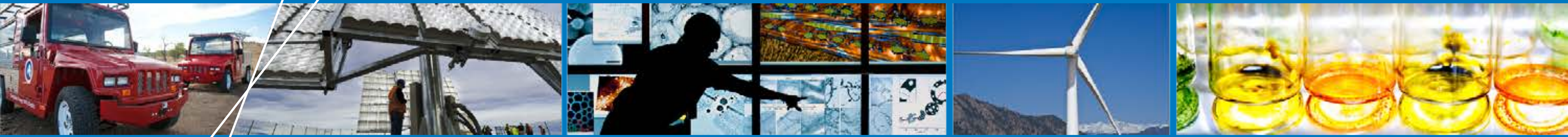
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Overview of the National Renewable Energy Laboratory



HTAC Meeting

Tuesday, October 29, 2013

Presentation by: Dana Christensen,

Deputy Laboratory Director, Science & Technology

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Laboratory Snapshot

Dedicated Solely to Advancing Energy Efficiency and Renewable Energy

- Physical Assets Owned by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
- Operated by the Alliance for Sustainable Energy under Contract to DOE
- 2400 staff and world-class facilities
- More than 350 active partnerships annually
- Campus is a living model of sustainable energy

Scope of Mission

Energy Efficiency

- Residential Buildings
- Commercial Buildings
- Personal and Commercial Vehicles

Renewable Energy

- Solar
- Wind and Water
- Biomass
- Hydrogen
- Geothermal

Systems Integration

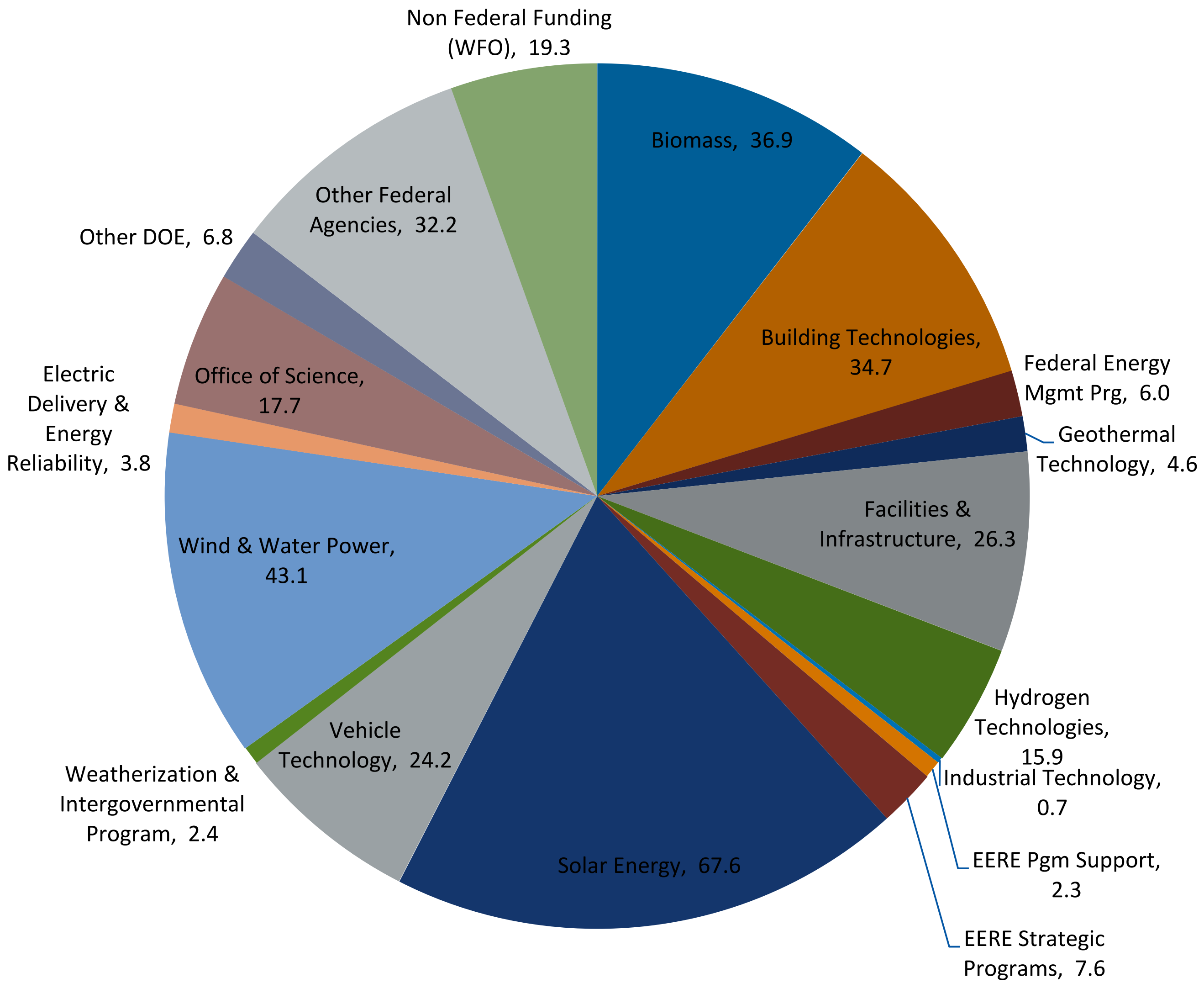
- Grid Infrastructure
- Distributed Energy Interconnection
- Battery and Thermal Storage
- Transportation

Market Relevance

- Industry
- Federal Agencies
- State and Local Governments
- International

NREL FY2012 Program Funding by Source

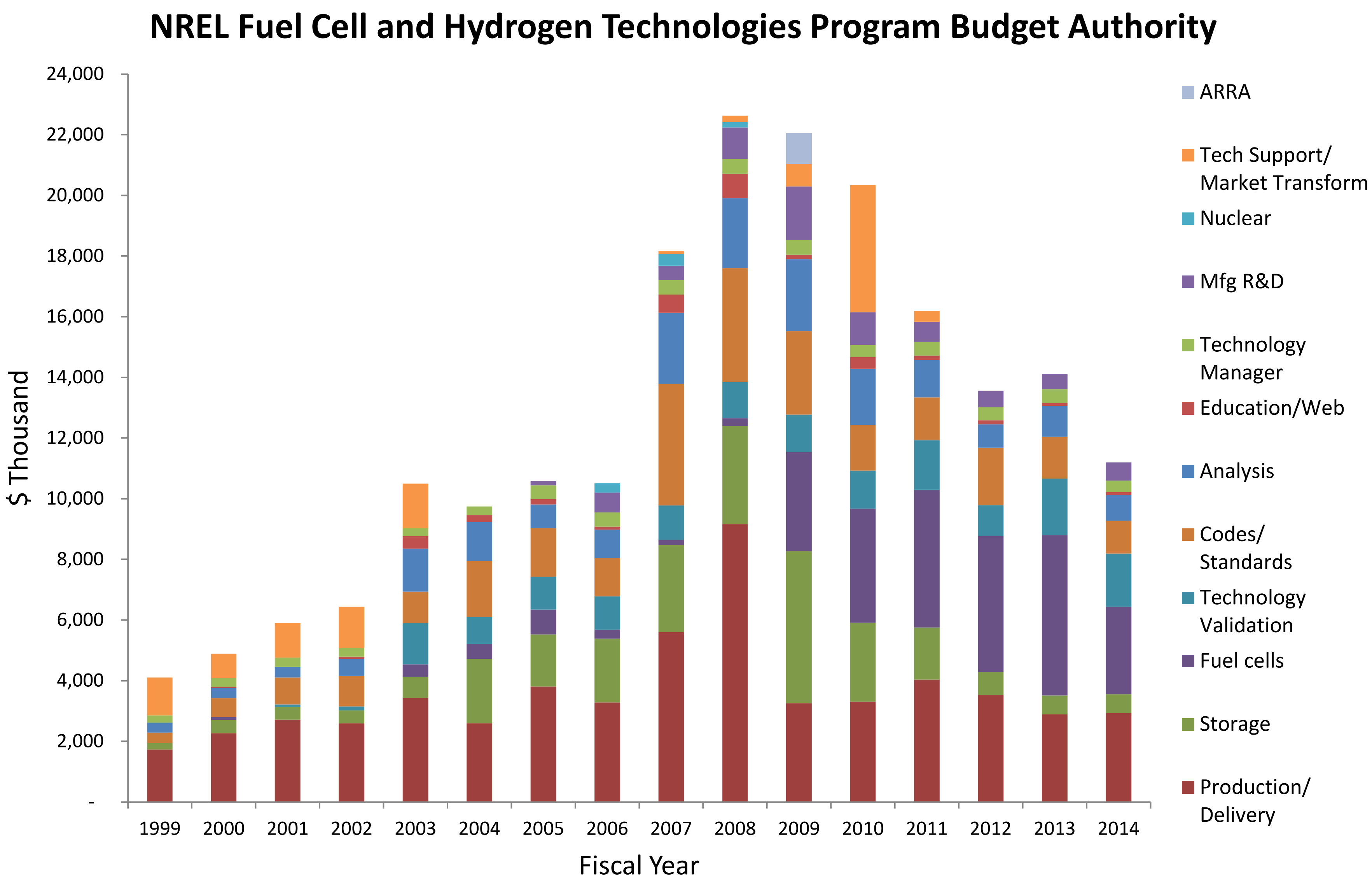
$352M



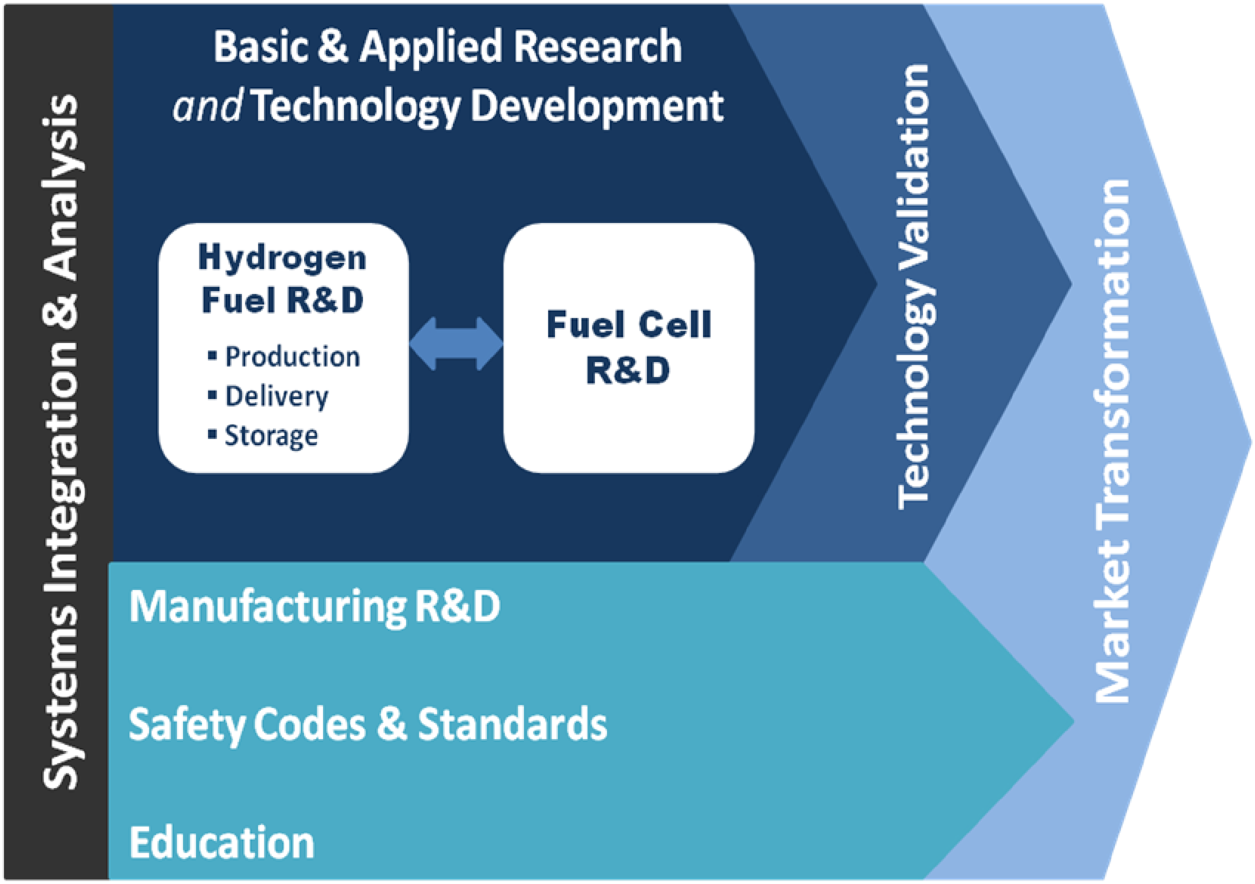
NREL FCHT Program Objectives

- Maintain a robust **portfolio of technology development activity** in hydrogen production, hydrogen delivery, hydrogen storage, and fuel cells that **grows out of advances in scientific underpinnings and is informed by rigorous analysis**
- Enable more rapid penetration of fuel cell and hydrogen technologies into the marketplace by **partnering with industry** in evaluating and optimizing integrated energy systems and in helping to overcome barriers in codes and standards
- **Provide analysis** to DOE to guide its portfolio selection, to NREL to guide our RD&D, and to the energy analysis and investment communities to convey the role of fuel cells and hydrogen in the national energy sector.

NREL FCHT Program Budget



Fuel Cell Technologies Office Structure



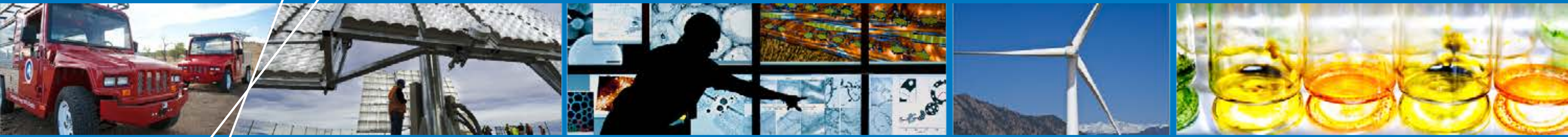
WIDESPREAD COMMERCIALIZATION ACROSS ALL SECTORS

- Transportation
- Stationary Power
- Auxiliary Power
- Backup Power
- Portable Power

NREL Fuel Cell & Hydrogen Technologies Program

- **Hydrogen production and delivery**
- **Hydrogen storage**
- **Fuel cells**
- **Fuel cell manufacturing R&D**
- **Technology validation**
- **Market transformation**
- **Safety, codes and standards**
- **Systems analysis**

NREL Fuel Cell and Hydrogen Technologies Program Overview



HTAC Meeting

October 29, 2013

Keith Wipke

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Hydrogen Production and Delivery

Photoelectrochemical (PEC) water splitting

Photobiological water splitting

Fermentation

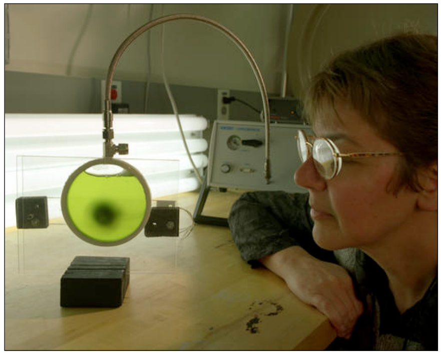
Conversion of biomass and wastes

Solar thermochemical water splitting

Renewable electrolysis

Dispenser hose reliability testing

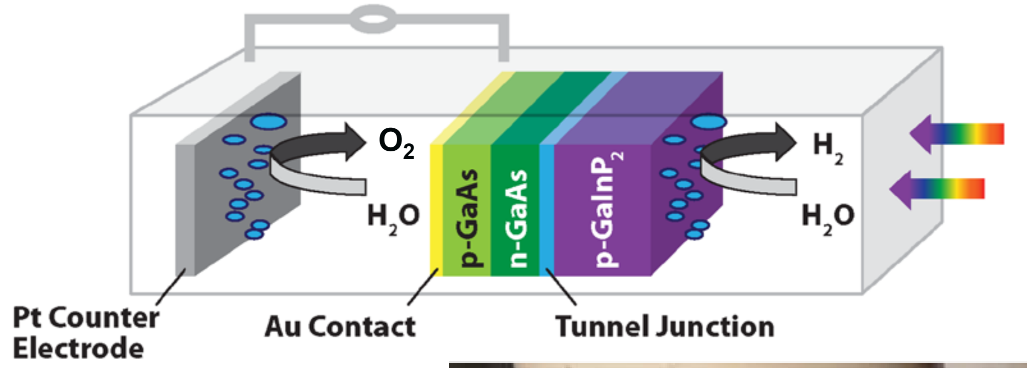
Pathway analysis



Research Highlight: Photelectrolysis

Unique approach utilizes state-of-the-art III-V semiconductor materials

- **Highest efficiency**
  - Only demonstrated system that exceeds unbiased 10% solar-to-hydrogen
    - 12.4% with Pt-black counter electrode,
    - over 16% with RuO_2 CE at moderate bias
  - Metal organic chemical vapor deposition (MOCVD) synthesis
    - Synthesis by NREL's III-V team
- **Current focus—mitigate photocorrosion**
  - Developed surface treatment that passivates the surface under high photocurrent conditions (provisional patent filed)
  - Investigating $In_xGa_{1-x}N$, an emerging III-V system that could have high native stability and efficiency
- **Addressing high synthesis costs of III-V's**
  - Working with NREL analysts and synthesis groups to model achievable cost reductions from innovative synthesis routes
    - Spalling and epitaxial lift-off can meet targets

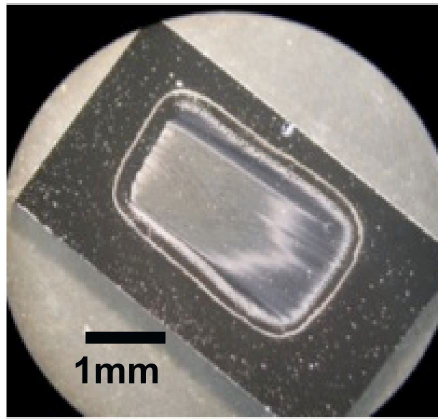


Photoelectrolysis Accomplishment

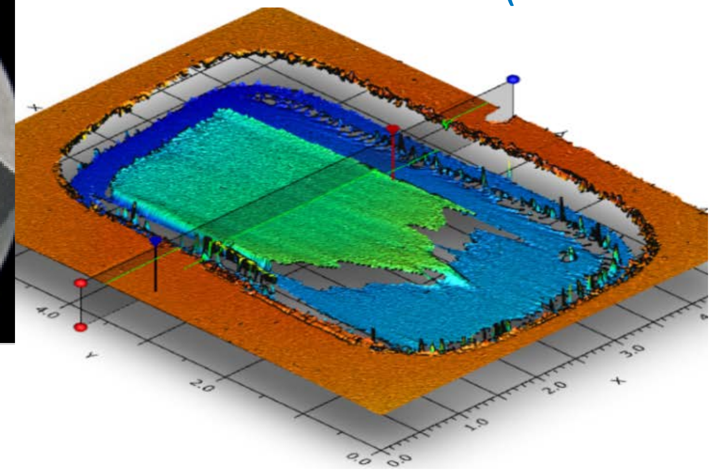
Breakthrough in surface protection of a III-V during extended operation

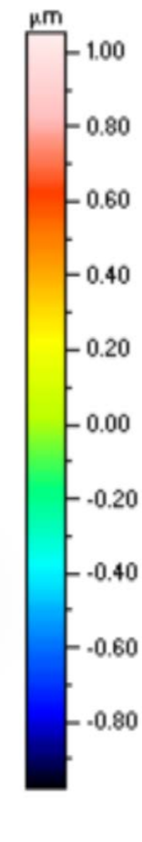
Control (untreated p-$GaInP_2$ epilayer) etched significantly (~1 µm)

- Constant current ($-10 mA/cm^2$) for 24 hours in 3M H_2SO_4



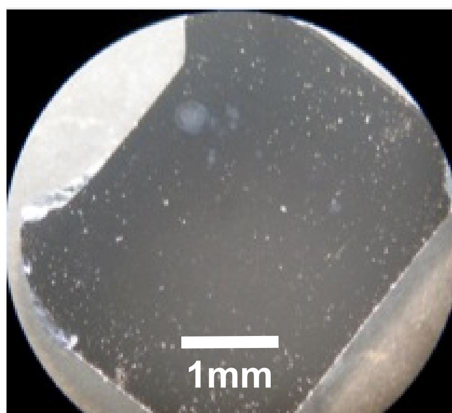
Control (no treatment)

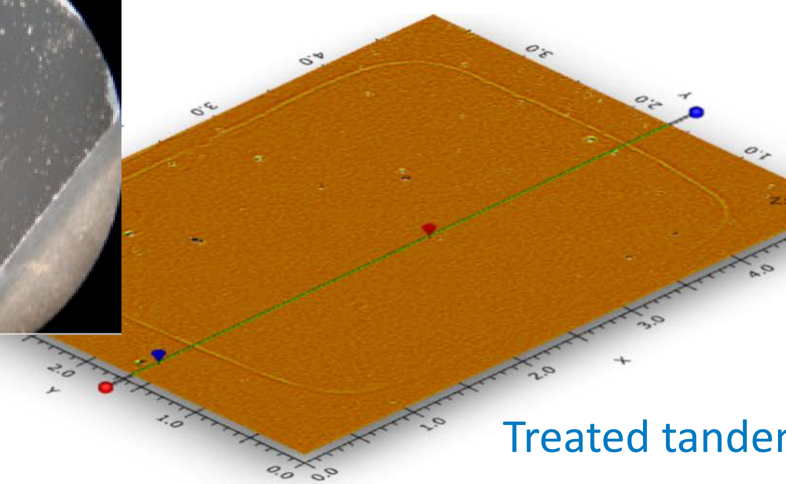




Tandem electrode (p-$GaInP_2$ on p/n-GaAs) had no detectable etching after 24 hours at about twice the current density

- Constant voltage (-1V vs Pt CE)
- Average ~ $-18.5mA/cm^2$
  - Equivalent flux of 23% efficiency
- Important step toward future ultra-high efficiency devices





Treated tandem

Research Highlight: Photobiological H_2

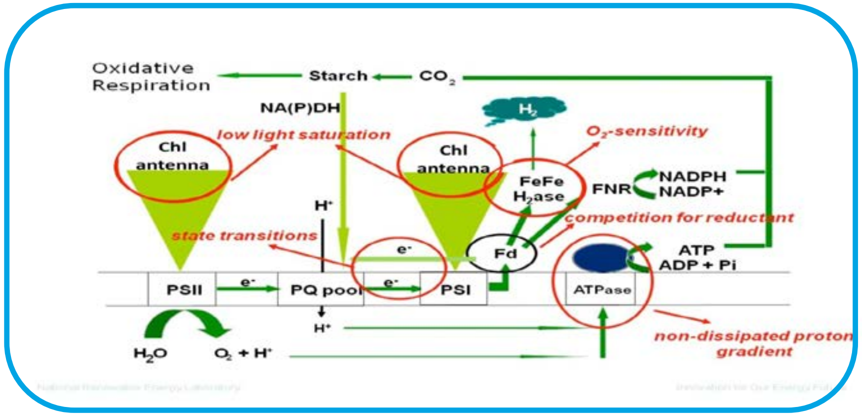
NREL develops photobiological systems for large-scale, low cost and efficient H_2 production from water

Objectives:

- Address the O_2 sensitivity of hydrogenases that prevents continuity of H_2 photoproduction under aerobic, high solar-to-hydrogen (STH) conversion efficiency conditions
- Start to genetically combine other traits that address competition for photosynthetic reductant, non-dissipation of the proton gradient, and low light-saturation of H_2 photoproduction.

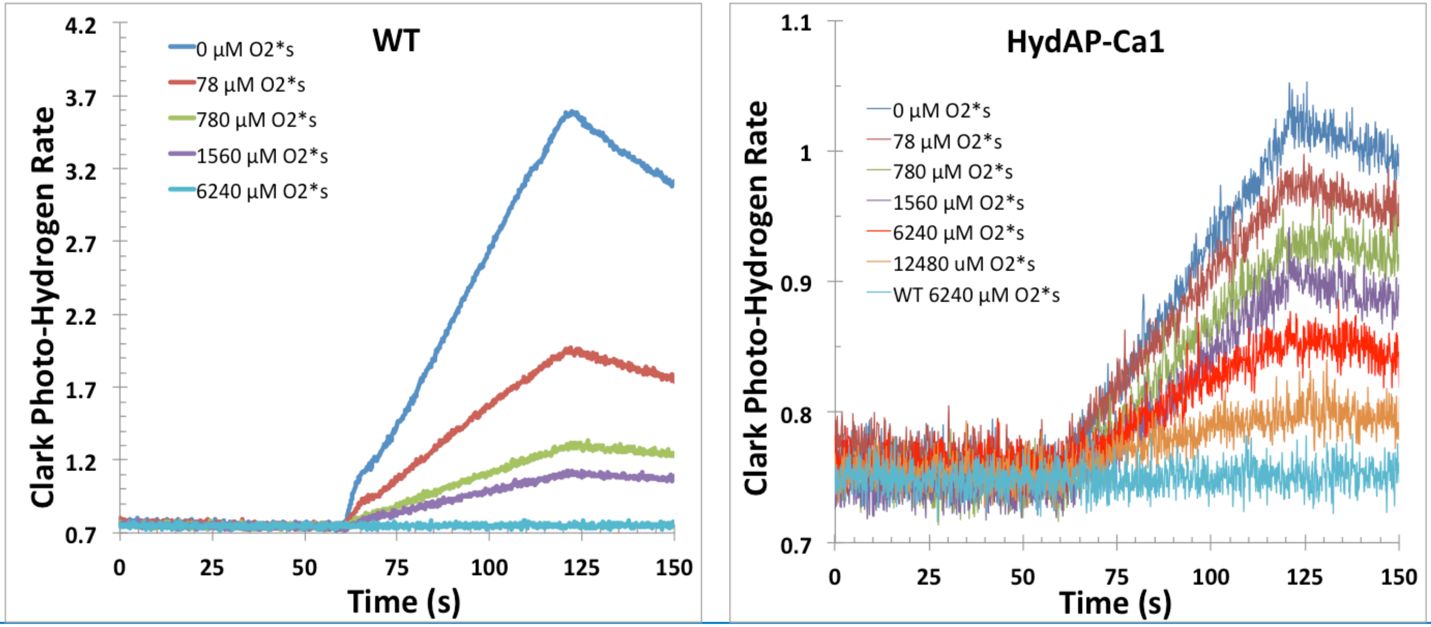
Approach:

- Introduce the gene encoding for a more O_2-tolerant hydrogenase from *Clostridium acetobutylicum in vitro* into the photosynthetic alga *Chlamydomonas reinhardtii*
- Measure its linkage to water oxidation and *in vivo* O_2 tolerance.



Photobiological H_2 Accomplishment

NREL generated strains of Chlamydomonas containing the clostridial hydrogenase Ca1 gene; these strains, including HydAP-Ca1 (see below) photoproduce H_2 in the presence of higher O_2 concentrations than the untransformed strain (WT).

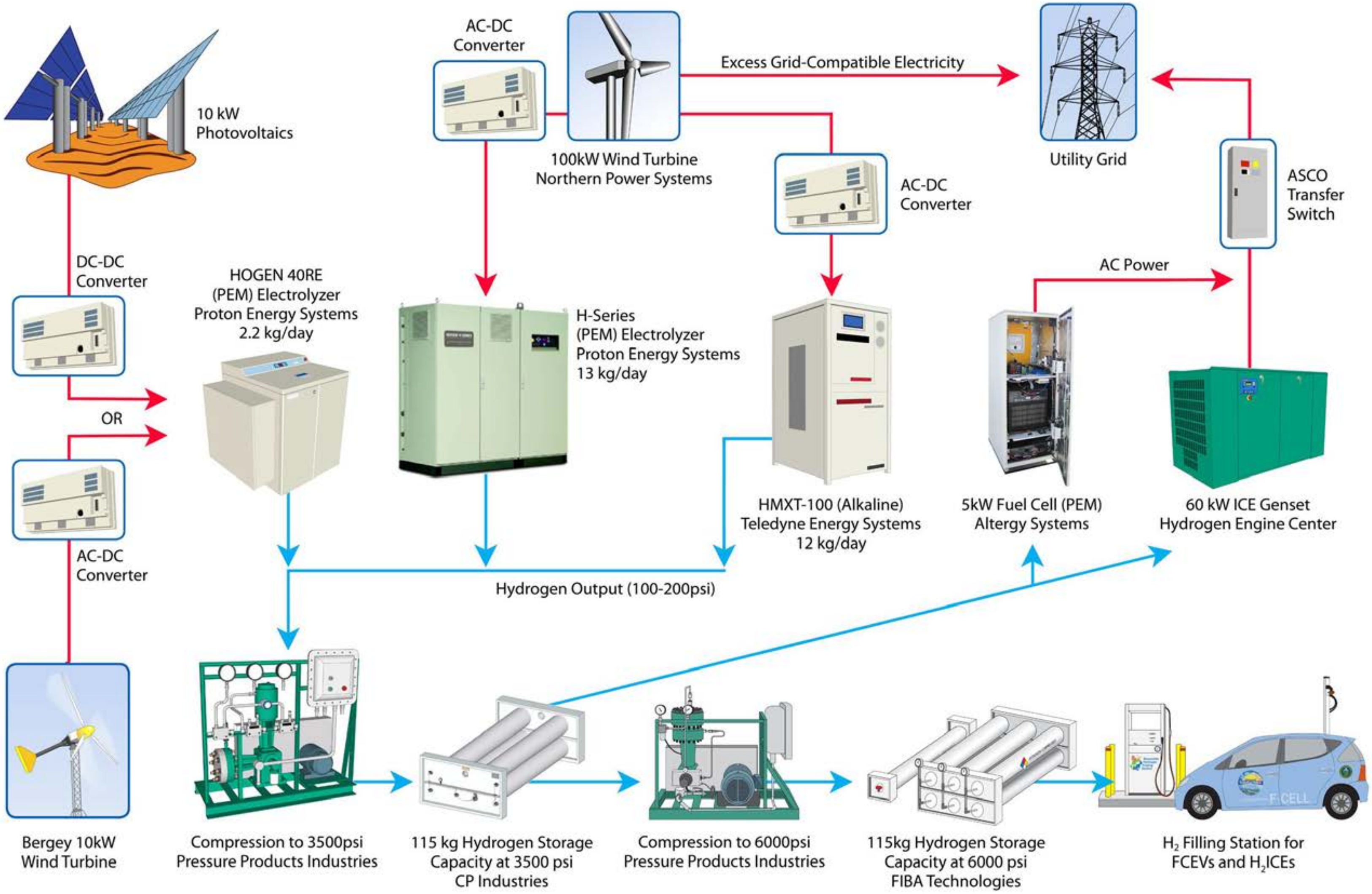


Light-induced H_2 photoproduction by WT and the Ca1 transformant was measured with a Clark electrode, following a 1-min dark incubation in the presence of different amounts of added O_2. Relative rates are shown above.

Equivalent to exposure to atmospheric O_2 concentration = 15,600 µM O_2•s

O_2-tolerance of Ca1 in Chlamydomonas was 5–19-fold higher than that of the native hydrogenase in WT.

Research Highlight: Wind-to-Hydrogen at NREL



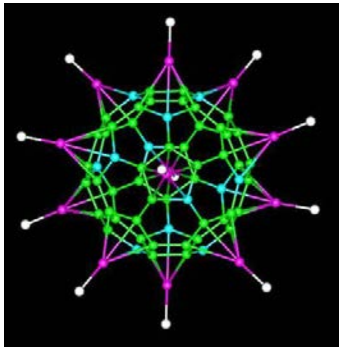
Hydrogen Storage

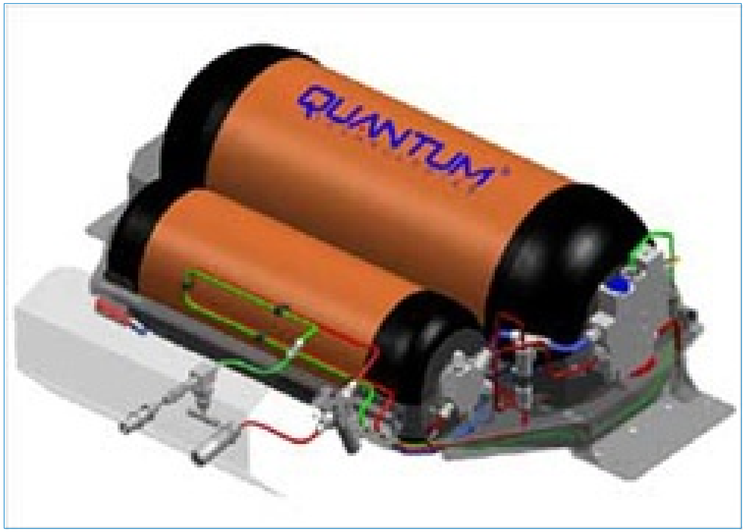
Materials testing and characterization

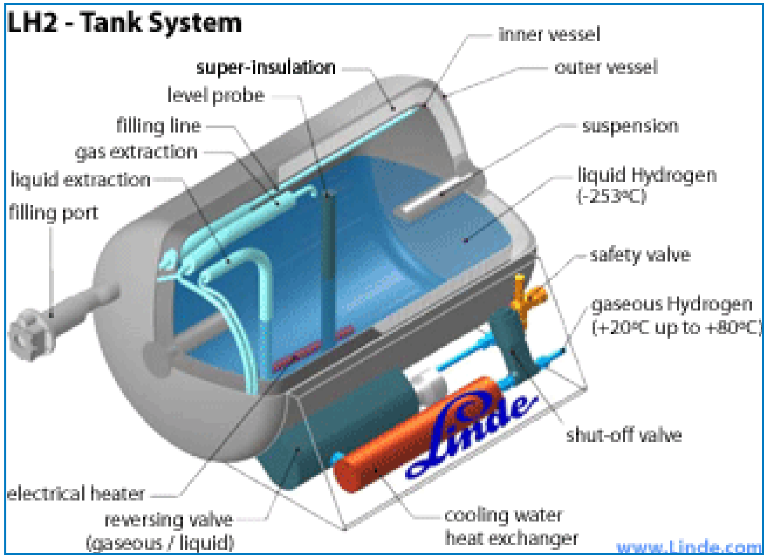
Validation of hydrogen storage measurements

Development of advanced materials

Storage system design, analysis, and modeling







Fuel Cells R&D

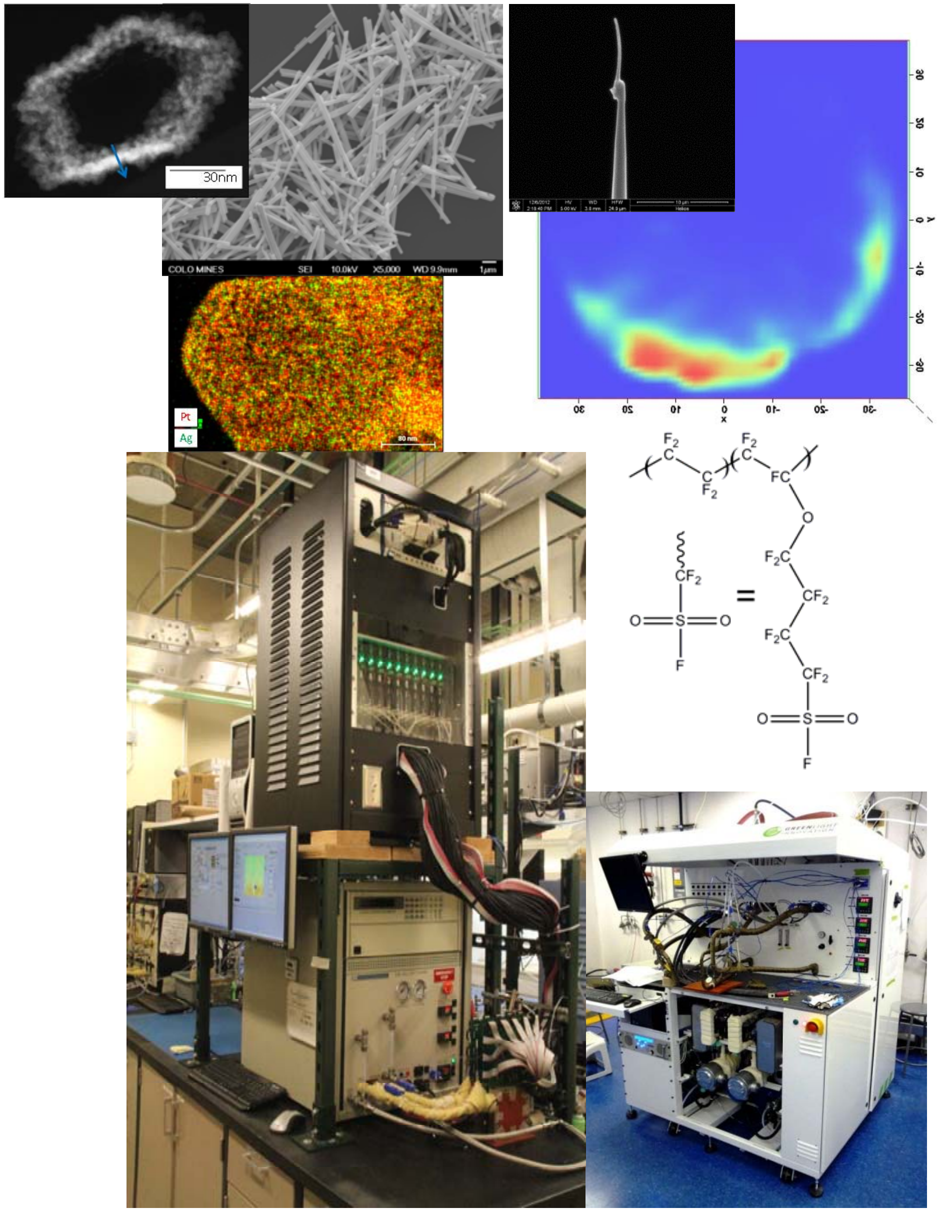
Focused on improving the cost, performance, and durability of fuel cells

Types of fuel cells

- Polymer electrolyte (PEMFCs)
- Alkaline membrane (AMFCs)
- Direct methanol (DMFCs)

Focus areas

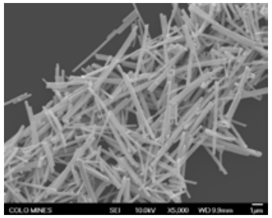
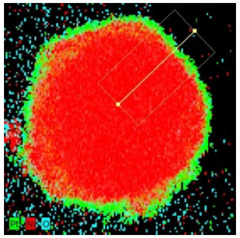
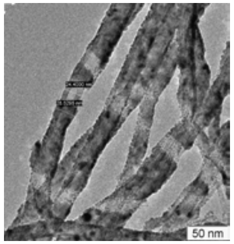
- Catalysts
- Polymer electrolytes
- Electrodes
- Effects of contaminants
- Bipolar plates

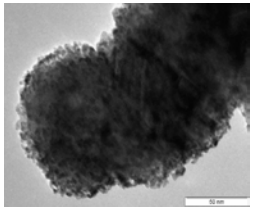


Fuel Cells R&D—Catalysis

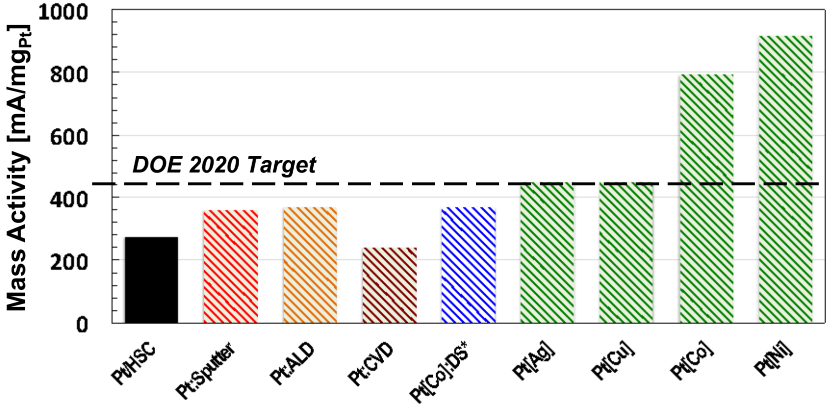
Catalysis remains a primary concern for fuel cell cost, performance, and durability. NREL's R&D efforts are highly focused on advanced electrocatalysis and novel synthesis.

Extended Surface Catalysts

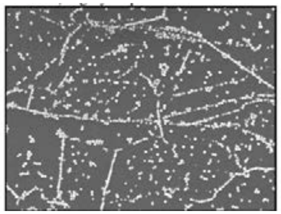
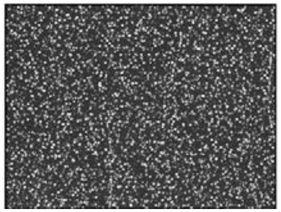






Novel, extended surface catalysts have shown improved catalytic performance and durability compared to standard Pt/C materials.

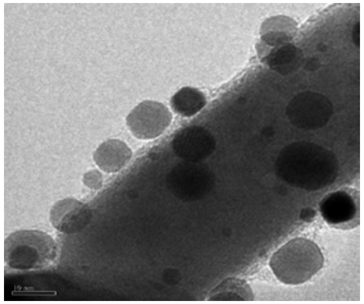


Modified Carbon Supports

Improved performance and durability demonstrated through N-doping of carbon supports.

Non-Carbon Supports



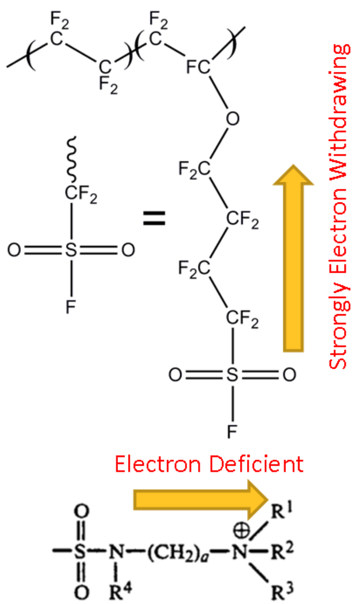
Pt on WO_3 Nanorods

Investigation of improved corrosion resistant support materials for catalyst dispersion.

Fuel Cells R&D—Polymer Electrolytes

NREL's R&D is highly focused on alkaline membranes as a next generation technology that enables non-precious metal catalysis.

Perfluorinated Alkaline Membranes

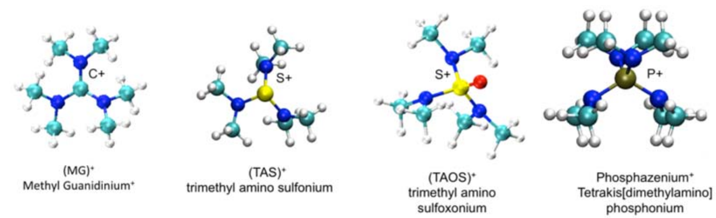


Developing novel chemistries to enable higher temperature and higher current density operation of AMFCs.

High Temperature Membranes

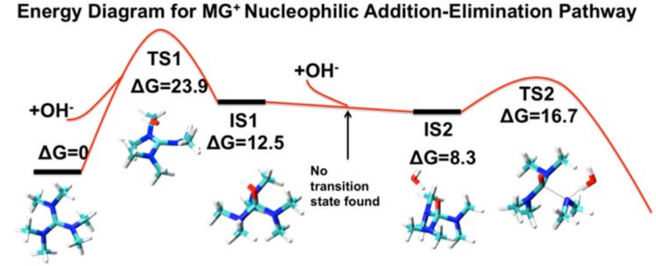
Exploring traditional PEM membranes with tethered heteropolyacid (HPA) functionality to allow higher temperature, lower humidity operation.

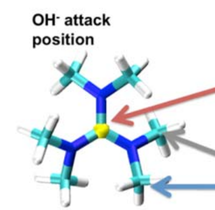
Covalently Tetherable Cations



Investigating cations for stability under highly basic conditions for incorporation into membranes.

Energy Diagram for MG+ Nucleophilic Addition-Elimination Pathway



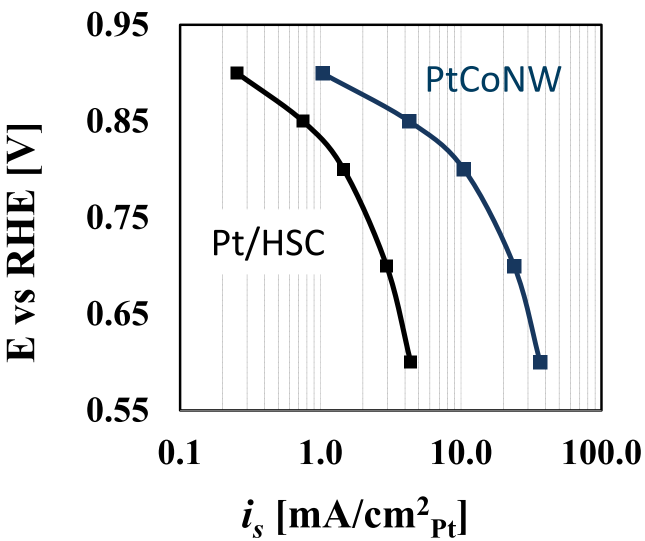


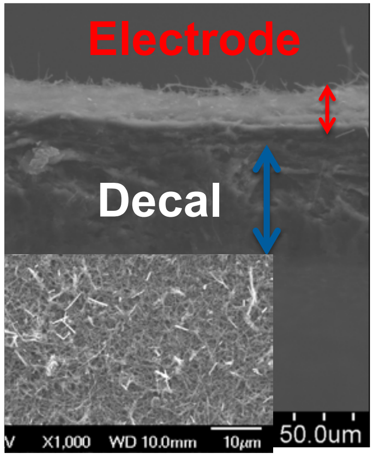
Cations		MG+	TAS+	TAOS+	Phosphazenium+
Central Atom		C	S	S=O	P
Nucleophilic Addition-Elimination Pathway	TS1	23.9	NA	29.7	32.7
	IS1	12.5	NA	27.3	24.5
	IS2	8.3	NA	-1.0	28.5
	TS2	16.7	NA	1.0	37.0
S_N2 Pathway		38.2	33.3	27.7	40.1
Ylide Pathway		NA	21.2	17.6	NA

Fuel Cells R&D—Electrodes/Contaminants

Advanced electrode design and high current density operation are additional areas of focus that crosscut catalyst and polymer electrolyte development. The impact of contaminants is also being studied.

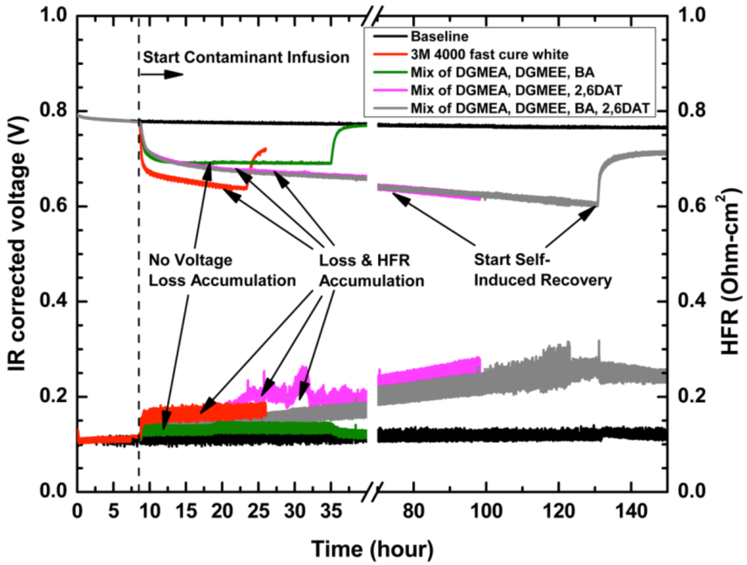
Electrode Design/High Current Density





Focus being placed on the incorporation of novel catalysts into highly performing devices. Also investigating the implications of going to low loadings on high current density, key enabling elements of decreasing cost.

System Contaminants



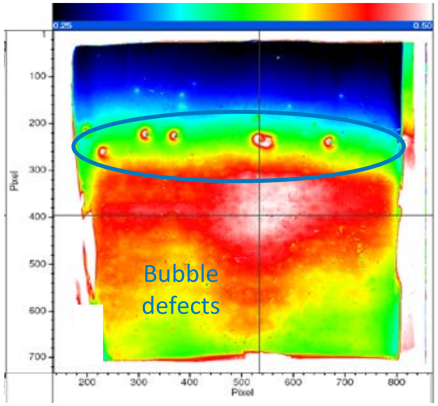
The impact of contaminants is also being investigated to develop materials approaches that can meet targets.

Fuel Cell Manufacturing R&D

Assessment of industry manufacturing methods

Development of improved in-line quality control techniques

Validation of techniques on NREL's web-line



Technology Validation

Confirmation of component and system technical targets

Technology validation in real-world settings

Evaluation, optimization, and demonstration in integrated energy systems

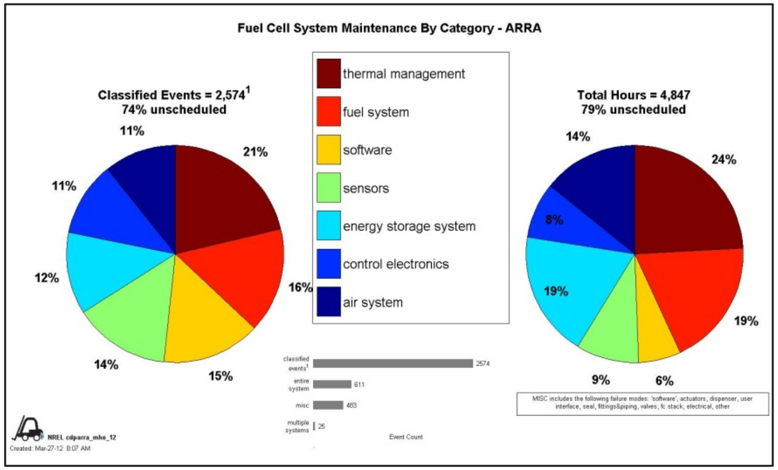


Photo by Dennis Schroeder, NREL
Figures and illustrations: NREL

Market Transformation

- Accelerated commercialization
- Removal of non-technical barriers
- Technology assessments
- Evaluations of market viability
- Cost of ownership analysis

Top photo by Dennis Schroeder, NREL; bottom photo courtesy of Hydrogenics

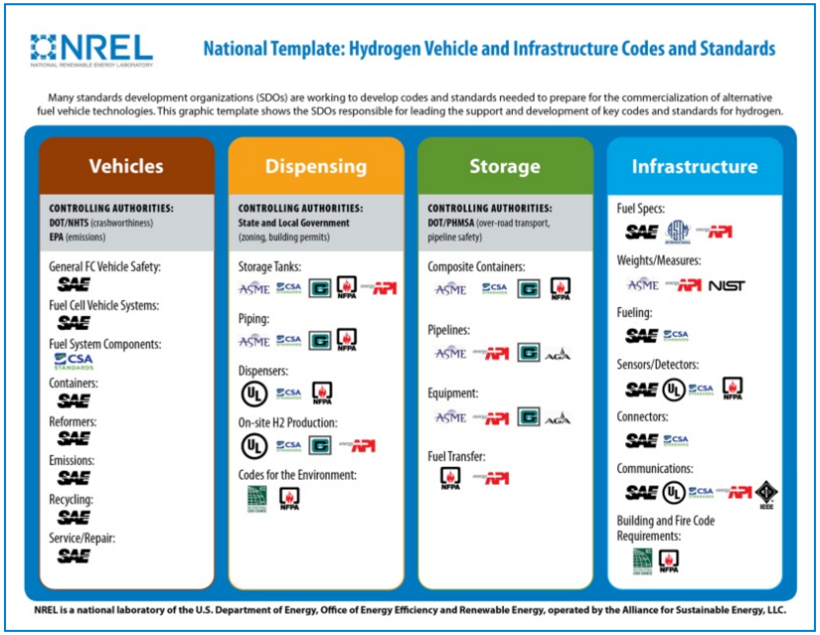
Photo by Chris Ainscough, NREL

Safety, Codes, and Standards

Guidance on safe operation, handling, and use

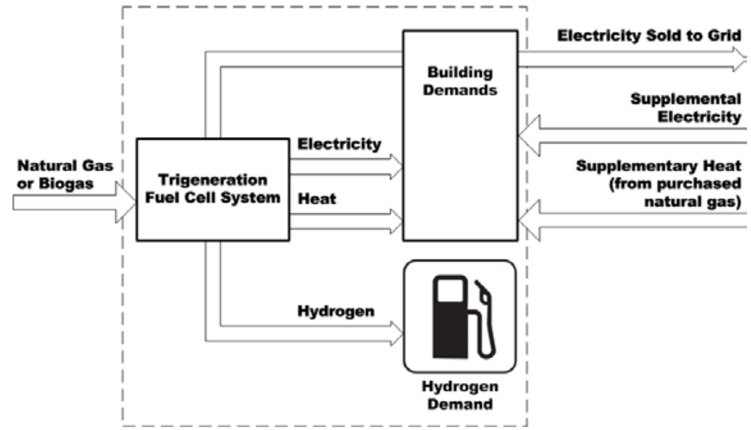
Safety testing and sensors

Vehicle, equipment, and building codes and standards



Top and middle photos by Keith Wipke, NREL; bottom photo by Dennis Schroeder

Systems Analysis



Evaluation of R&D goals

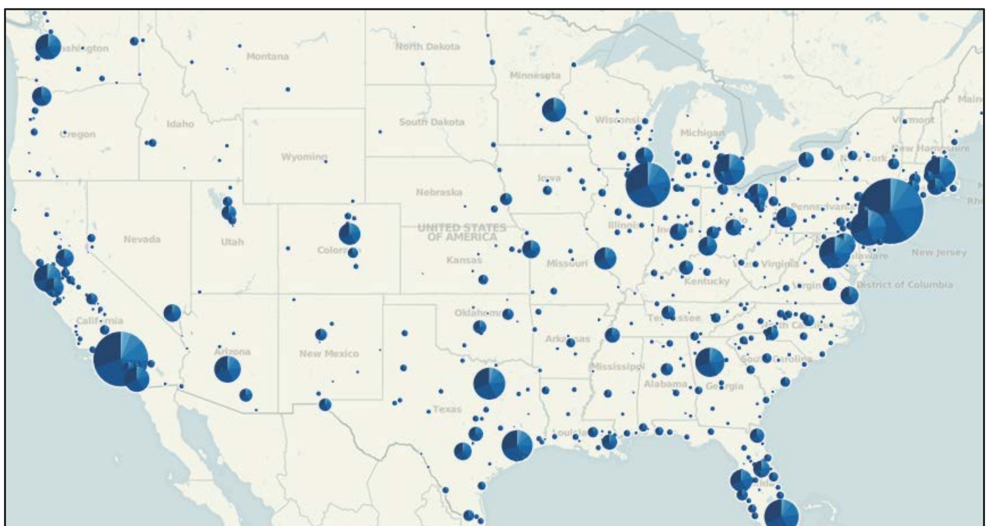
Resource assessments

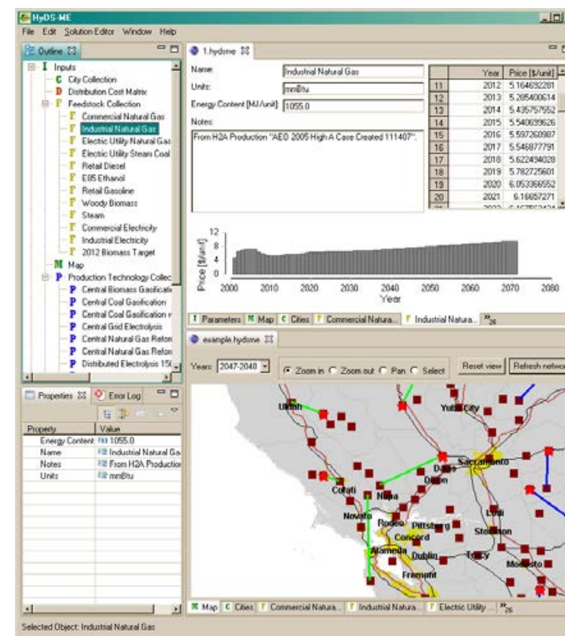
Techno-economic comparisons

Market-potential projections

Financial modeling

Infrastructure scenario deployment analysis





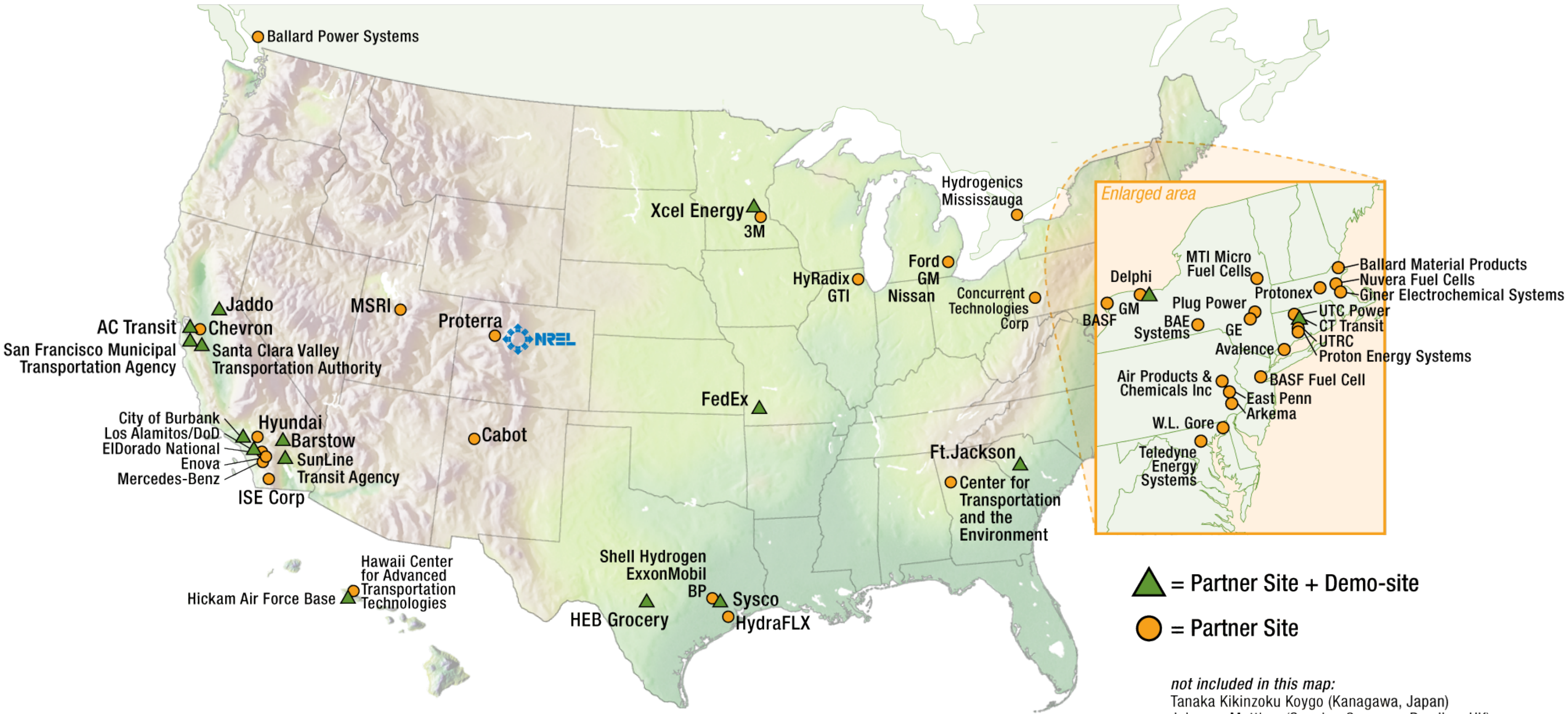
Figures and illustrations: NREL

NREL-Toyota Partnership

Four fuel cell hybrid vehicles—advanced (FCHV-adv) on two-year lease from Toyota

- **Enhanced NREL R&D**
  - Hydrogen fueling infrastructure
  - Renewable hydrogen production
  - Vehicle performance
- **Public/staff education opportunities**

H2 Industry Partnerships



not included in this map:
Tanaka Kikinzoku Koygo (Kanagawa, Japan)
Johnson-Matthey (Sonning Common, Reading, UK)

NREL Partners for Fuel Cell R&D

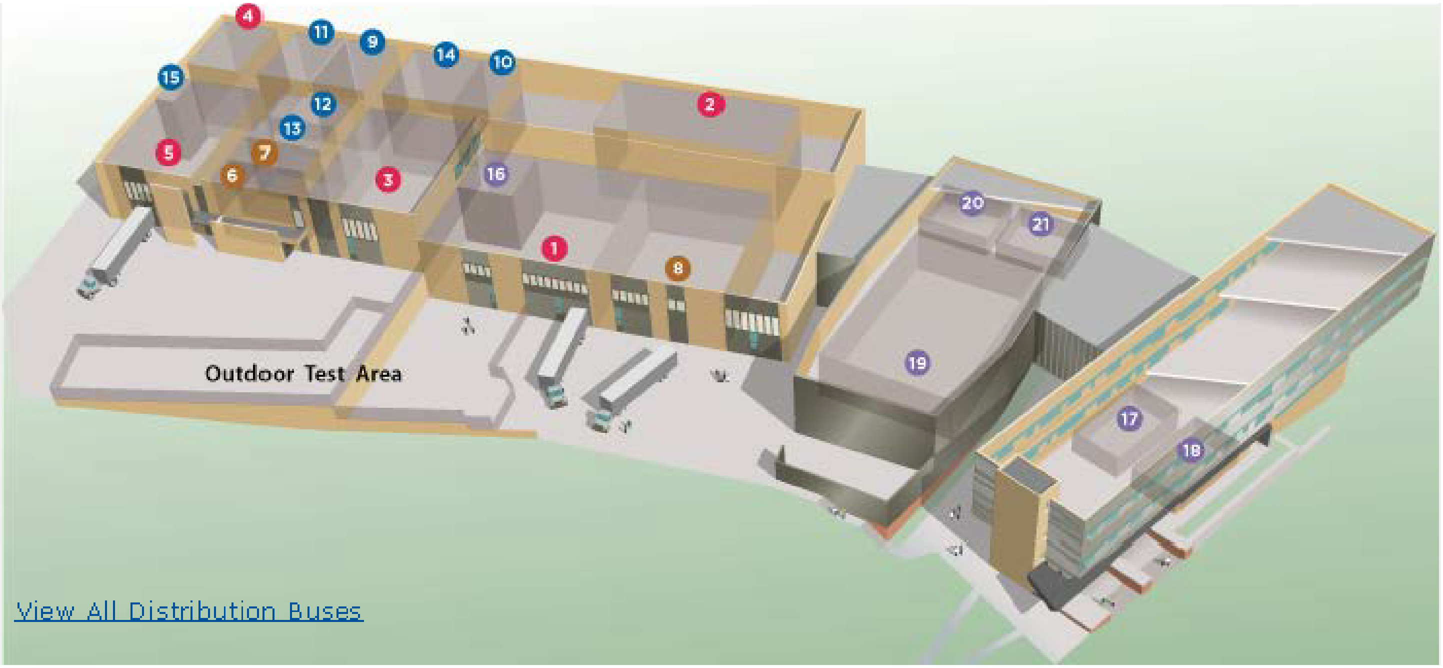
not included in this map:

- Tanaka Kikinzoku Koygo (Kanagawa, Japan)+
- CellEra (Israel)

KEY

- ■ = National Laboratory
- ▲ = University
- ● = Industry
- + Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes
- ⊗ Effect of System and Air Contaminants on PEMFC Performance and Durability
- ° Novel Approach to Advanced Direct Methanol Fuel Cell Anode Catalysts
- * Tungsten Oxide and Hetero-poly Acid Based System for Ultra-High Activity and Stability of Pt Catalysts in PEM Fuel Cell Cathodes

Major ESIF Laboratories/Capabilities



Electricity Laboratories

1. Power Systems Integration
2. Smart Power
3. Energy Storage
4. Electrical Characterization
5. Energy Systems Integration

Research Electrical Distribution Bus (REDB) – AC and DC

Thermal Laboratories

6. Thermal Systems
7. Thermal Storage Materials
8. Optical Characterization and Thermal Systems

Thermal Distribution Bus

Fuel Laboratories

9. Energy Systems Fabrication
10. Manufacturing
11. Materials Characterization
12. Electrochemical
13. Energy Systems Sensor
14. Fuel Cell Development
15. High-Pressure Testing

Fuel Distribution Bus

Data, Analysis, and Visualization

16. ESIF Control Room
17. Visualization Room
18. National Fuel Cell Technology Evaluation Center
19. High Performance Computing

Supervisory Control and Data Acquisition (SCADA) System

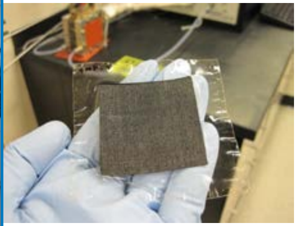
ESIF Fuel Cell R&D Laboratories

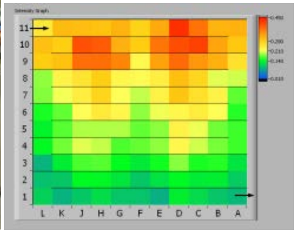
Dedicated Lab Space for Fuel Cell R&D

Laboratory	Pre-ESIF	Current
Electrochemical Char.	600	900
Fuel Cell Lab	450	1942
Manufacturing Lab	500	915
Materials Characterization	600	1412
MEA Lab	300	1450
Total	2450	6619

World class lab facilities:

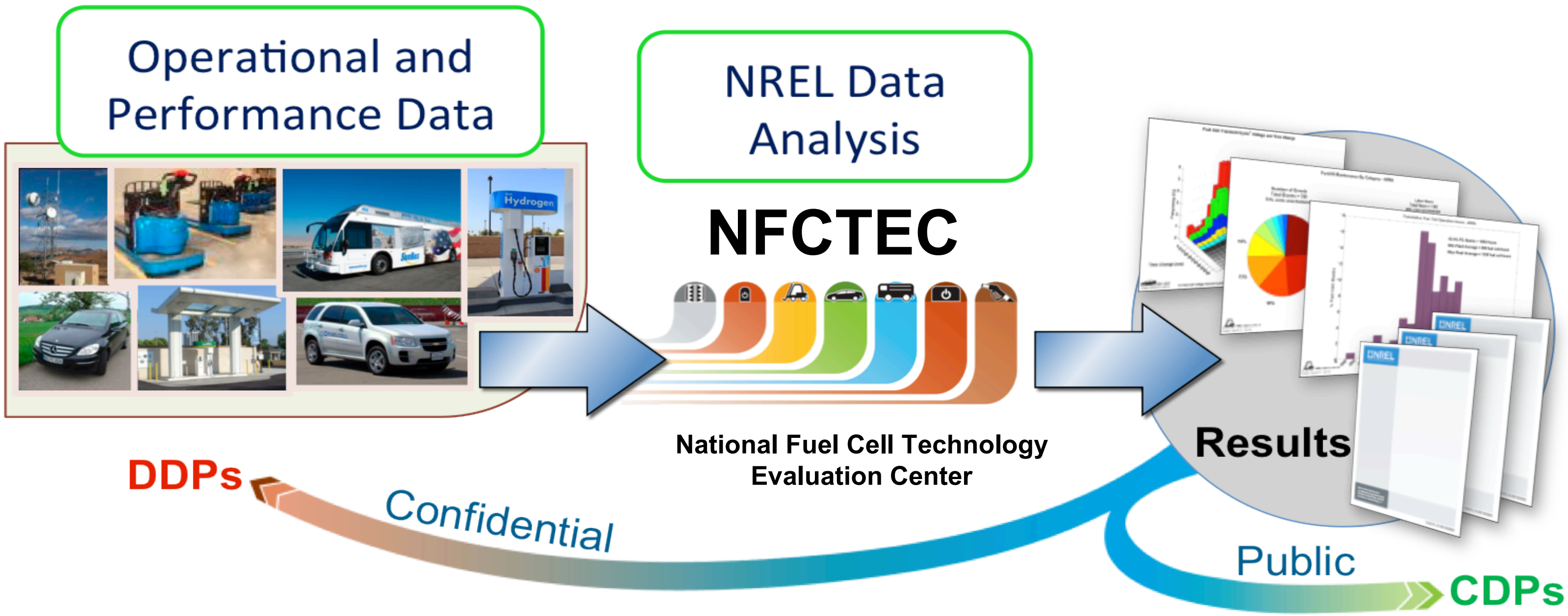
- Significantly enhanced testing competencies
- Hazard gas/material safety precautions (venting/hoods/enclosures)
- HEPA filtration throughout (nanomaterials)





National Fuel Cell Technology Evaluation Center

Analysis and reporting of real-world operation data



Detailed Data Products (DDPs)
- Individual data analyses, shared only with partner supplying data
- Identify individual contribution to CDPs

Composite Data Products (CDPs)
- Aggregated data across multiple systems, sites, and teams
- Publicly available analyses, published without revealing proprietary data

www.nrel.gov/hydrogen/proj_tech_validation.html

NREL Key Hydrogen and Fuel Cell Takeaways

- Hydrogen FCEVs are clean, efficient, refuel quickly, and provide long driving range
- Auto OEMs are coming to market with commercial vehicles in the 2015–2017 timeframe
- Additional support for hydrogen infrastructure is needed for these vehicles
- Abundant supplies of clean domestic sources (including natural gas and renewables) make fuel cells a good choice for the future
- Using hydrogen in a fuel cell vehicle, coming from a natural gas source originally, is still more efficient than burning it in an ICE
- Remaining fuel cells research challenges focus on reducing cost and increasing durability, which are interrelated
- NREL is involved in most aspects of bringing hydrogen fuel cell technologies closer to market (production, storage, fuel cells, etc.)

Conclusions

- NREL's Fuel Cell and Hydrogen Technologies Program continues to grow through diversification of funding sources and by broadening its R&D focus.
- Integration of fuel cells with renewable energy sources and systems for power production and for energy storage is an important growth area.
- Crosscutting analysis and technology validation are essential tools for decision making and for identifying new opportunities for advances.
- NREL maintains a customer focus to understand DOE's needs and focus our efforts on helping DOE achieve its goals.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