Worldwide by Application



>50,000 Fuel Cells Shipped in 2014

Source: Navigant Research (2008-2013) & E4tech (2014)

- **Consistent ~30% annual growth since 2010**
- **Global Market Potential in 10- 20 years***

$14B – $31B/yr for stationary power
$11B /yr for portable power
$18B – $97B/yr for transportation

Fuel Cell Electric Vehicles (FCEVs) are here

Lease

Hyundai Tucson Fuel Cell SUV

Sale

Toyota Mirai Fuel Cell Vehicle

Auto Shows

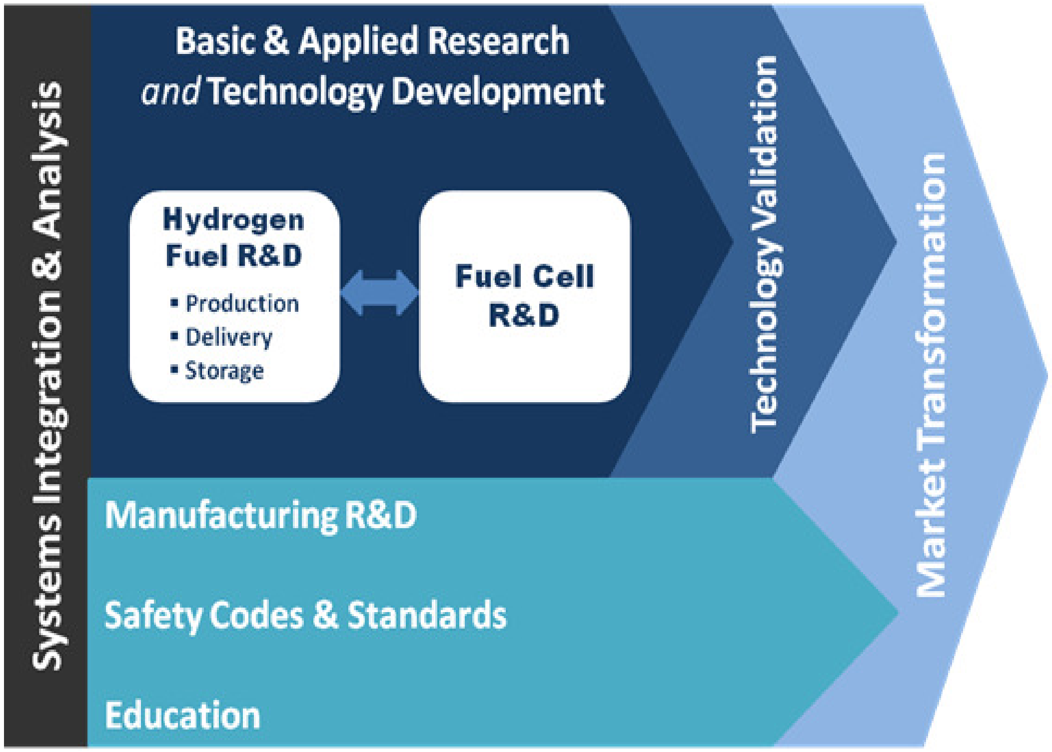
Honda Clarity Fuel Cell Vehicle

**Fuel Cell Economic Development Plan*, Connecticut Center for Advanced Technology, Inc. January 2008

DOE Hydrogen and Fuel Cells Program

Mission

To enable the ***widespread commercialization of hydrogen and fuel cell technologies***, which will reduce petroleum use, greenhouse gas (GHG) emissions, and criteria air pollutants, and will contribute to a more diverse energy supply and more efficient use of energy.



Systems Integration & Analysis

Basic & Applied Research *and* Technology Development

Hydrogen Fuel R&D
- Production
- Delivery
- Storage

Fuel Cell R&D

Technology Validation

Market Transformation

Manufacturing R&D

Safety Codes & Standards

Education

2020 Targets by Application

Fuel Cell Cost	$40/kW	$1,000/kW* $1,500/kW**
Durability	5,000 hrs	80,000 hrs
H_2 Storage Cost (On-Board)	$10/kWh 1.8 kWh/L, 1.3 kWh/kg	
H_2 Cost at Pump	<$4/gge <$7/gge (early market)	

*For Natural Gas
**For Biogas

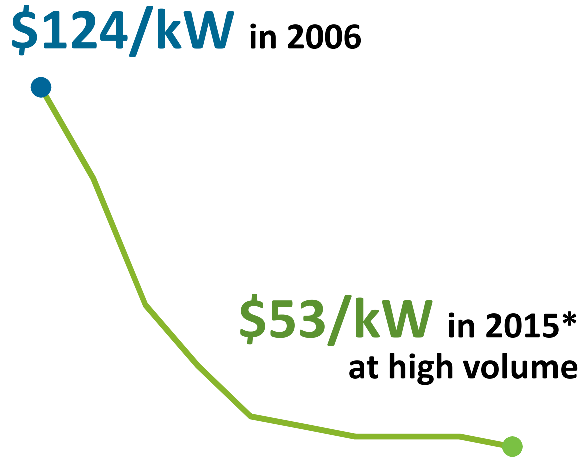
Integrated approach to widespread commercialization of H_2 and fuel cells

DOE Activities Span from R&D to Deployment

1. Research & Development

Fuel Cells

- **>50% decrease in cost since 2006**
- **5X less platinum used**
- **>4X increase in durability**



$124/kW in 2006

$53/kW in 2015* at high volume

*$280/kW low volume

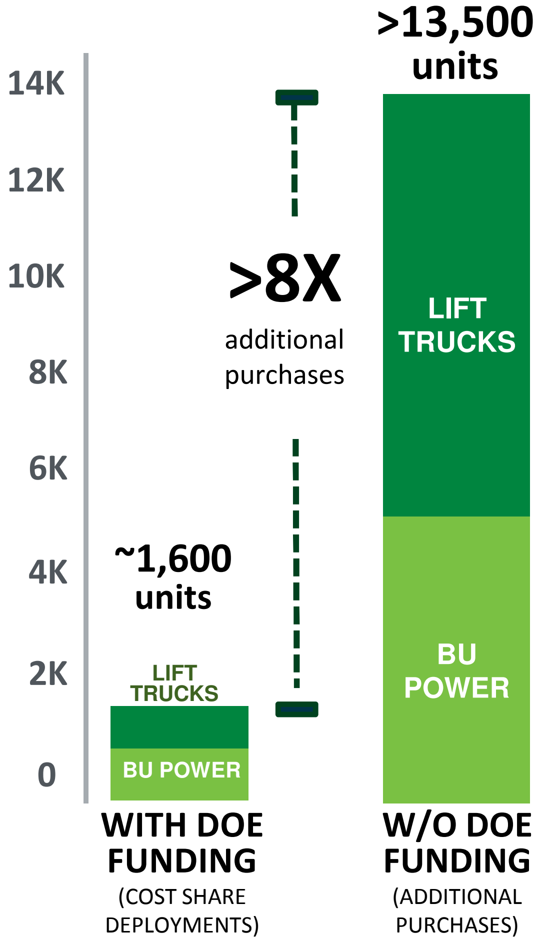
2. Demonstration

Forklifts, back-up power, airport cargo trucks, parcel delivery vans, marine APUs, buses, mobile lighting, refuse trucks

>220 FCEVs, 30 stations, 6M miles traveled

World's first tri-gen station

3. Deployment

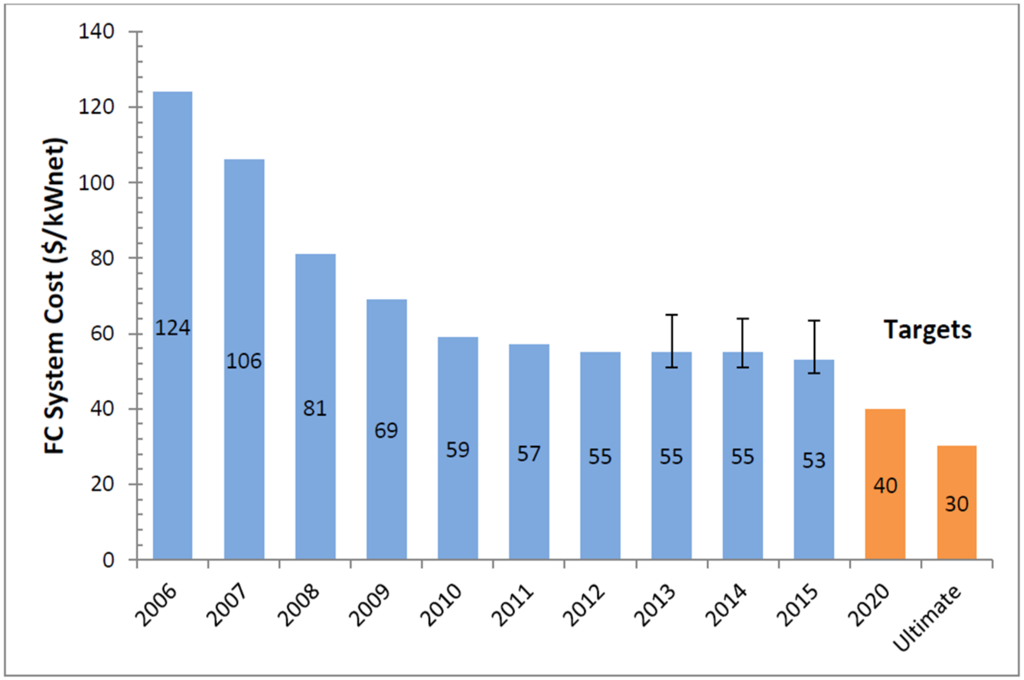


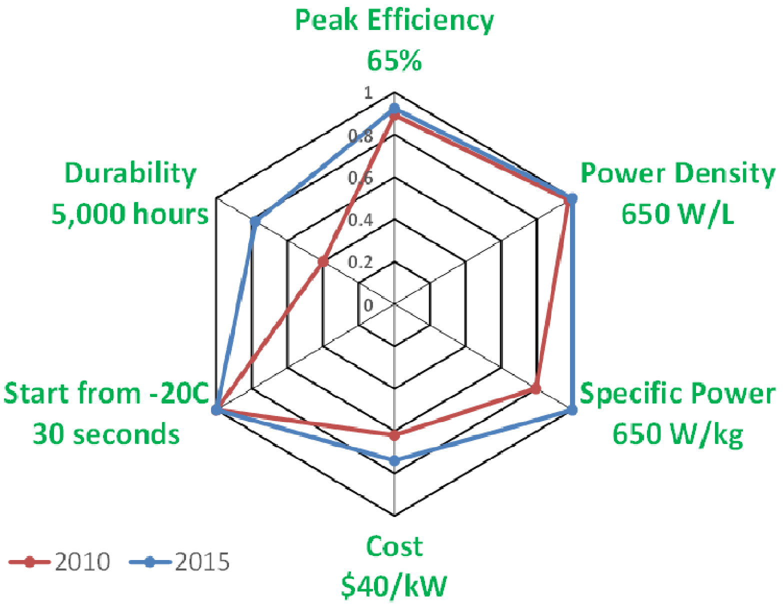
BU: Back Up Power

Fuel Cell Progress and Status

2020 Goals: 65% peak efficiency, $40/kW, 5000 hour durability

2015 Status: 60% peak efficiency, $53/kW, 3900 hour durability



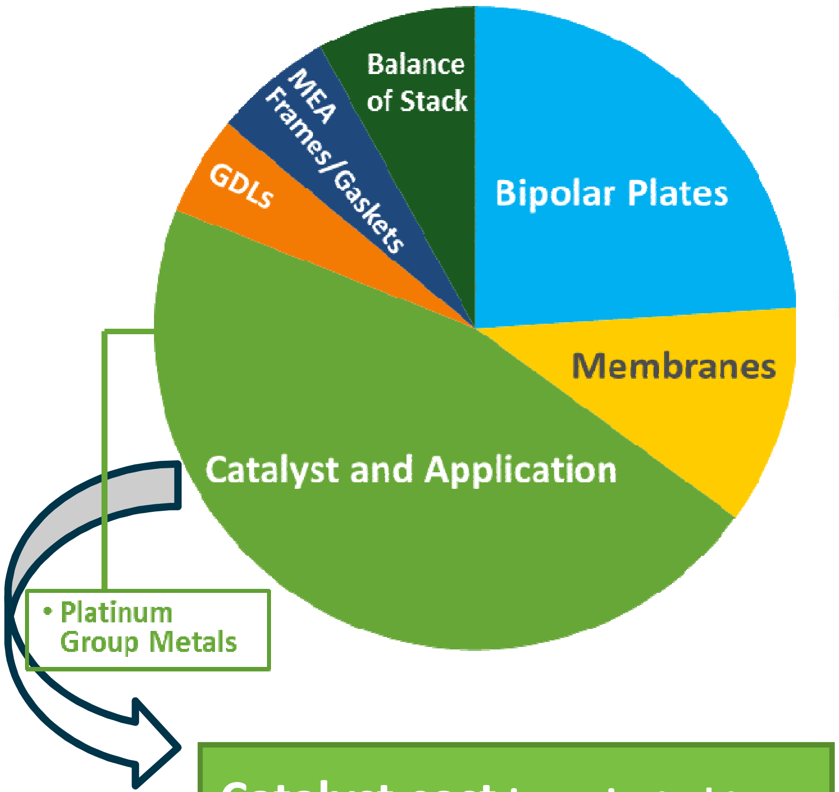


Significant progress but fuel cell cost reduction is leveling off.

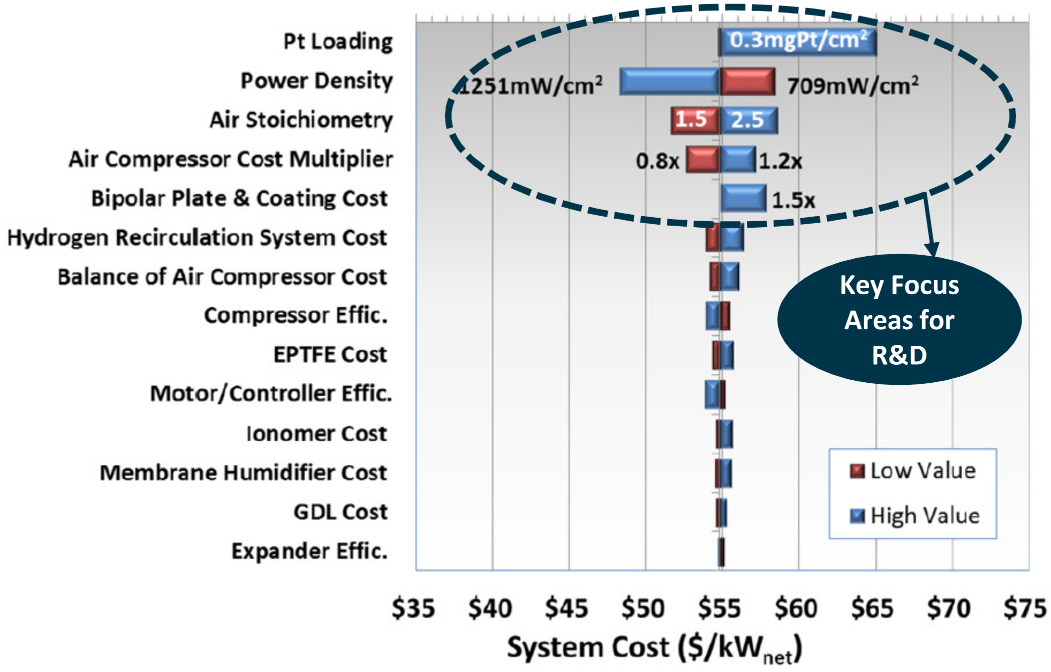
Further R&D is needed to overcome challenges - durability and cost.

Fuel Cell R&D Focus and Priorities

PEMFC Stack Cost Breakdown



Sensitivity Analysis



Catalyst cost is projected to be the largest single component of the cost of a PEMFC manufactured at high volume.

*500,000 systems/year

Strategy

- Lower PGM Content
- Pt Alloys
- Novel Support Structures
- Non-PGM catalysts

Strategic Technical Analysis Guides Focus Areas for R&D and Priorities

Technical Targets: Membrane Electrode Assemblies

Characteristic	Units	Status	2020 Targets
Cost[a]	$ / kW_{net}	17	14
Durability with cycling	Hours	2,500	5,000
Startup/shutdown durability[e]	Cycles	–	5,000
Performance @ 0.8 V	mA / cm^2	240	300
Performance @ rated power (150 kPa abs)	mW / cm^2	810	1,000
Robustness (cold operation)		1.09	0.7
Robustness (hot operation)		0.87	0.7
Robustness (cold transient)		0.84	0.7

**** Preliminary***

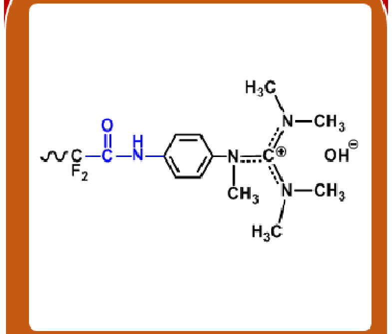
Updated technical targets to be released in 2016

AEMFC Milestones (Preliminary)

- **Q2, 2017:** Develop anion-exchange membranes with an area specific resistance ≤ 0.1 ohm cm^2, maintained for 500 hours during testing at 600 mA/cm^2 at $T > 60$ °C.
- **Q4, 2017:** Demonstrate alkaline membrane fuel cell peak power performance > 600 mW/cm^2 on H_2/O_2 (maximum pressure of 1.5 atma) in MEA with a total loading of ≤ 0.125 mg_{PGM}/cm^2 .
- **Q2, 2019:** Demonstrate alkaline membrane fuel cell initial performance of 0.6 V at 600 mA/cm^2 on H_2/air (maximum pressure of 1.5 atma) in MEA a total loading of < 0.1 mg_{PGM}/cm^2 , and less than 10% voltage degradation over 2,000 hour hold test at 600 mA/cm^2 at $T > 60$ °C. Cell may be reconditioned during test to remove recoverable performance losses.
- **Q2, 2020:** Develop non-PGM catalysts demonstrating alkaline membrane fuel cell peak power performance > 600 mW/cm^2 under hydrogen/air (maximum pressure of 1.5 atma) in PGM-free MEA .

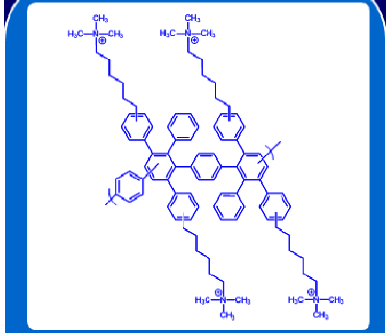
AEM Development of LANL-Led AMFC Project

Perfluorinated AEM



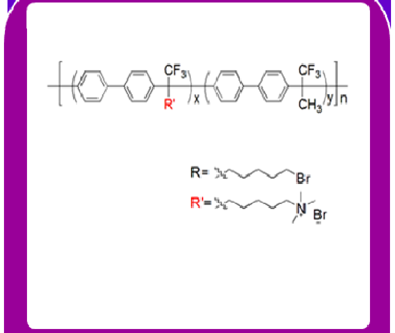
- **Perfluorinated AEM**
- **Guanidinium functionalized stable PF anion exchange polymer**
- **Strength**
  Low water uptake
  Excellent hydrophobicity ideal for ionomeric binder
- **Research focus**
  Amide
  hydrolytic stability

Diels-Alder Poly(phenylene)



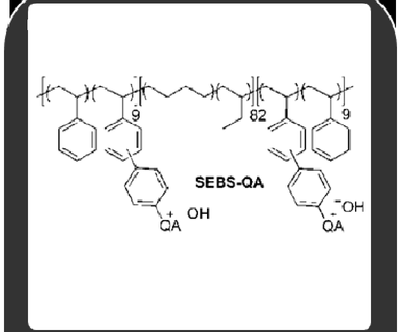
- **Hexamethyl ammonium functionalized poly(phenylene) AEM**
- **Strength**
  Improved cation stability
  Better gas permeability
- **Research focus**
  Incorporation with resonance stabilized cationic functional group

Ether-Free Poly(phenylene)



- **Acid-catalyzed, high molecular weight (Mw: > 100 kg/mol), solution processible AEM.**
- **Strength**
  Improved mechanical properties
  Exceptional alkaline stability
- **Research focus**
  water uptake control and solvent resistance

Flexible SEBS AEM



- **Highly conductive and stable polymers prepared from C-H borylation and coupling reactions**
- **Strength**
  High conductivity
  Good polymer stability
  High elongation (> 300%)
- **Research focus**
  AEM Processibility and water uptake control

Summary of Stability

AEM	Test conditions	IEC loss (%)
Perfluorinated	0.5M NaOH, 80°C, 3 days	8
Diels-Alder PP	4M KOH, 90°C, 14 days	0
Ether-free PP	1M NaOH, 80°C, 30 days	0
SEBS	1M NaOH, 80°C, 28 days	3

Perfluorinated AEM: Kim et al. Macromolecules 46. 7826 (2013)

Diels-alder poly(phenylene): Hibbs, J. Polym. Sci. Part B, 51, 1736, (2013)

Ether-free poly(phenylene): Lee et al. ACS Macro Letters, 4, 814 (2015)

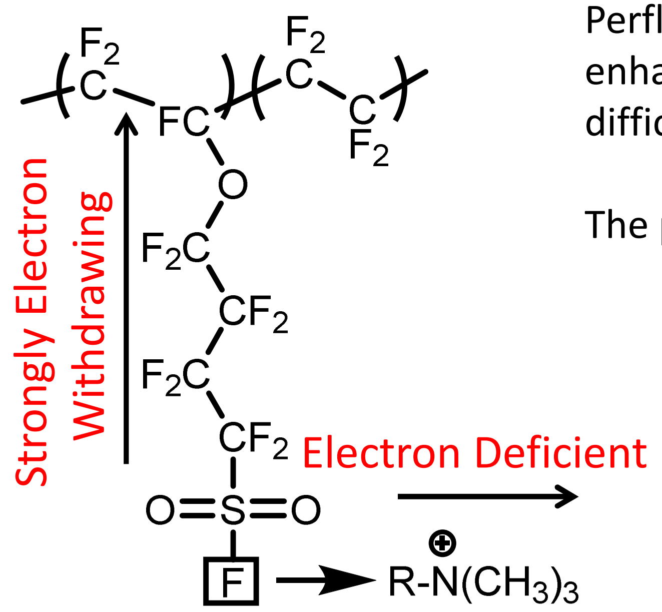
SEBS-QA: Mohanty et al. Macromolecules, 48, 7085 (2015)

Los Alamos
NATIONAL LABORATORY

Sandia National Laboratories

Rensselaer

Perfluoro AEM Development of NREL-Led AMFC Project

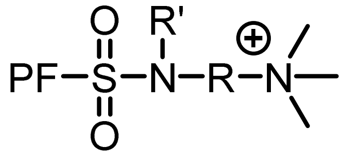


Perfluoro (PF) polymer electrolytes exhibit chemical robustness, enhanced water transport and conductivity properties, but have difficulties in coupling cations with electron withdrawing polymers.

The project team is:

1. Developing Novel Chemistries
2. Characterizing AEMs for properties and durability
3. Developing and applying novel diagnostics and computational models to elucidate AMFC performance/losses.

1. Novel Chemistry

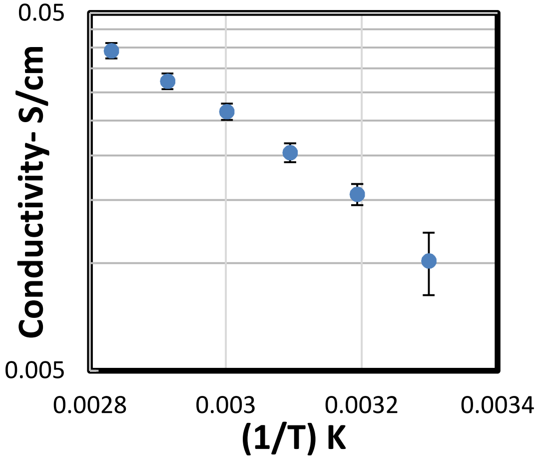


Project Partners:

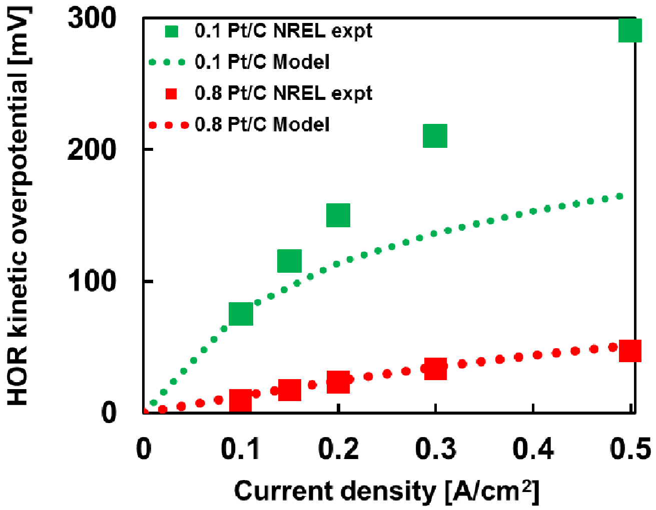
LBNL
ORNL/Univ. of Tennessee
Colorado School of Mines
3M

2. AEM Characterization

Cl^- Conductivity at 95%RH



3. HOR exchange current density model vs data



Other AEMFC Related Projects

Advanced Catalysts and MEAs for Reversible Alkaline Membrane Fuel Cells

Giner, Inc. with University of Buffalo-SUNY and NREL

Develop innovative non-PGM bifunctional catalysts for alkaline membrane reversible fuel cells for hydrogen energy storage.

Development of non-PGM Catalysts for Hydrogen Oxidation Reaction in Alkaline Media

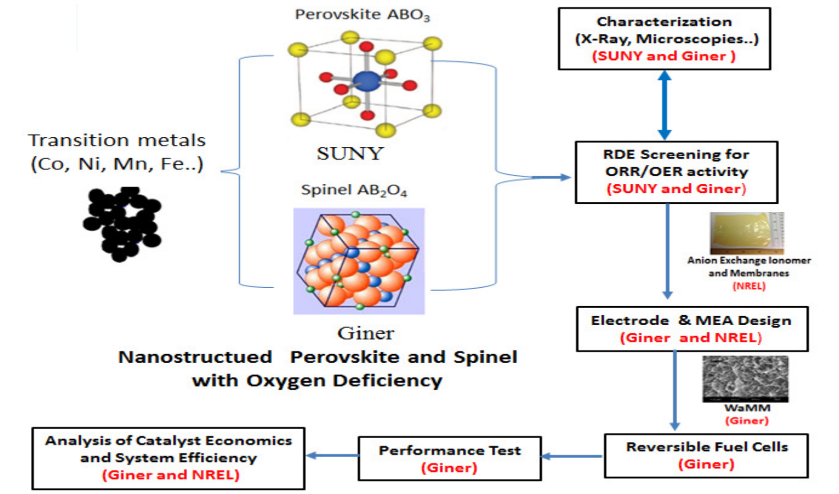
University of New Mexico with IRD Fuel Cells, Pajarito Powder, and LANL

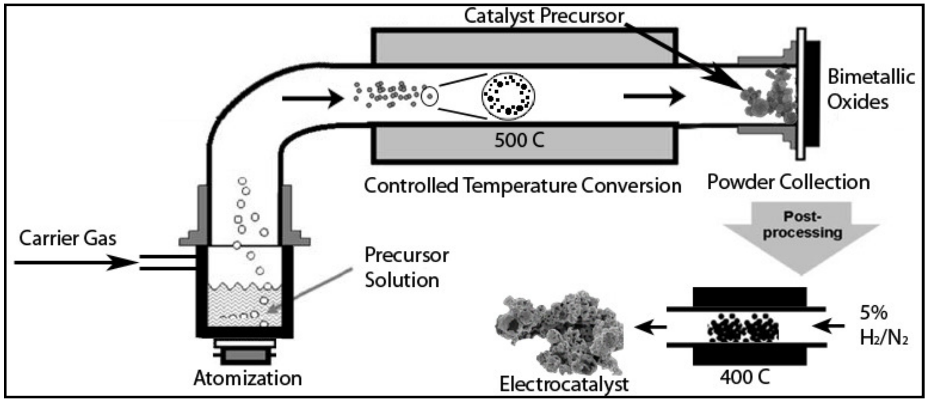
Develop Non-PGM Catalysts for HOR in AMFC and integrate with LANL ionomer technology into catalyst layer in an MEA.

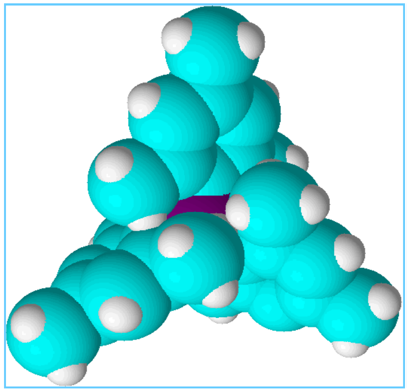
Highly Stable Anion-Exchange Membranes for High-Voltage Redox-Flow Batteries

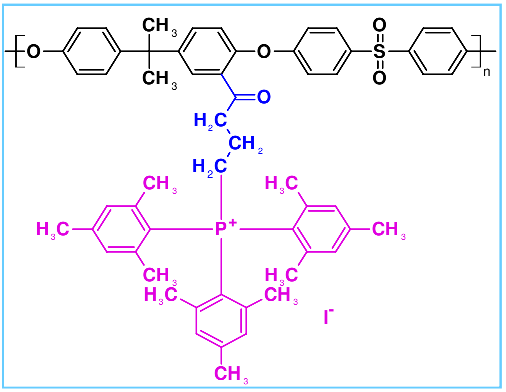
University of Delaware with NREL

Develop sterically protected cation for stable alkaline membranes for energy storage and power generation applications.









AEM Electrolysis Projects

High Performance Platinum Group Metal Free Membrane Electrode Assemblies Through Control of Interfacial Processes

Proton OnSite with Northeastern University, Penn State, and University of New Mexico

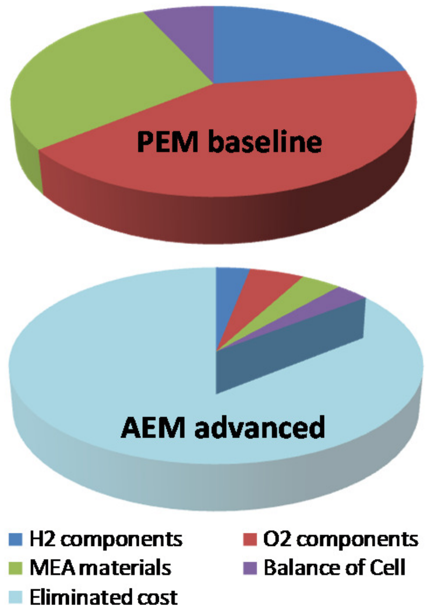
Development and scale-up of PGM-free AEM electrolysis cells to enable up to 75% reduction in stack capital cost compared to PEM electrolysis

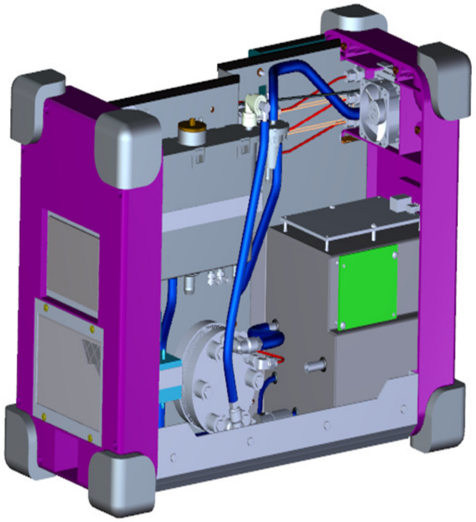
Economical Production of Hydrogen Through Development of Novel, High Efficiency Electrocatalysts for Alkaline Membrane Electrolysis (SBIR)

Proton OnSite with Illinois Institute of Technology, Georgia Tech, and Pajarito Powder

Work toward commercializing the first alkaline membrane-based water electrolysis product through the use of high efficiency, low pgm electrocatalysts and other advanced, low cost materials as well as system development.

Cost Comparison of PEM and AEM electrolyzer stacks





ElectroCat (Electrocatalysis Consortium)

Goal

Accelerate the deployment of fuel cell systems by **eliminating the use of PGM catalysts**

Mission

Develop and implement PGM-free catalysts by:

- **streamlining access** to unique synthesis and characterization tools across national labs
- **developing missing strategic capabilities**
- **curating a public database** of information

Partners

Argonne NATIONAL LABORATORY

High-throughput materials discovery, characterization, and testing

Los Alamos NATIONAL LABORATORY

Design and synthesis of PGM-free catalysts and electrodes

www.electrocat.org

The Bigger Picture

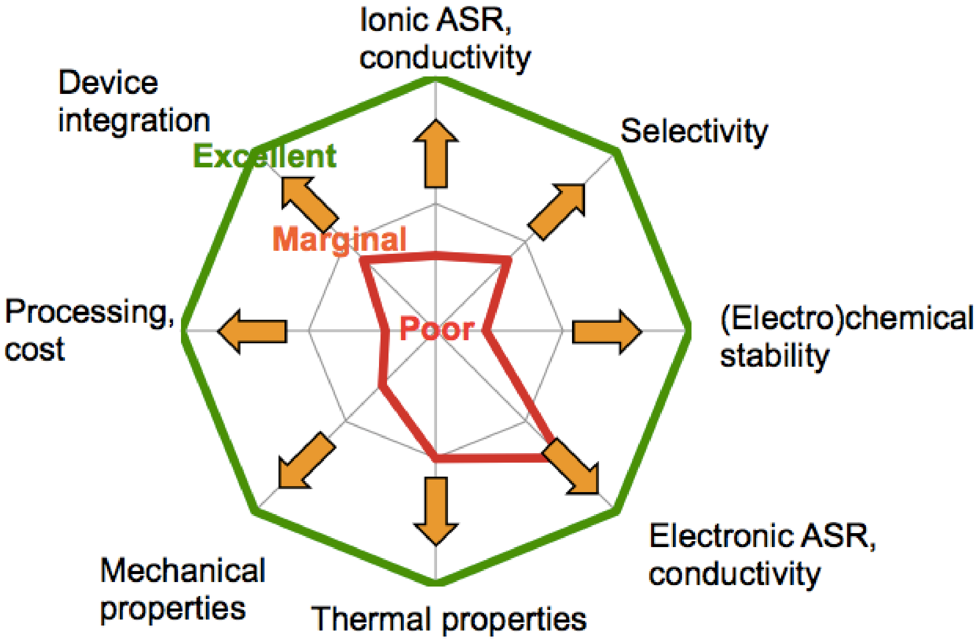
ElectroCat Electrocatalysis Consortium

Part of

Energy Materials Network U.S. Department of Energy

IONICS* objectives and categories

ARPA-E believes tremendous opportunities exist in developing a new generation of enabling **components** built with solid ion conductors.



FOA Categories

1. Li ion conductors that enable the cycling of Li metal without shorting
2. Selective and low-cost separators for batteries with liquid reactants (*e.g.*, flow batteries)
3. Alkaline conductors with high chemical stability and conductivity
4. Other approaches that could achieve the IONICS Program Objectives.

*Integration and Optimization of Novel Ion Conducting Solids

IONICS FOA Sect. I.B.1 (Summary), pg. 4; Sect. I.B.2 (Program Context and Background), pg. 5; 1.C (Program Objectives), pg. 10.

Thank You

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