U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Hydrogen and Fuel Cell Activities: Progress and Opportunities

Dr. Sunita Satyapal, Director – Fuel Cell Technologies Office

232nd ECS Meeting

October 2, 2017– National Harbor, MD

Overview

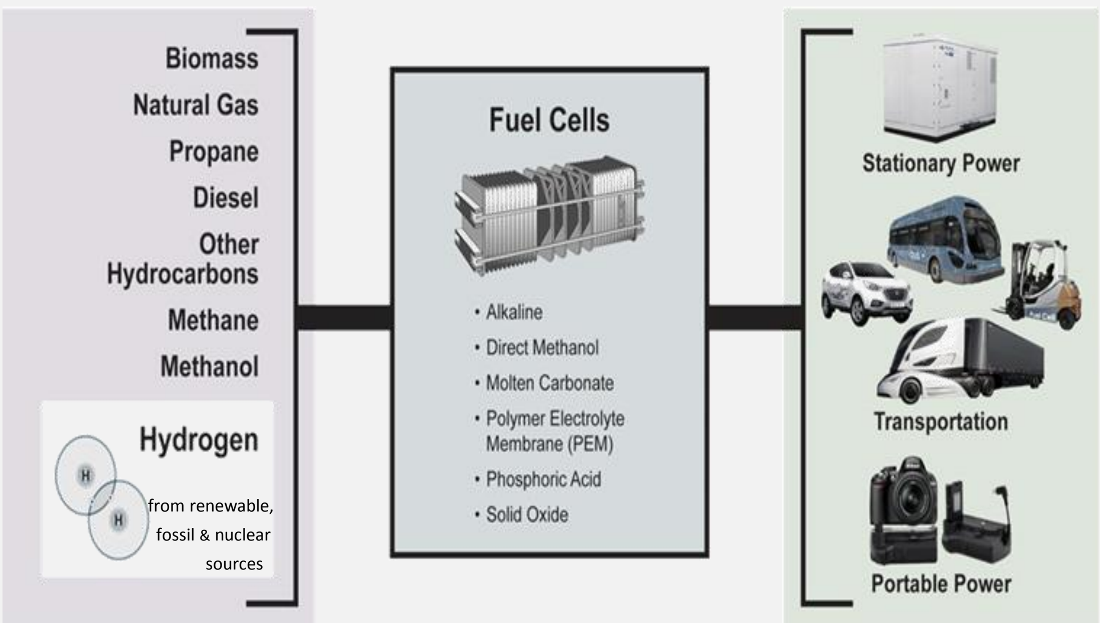
- Technology Status
- Targets and Goals
- Strategy

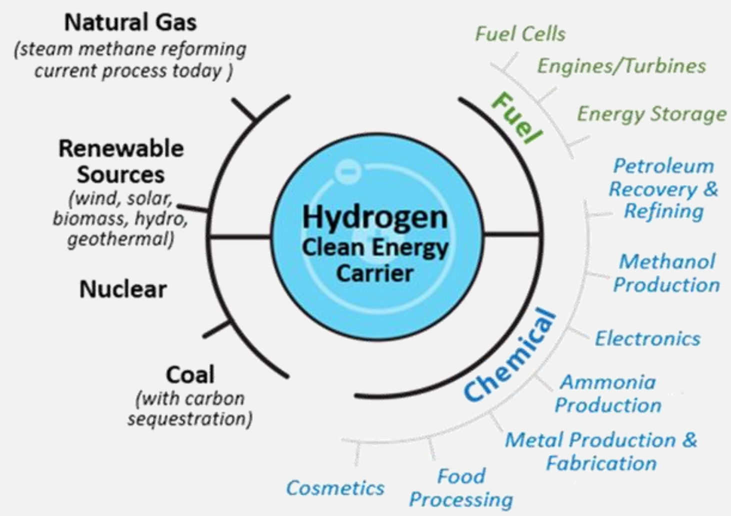
Fuel Cells and Hydrogen Benefits

Clean, Efficient Energy Conversion

Multiple, Diverse and Versatile Uses

Diverse, Domestic Energy Sources





Aligns with priorities: "Agencies should invest in early-stage, innovative technologies that show promise in harnessing American energy resources safely and efficiently." -Aug. 17, 2017 OMB/OSTP Memo

The Beginning of the DOE Fuel Cell Program…

1970s | **A group from labs, government and industry met at Los Alamos to set the foundation for DOE fuel cell programs**

Lab researchers taught scientists around the world how to fabricate fuel cell electrodes. Group from GM relocated to Los Alamos.

Forty years later, for the first time in history….


Hyundai Tucson Fuel Cell SUV


Toyota Mirai


Honda Clarity

Commercial
fuel cell electric cars are here!

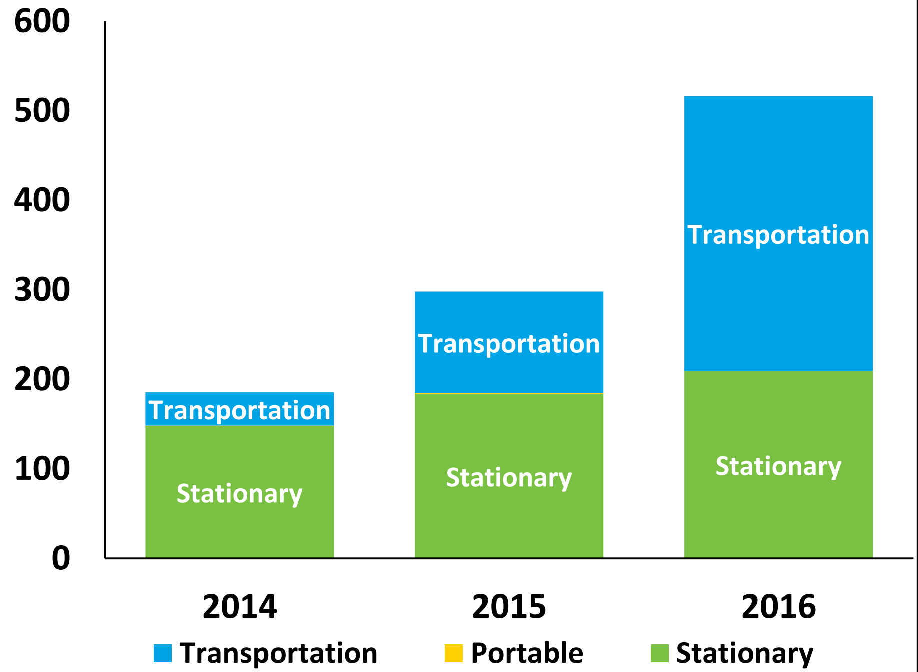
Power, performance, petroleum-free, pollution-free

- ✓ **Refuels in minutes**
- ✓ **More than 360 mi driving range**
- ✓ **Over 60 mpgge**

Market Growth - Global Shipment Trends

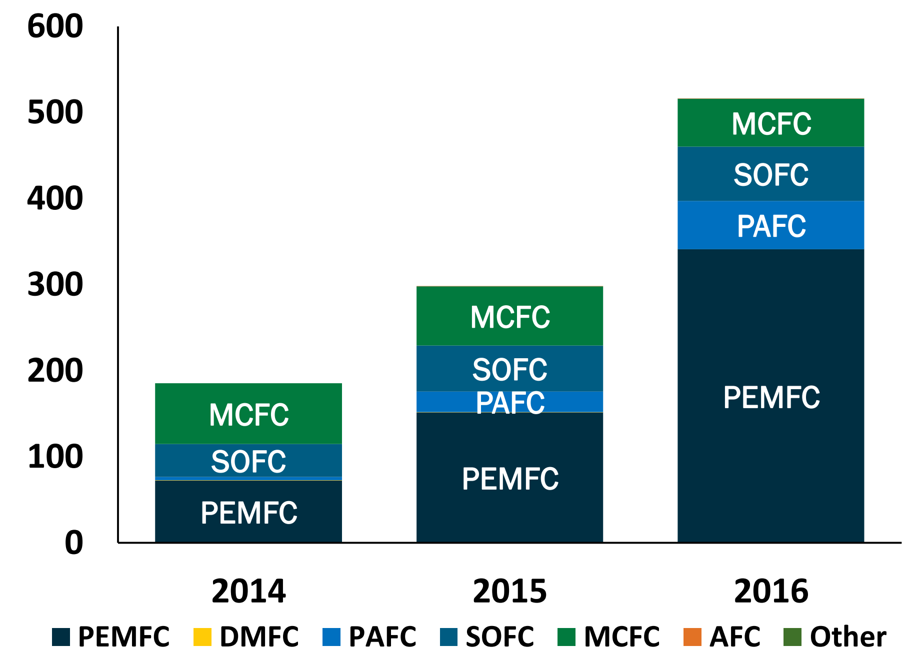
Total power (in MW) shipped by application

Growth in Transportation



Total power (in MW) shipped by fuel cell chemistry

Growth in PEMFC



500 MW fuel cell power shipped worldwide

62,000 fuel cell units shipped worldwide

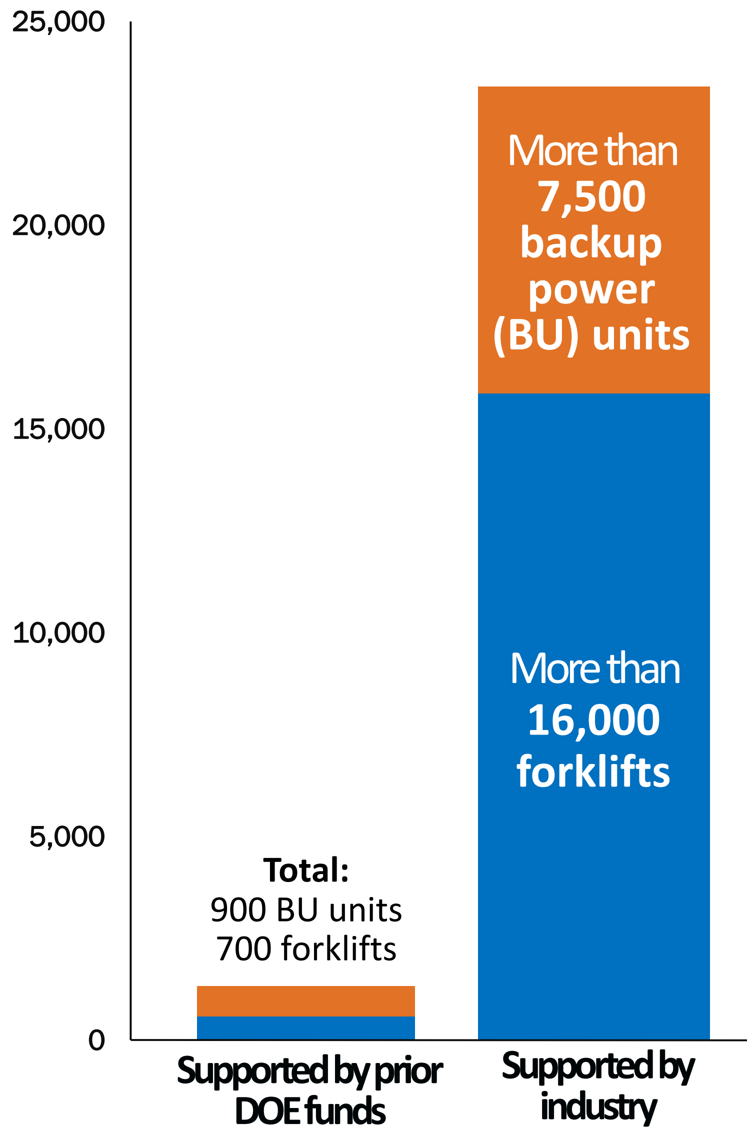
Approximately **$1.6 Billion** fuel cell revenue

Source: E4tech

Fuel Cell Early Markets Growing

Credit: BMW Manufacturing

Credit: Fuel Cell Energy



Fuel Cells: Big leaps in the last couple of years

Fuel cell electric delivery and parcel trucks – First of its kind demonstration starting deliveries this summer!

ZH2: U.S. Army and GM collaboration First of its kind

Industry demonstrates first heavy duty truck

Stationary Fuel Cells- Opportunities Emerging

Fuel cells provided backup power during hurricane Sandy

8,000 back up power units deployed or on order

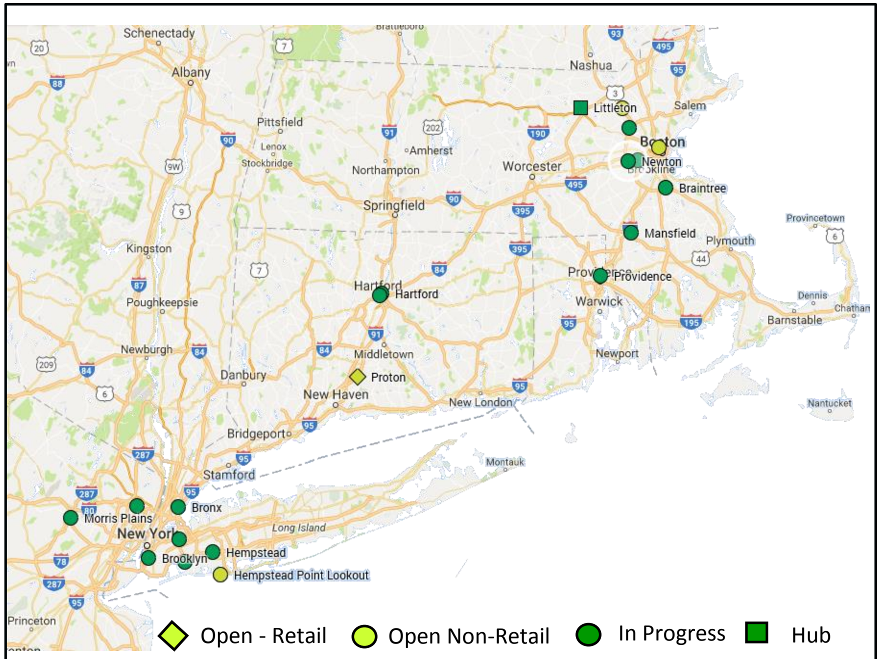
Key for critical loads

Hydrogen Stations: Strong State Support

California

Over 30 open retail

Funding for 100



Northeast

Approx. 12 to 25 stations planned

Others with interest: Hawaii, Ohio, Texas, Colorado, South Carolina, and others

Other New Infrastructure Options

DOE awards $1M H-Prize to Simple Fuel for winner of small-scale H_2 fueling design

H2refuel
U.S. Department of Energy
www. hydrogenprize.org

simple.fuel.™

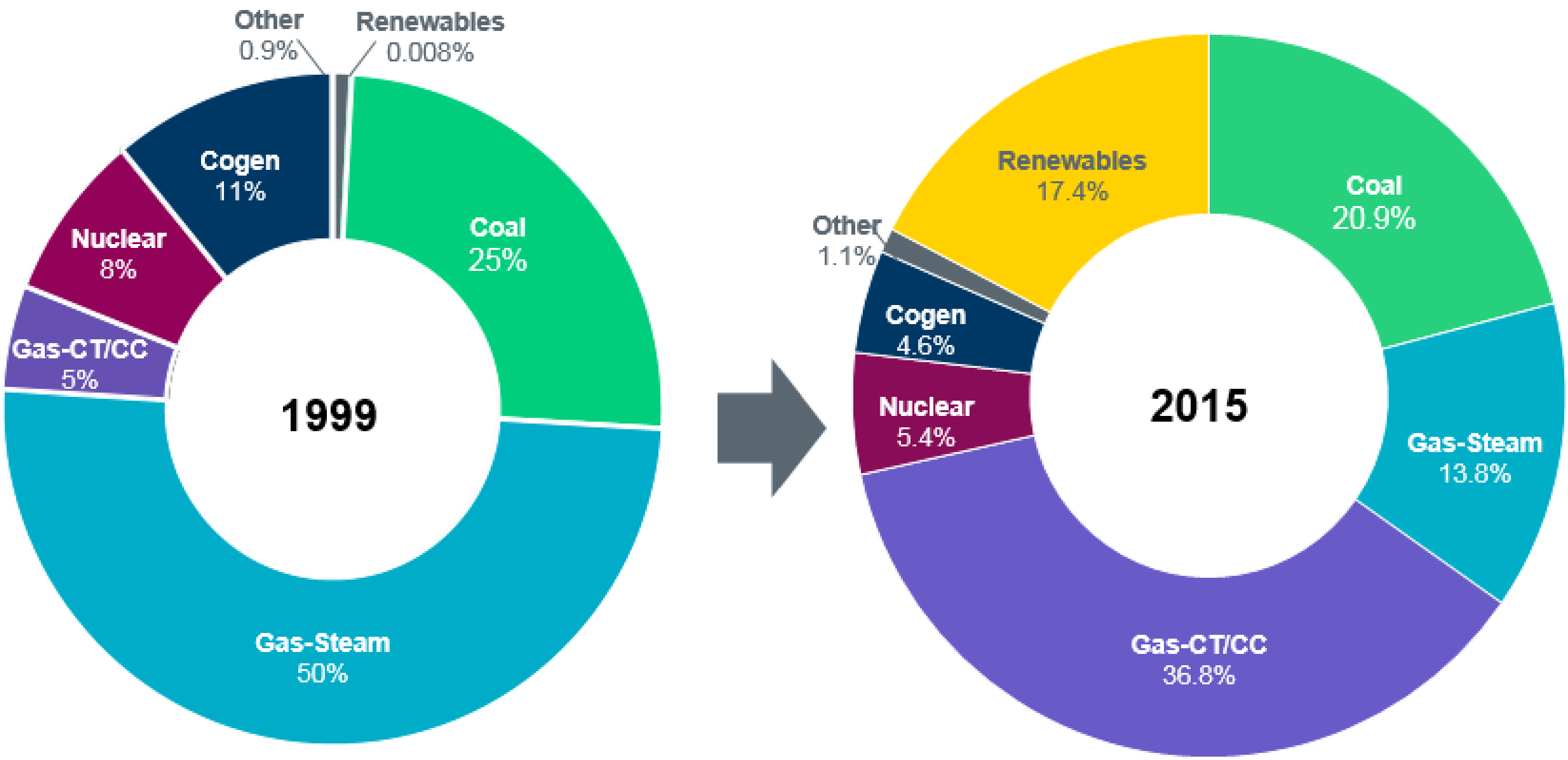
Email: connect@ivysinc.com
More info: www.teamsimplefuel.com

Ivys Energy Solutions (MA)
McPhy Energy (MA)
PDC Machines (PA)

What is different now?

Changing Energy Resource Mix - Example

Installed Capacity in Texas



Source: ERCOT; DOE H2@Scale workshop, Houston, 2017

A Global Initiative Supporting Hydrogen

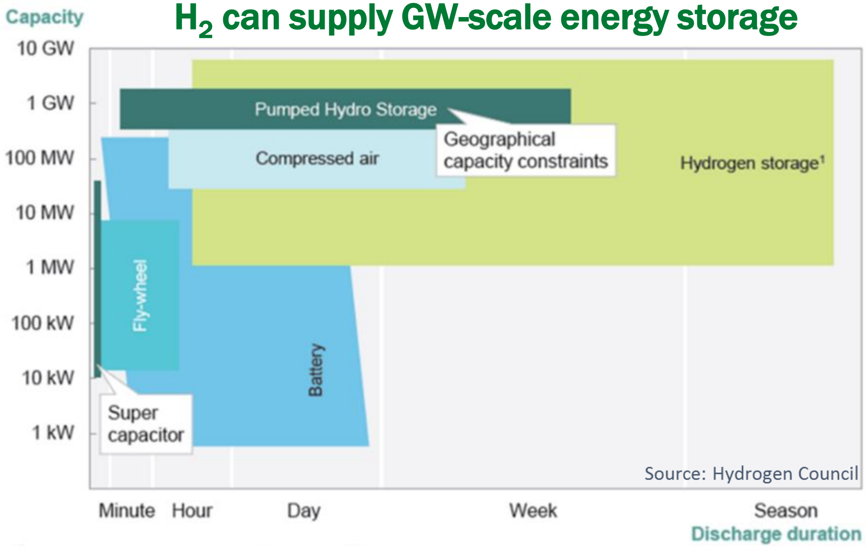
The Hydrogen Council formed 2017

Investment	Members
Over $10 billion	**Over 15 companies**
towards	representing
hydrogen and fuel cells	**$1T in revenues and 1.7M jobs**

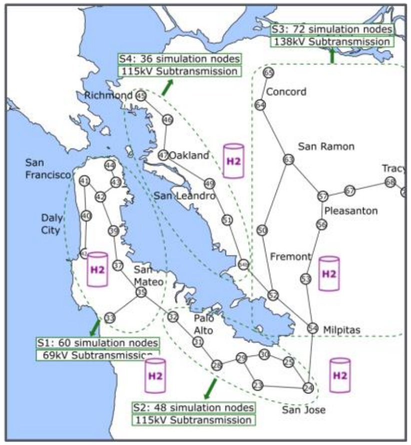
More information: hydrogeneurope.eu

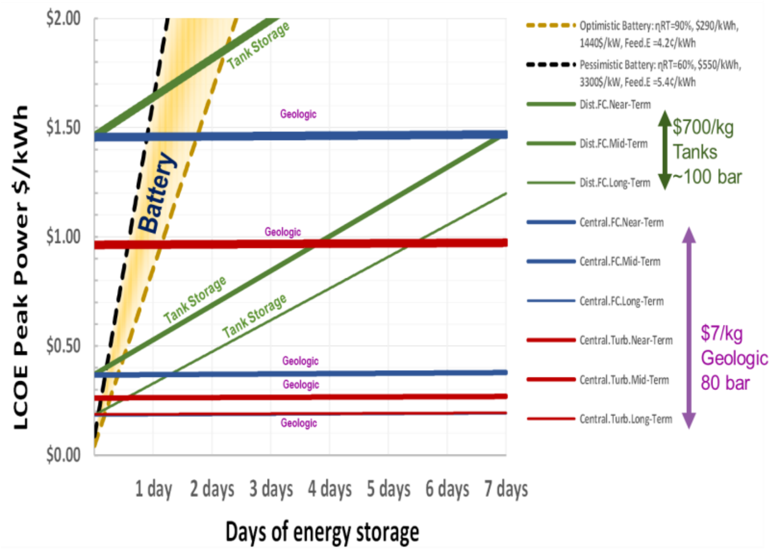
Examples of H_2 and Electrolyzer Benefits

H_2 can supply GW-scale energy storage

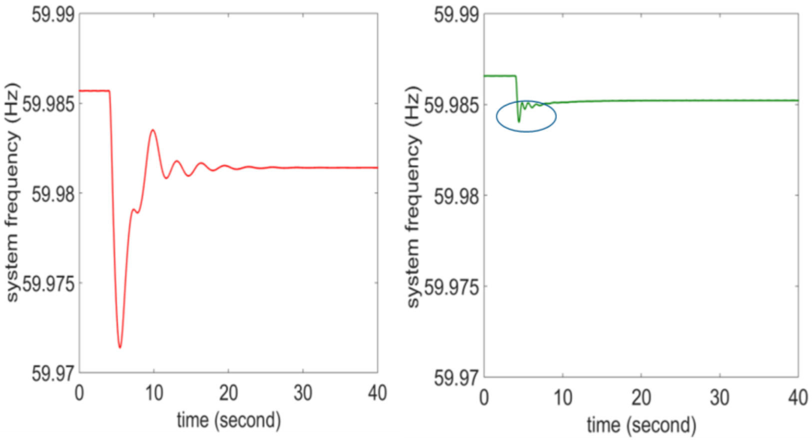


First ever validation of real time grid simulation with electrolyzers



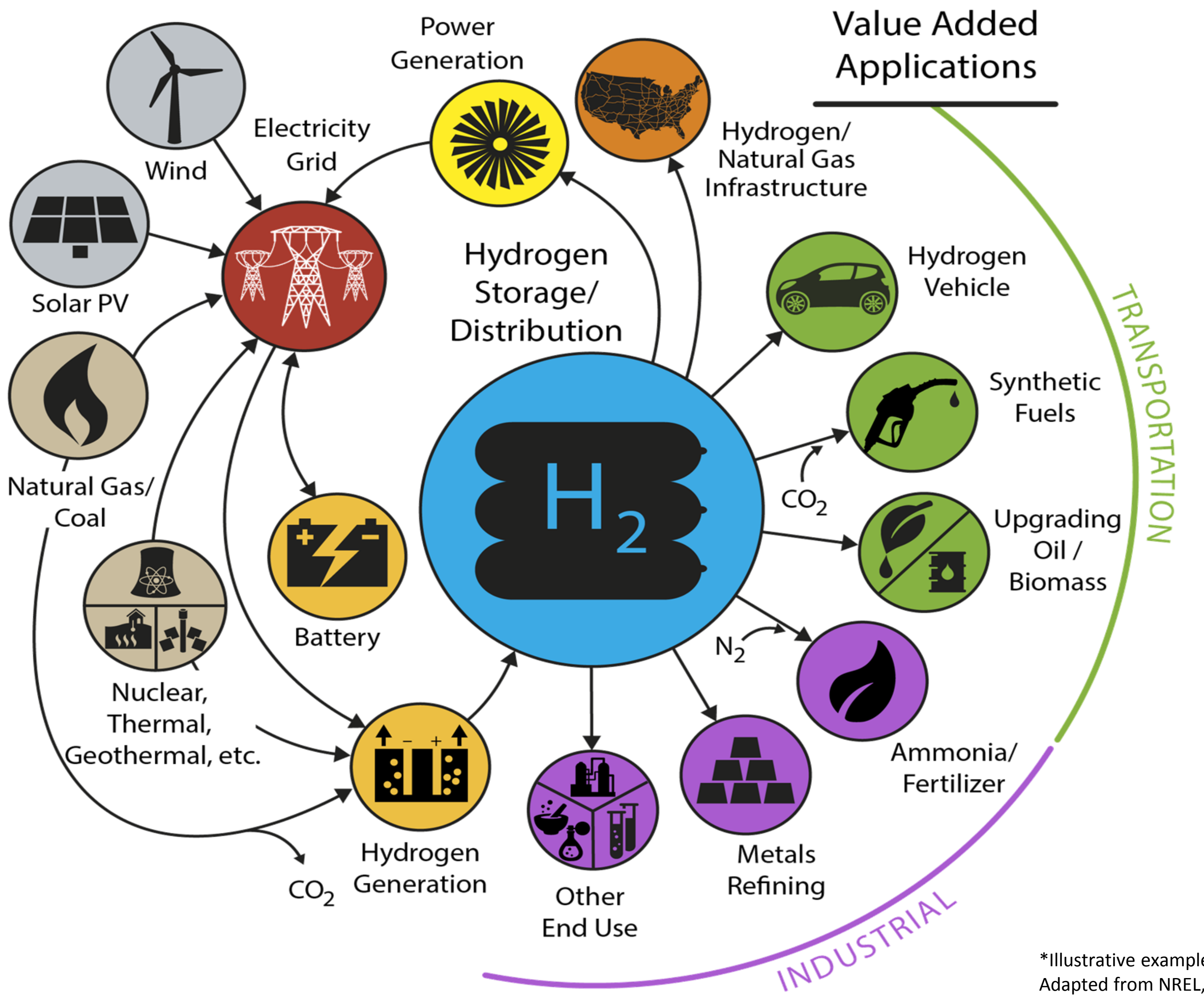


Preliminary analysis- to be updated



First independent validation of frequency regulation with electrolyzers and sub-second response times (INL, NREL)

H2@Scale Energy System Vision



*Illustrative example, not comprehensive
Adapted from NREL, Lab Big Idea Team

What can we learn from history?

Henry Ford's Quadricycle in 1896 to Model T in 1908

FORD CARS

1909 MODELS

The enormous demand for the new 4-cylinder Model "T" touring car makes it impossible for us to get these cars on short notice; deliveries will be made strictly in the order given. If you want one of these cars, see us soon.

$850 f. o. b. factory

Colorado Auto Supply Co.
Distributers
8-10 E. BIJOU STREET

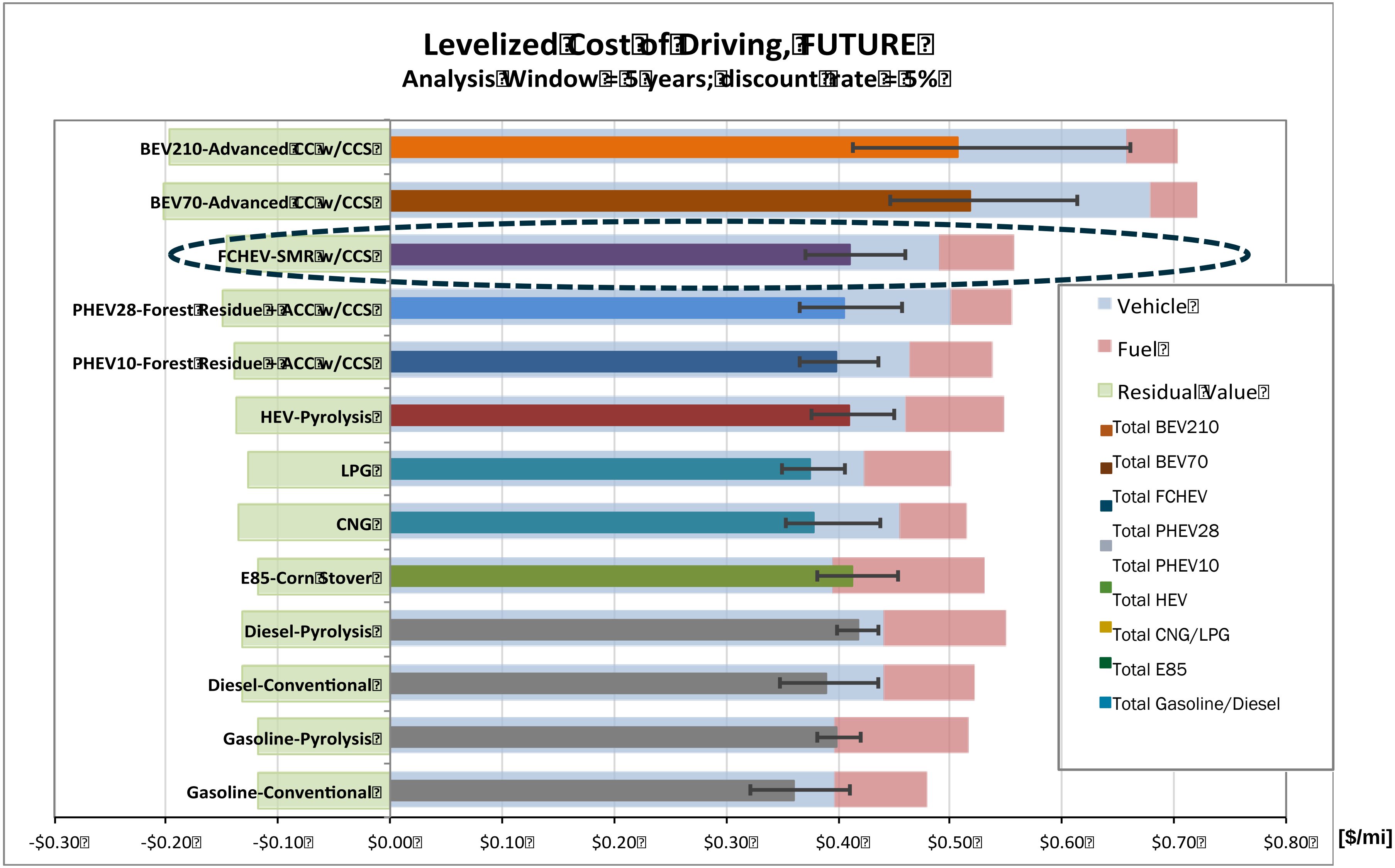
Three or four splendid second-hand cars for sale cheap.

Affordability

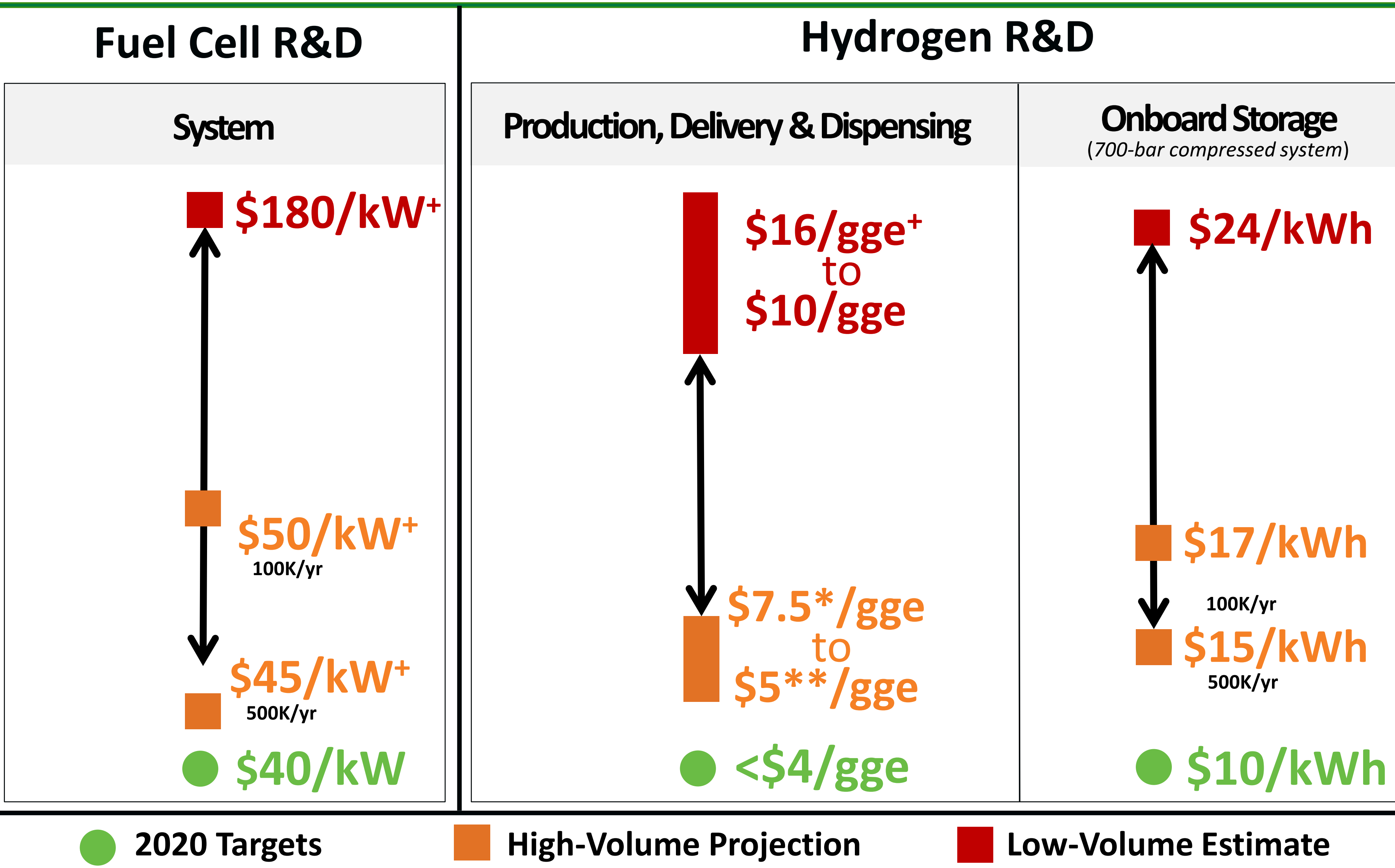
Performance

Availability

Setting Targets - Market Driven: Example



DOE Cost Status and Targets



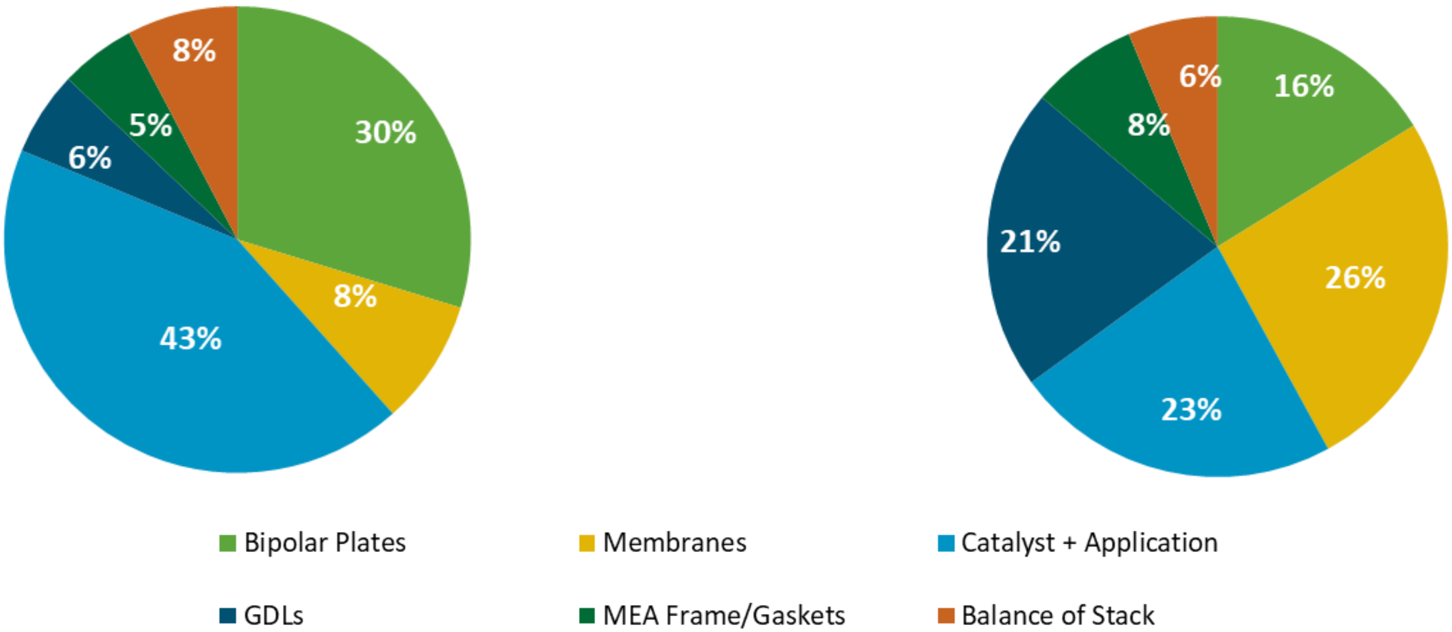
*Based on Electrolysis **Based on NG SMR ⁺ Preliminary, updates underway
Onboard storage cost status from DOE Program Record 15013

Note: Graphs not drawn to scale and are for illustration purposes only.

Fuel Cell Major Cost Components – Example

Cost contributors depend on manufacturing volumes & scale

Cost by Component – Independent peer-reviewed analysis



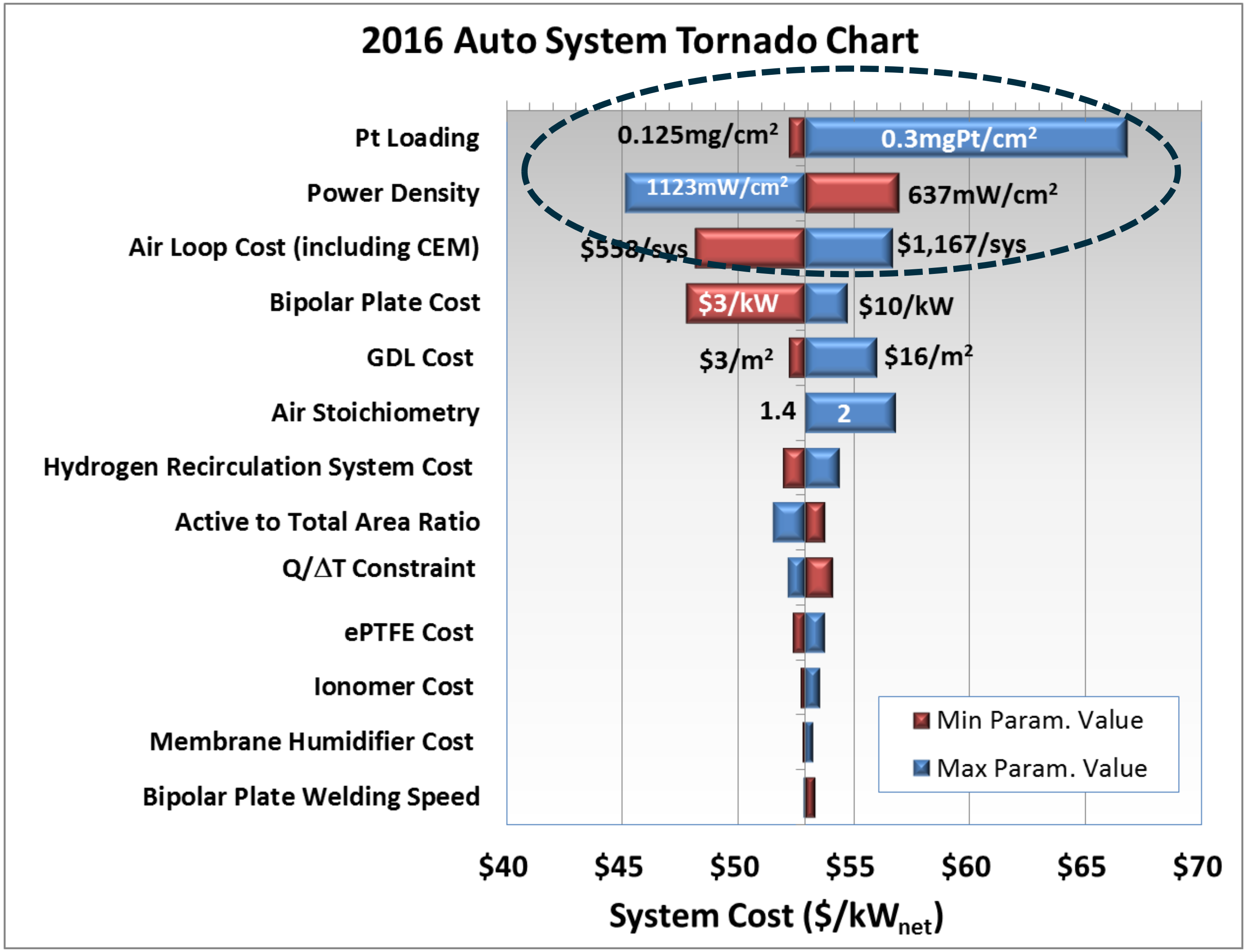
High-Volume (500,000/yr)
Key Challenges: Catalyst and Bipolar Plates

Low-Volume (1,000/yr)
Key Challenges: Membrane, GDL, Catalyst

**https://www.hydrogen.energy.gov/pdfs/15015_fuel_cell_system_cost_2016.pdf*

Sensitivity analysis helps guide priorities

Low PGM content and improved activity key to reduce cost



DOE AMR 2017, SA (Brian James)

Example of Detailed Technical Targets

Technical Targets: PGM-free Electrocatalysts for Transportation Applications		
Characteristic	**Units**	**Targets**
PGM-free catalyst activity* (H_2/O_2)	A / cm^2 @ 900 $mV_{IR\text{-}free}$	> 0.044**
Loss in initial catalytic activity	% mass activity loss	< 40
Loss in performance at 0.8 A/cm^2	mV	< 30
Startup/shutdown stability	% activity loss	< 40
Loss in performance at 1.5 A/cm^2	mV	< 30

*2017 status: 0.022 A/cm^2 @ 900 $mV_{iR\text{-}free}$

**Target is equivalent to PGM catalyst mass activity target of 0.44 A/mg_{PGM} at 0.1 mg_{PGM}/cm^2

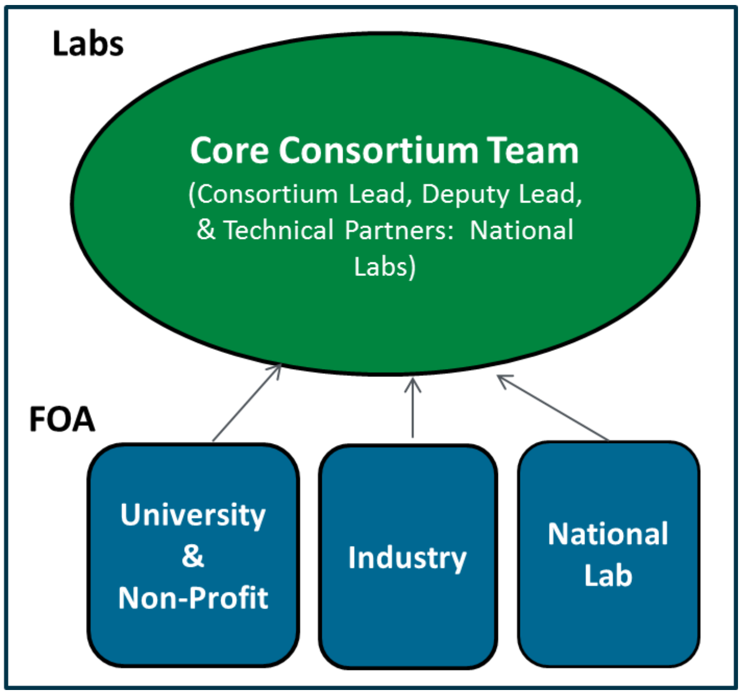
Targets and status peer- reviewed by Tech Team and industry

ElectroCat
Electrocatalysis Consortium

Strategy: Leveraging National Labs and Partners

Consortium Approach

Multi-lab core capabilities with steady influx of new partners



Energy Materials Network
U.S. Department of Energy

Consortia Launched

Improved PEM fuel cells

FCPAD
FUEL CELL PERFORMANCE AND DURABILITY

PGM-free catalysts

ElectroCat
Electrocatalysis Consortium

Advanced H_2 materials storage

HyMARC
Hydrogen Materials Advanced Research Consortium

Materials for renewable H_2 production

HydroGEN
Advanced Water Splitting Materials


A
B

EMN: A Platform for Accelerated Materials R&D

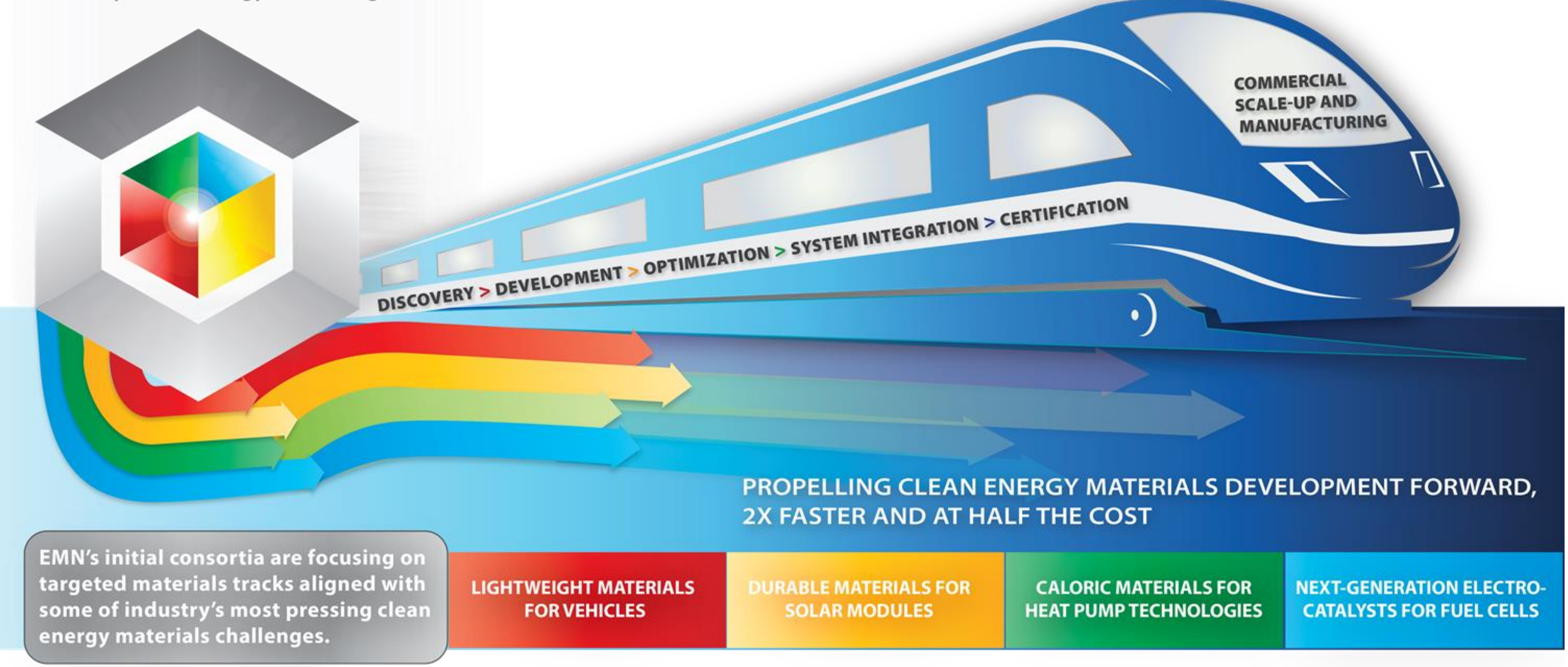
Energy Materials Network
U.S. Department of Energy

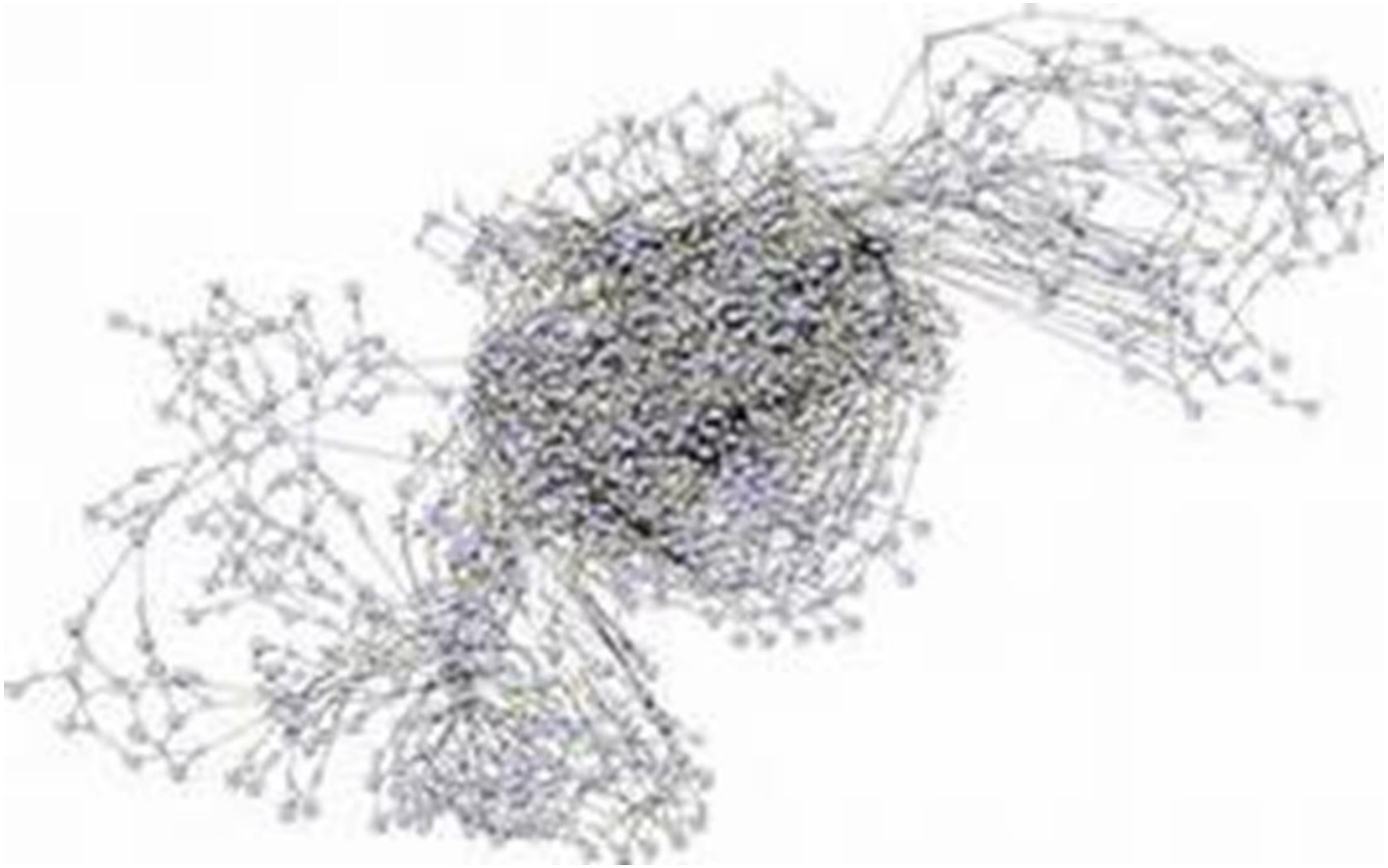
The Energy Materials Network (EMN) aims to dramatically decrease time-to-market for advanced materials that are critical to many clean energy technologies.

WORLD-CLASS INNOVATION
EMN is fueling U.S. industry with leading scientific and technical capabilities, data, and tools, and helping deliver innovative clean energy products to the world marketplace through its network of national lab-led consortia.

CLEAR POINTS OF ENGAGEMENT
In building an enduring, accessible network, EMN offers industry clear points of engagement and streamlined access to national lab resources by providing technical support, collaboration tools, and data platforms.

RAPID SCALE-UP
EMN is addressing market deployment barriers and getting new technologies to market faster by better integrating all phases of the materials development cycle, from discovery through deployment.





B

A

Lab Consortia to Address Key Materials R&D Challenges

Energy Materials Network
U.S. Department of Energy

Research Capabilities & Core Principles guiding EMN

Predictive Simulation Across Scales	Synthesis & Characterization	Rapid Screening	End Use Performance
Process Scalability	Process Control	Real-time Characterization	Reliability Validation

Data Management & Informatics

- Establishes **world class materials capability network**
- Sets up **clear point of engagement through concierge**
- Offers a **streamlined access through standard agreements**
- Encourages **data and tools collaboration**

Lab Consortia supporting EMN spanning multiple DOE offices and technologies

CaloriCool™ – Caloric Materials Consortium

ChemCatBio – Chemical Catalysis for Bioenergy

DuraMAT – Durable Module Materials Consortium

LightMAT – Lightweight Materials Consortium

ElectroCat – Electrocatalysis Consortium

HyMARC – Hydrogen Materials Advanced Research Consortium

HydroGEN – Advanced Water Splitting Materials

Energy Materials Network Consortia in Hydrogen and Fuel Cells R&D

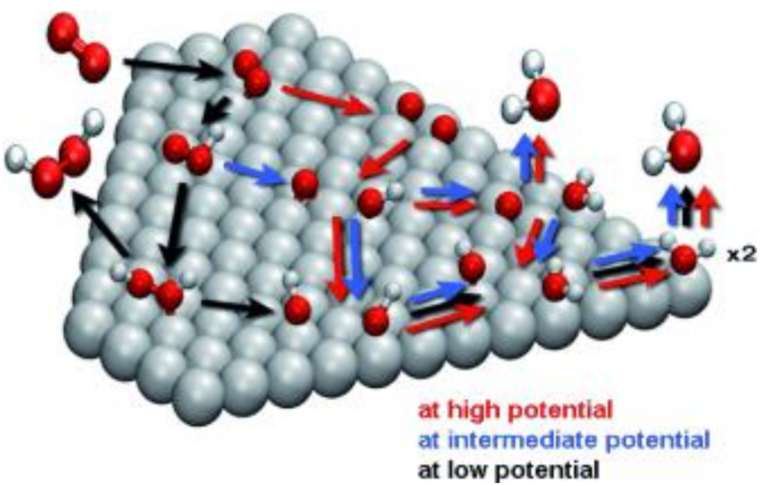
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Energy Materials Network
U.S. Department of Energy

DOE Focus: Beyond Platinum Group Metals

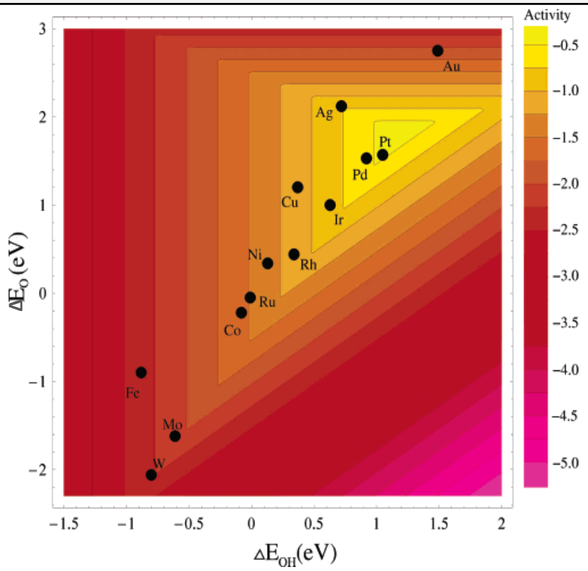
ORR is a complex 4-electron reaction

Anode: *$H_2 \rightarrow 2H^+ + 2e^-$*
Cathode : *$1/2O_2 + 2H+ +2e- \rightarrow H_2O$*
Overall: *$H_2 + 1/2O_2 \rightarrow H_2O$*



Pt <u>most active</u> for ORR, but is <u>expensive</u>

Pt adsorbs H and O strongly to generate intermediates, such as OH, but is able to release these relatively easily to form the final product



Experimental capabilities and advanced computational modeling need to be further developed to expedite PGM-free catalyst R&D

ElectroCat: Advanced PGM-Free Catalyst Materials

ElectroCat
Electrocatalysis Consortium

Argonne National Laboratory · Los Alamos National Laboratory · NREL National Renewable Energy Laboratory · Oak Ridge National Laboratory

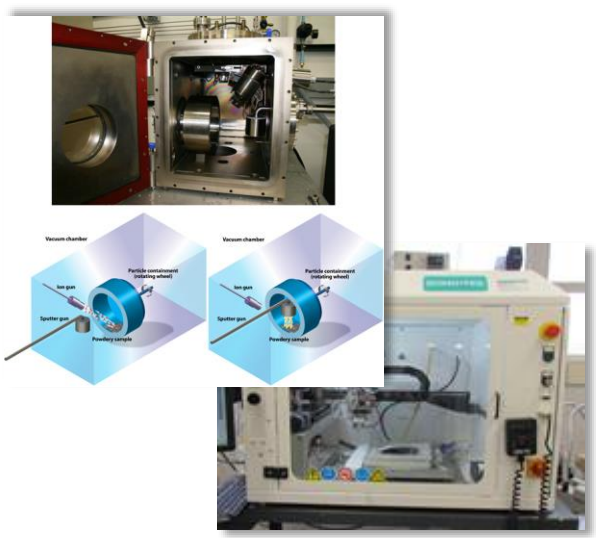
Accelerating the discovery & development of innovative catalyst and electrode materials critical to advanced PGM-free fuel cell technologies

Comprising nearly 30 world-class capabilities and expertise in:

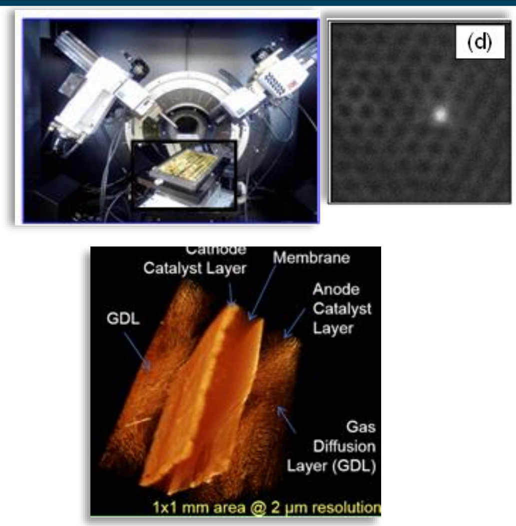
- catalyst synthesis, characterization, processing, and manufacturing
- high-throughput, combinatorial techniques
- advanced computational tools

More information available at: www.electrocat.org

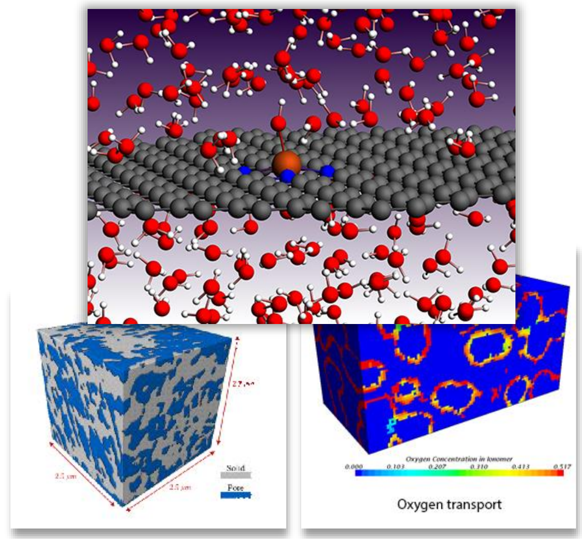
Synthesis, processing and manufacturing



Characterization and Testing



Computation, Modeling & Data Management

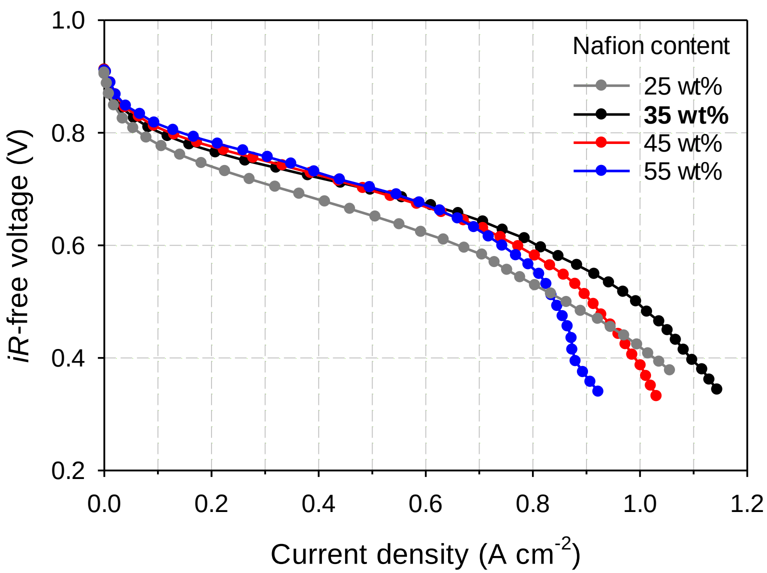


ElectroCat Accomplishment in ORR Activity

Performance Improvement

- Improved PGM-free H_2-air as-measured performance **by 25%** versus 2016 status by using Zn as a pore-forming component in Los Alamos' (CM+PANI)-Fe-C catalyst synthesis and by optimizing electrode ionomer content

Anode: 0.3 mg_{Pt} cm^{-2} Pt/C H_2, 200 sccm, 1.0 bar H_2 partial pressure; **Cathode:** *ca.* 4.8 mg cm^{-2} catalyst loading, air, 200 sccm, 1.0 bar air partial pressure; **Membrane:** Nafion®, 211; **Cell:** 5 cm^2, 80 °C

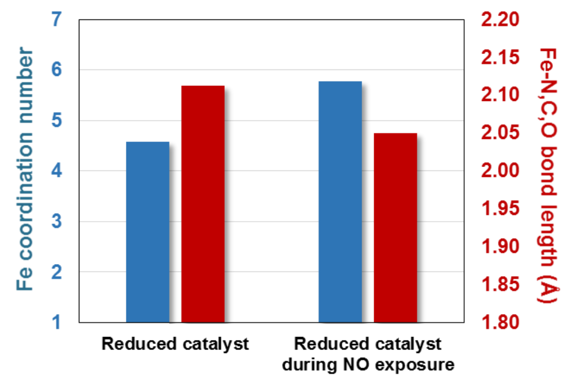


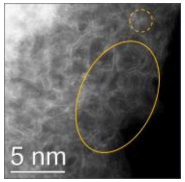
- Increased ORR activity for atomically-dispersed Fe-N-C catalyst **by 20 mV** at $E_{½}$

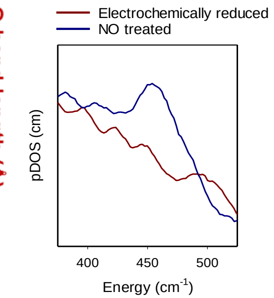
ElectroCat
Electrocatalysis Consortium

Characterization

- Obtained **direct microscopic and spectroscopic evidence** of a majority of **Fe sites being on the surface** and **atomically dispersed in (AD)Fe-N-C**

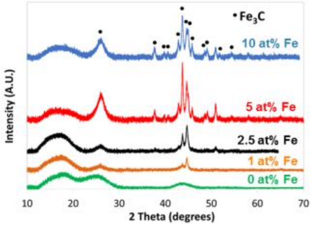




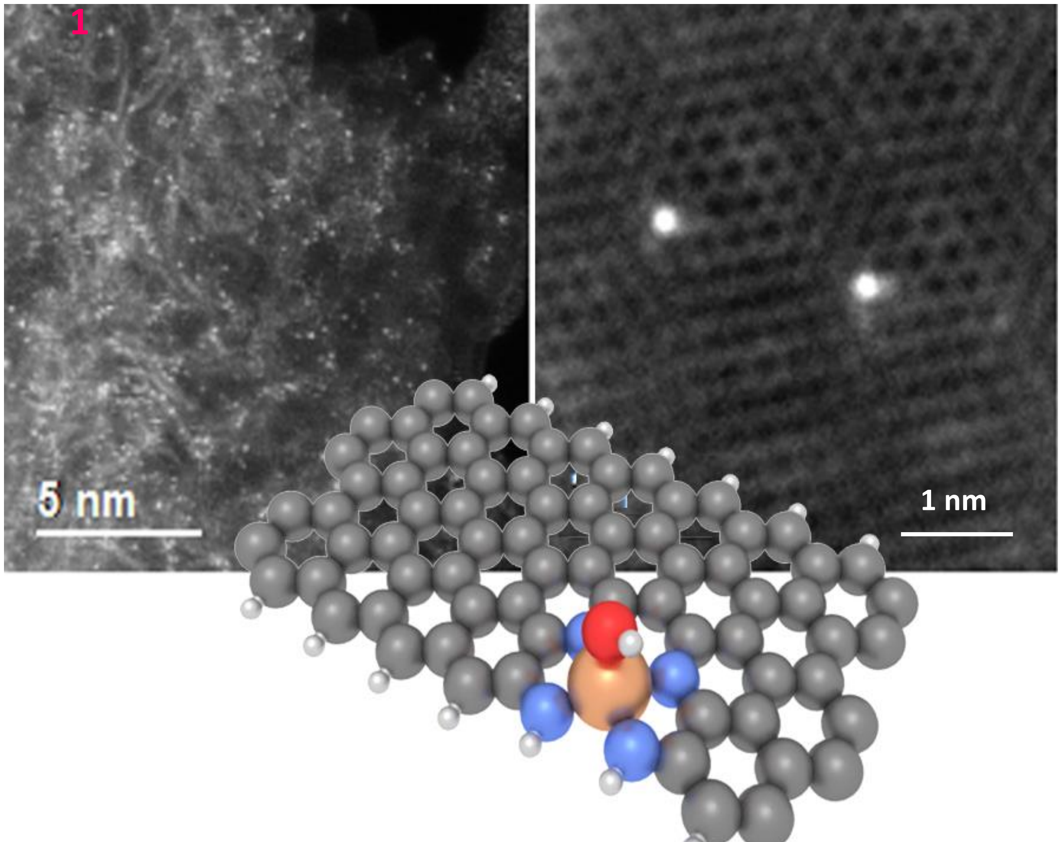


High-Throughput (HT)

- Used **HT software to calculate durability descriptor** for PGM-free cathode catalysts
- Used **HT robotic system to synthesize and characterize** 40 variations of (AD)Fe-N-C



Identification of active sites in PGM-free catalyst



(N: blue, Fe: yellow, O: red, and H: white)

Scientific Achievement

Active site(s) in PGM-free Fe-N-C catalyst are visualized with scanning transmission electron microscopy (STEM) and computationally correlated with specific lattice-level carbon structures.

Science Paper Highlight!

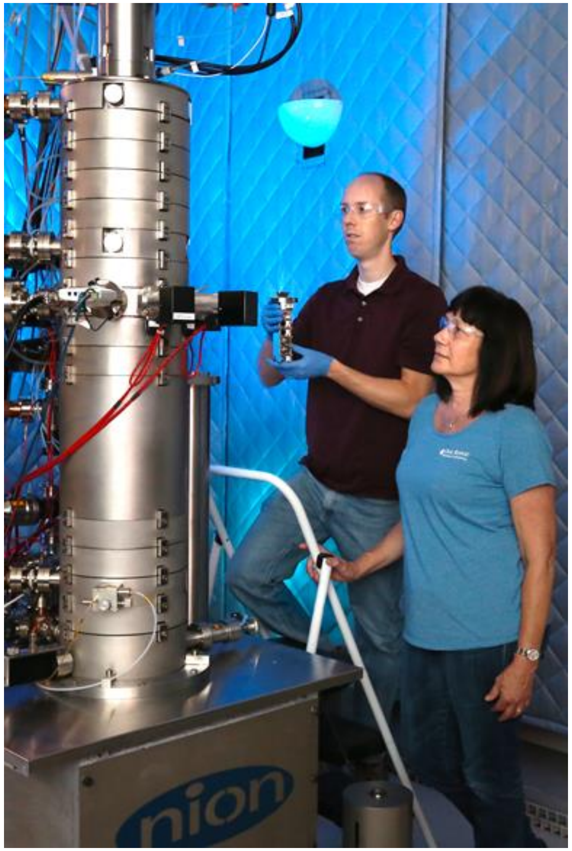
- (CM+PANI)-Fe-C catalyst
- STEM imaging, quantitative EELS, and quantum chemistry calculations confirm zigzag edge-hosted FeN_4 spontaneously ligated with OH lead to highly ORR-active structures.

EERE Collaboration with BES: Work was performed as User Project at the Center for Nanophase Materials Sciences

H.T. Hoon, D.A. Cullen, D. Higgins, B.T. Sneed, E.F. Holby, K.L. More, and P. Zelenay, “Direct atomic-level insight into the active sites of a high-performance PGM-free catalyst,” *Science* (2017). DOI: 10.1126/science.aan2255

Los Alamos NATIONAL LABORATORY

Unique STEM first-of-a-kind in the world coming soon…



Karren More, David Cullen, ORNL
Will be used for ElectroCAT

Studies of soft matter (ionomer) require specialized TEM/STEM configurations:
Variable low-voltage (30Kv-200kV); low-dose EM modes; Aberration-correction for Å-scale-resolution; Specialized detectors/cameras for rapid data acquisition (1000fps); Correlative spectroscopy (EDS; EELS); 3D tomography and reconstruction

Collaborate with ElectroCat!

Visit electrocat.org , use the "Contact ElectroCat" tab

HydroGEN: Advanced Water-Splitting Materials

HydroGEN
Advanced Water Splitting Materials
Core Labs

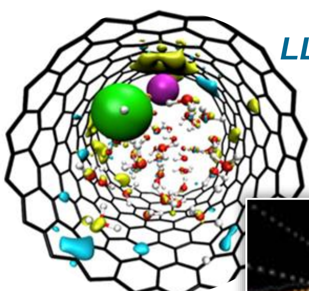
NREL · Berkeley Lab · Sandia National Laboratories · INL Idaho National Laboratory · Lawrence Livermore National Laboratory · SRNL

Accelerating the discovery & development of innovative materials critical to advanced technologies for sustainable H_2 production, including:

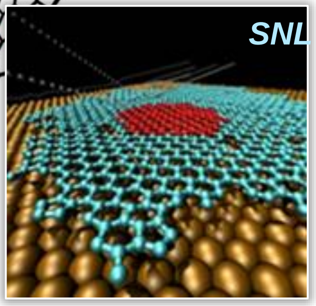
- ***Advanced high- and low-temperature electrochemical conversion***
- ***Direct photoelectrochemical solar water splitting***
- ***Direct solar thermochemical water splitting***

Comprising more that 80 unique, world-class capabilities/expertise in materials theory/computation, synthesis, characterization & analysis:

Materials Theory/Computation

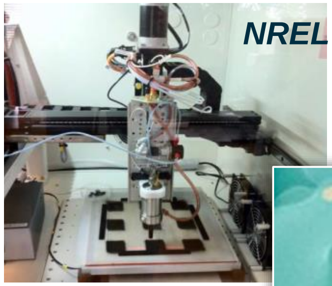

LLNL

Bulk & interfacial models of aqueous electrolytes

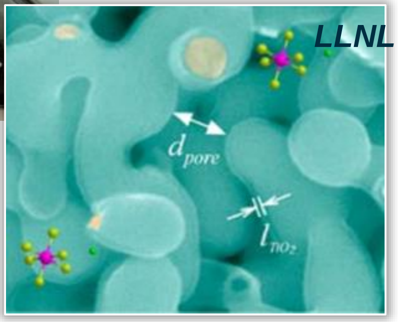


LAMMPS classic molecular dynamics modeling relevant to H_2O splitting

Advanced Materials Synthesis



High-throughput spray pyrolysis system for electrode fabrication



Conformal ultrathin TiO_2 ALD coating on bulk nanoporous gold

Characterization & Analytics

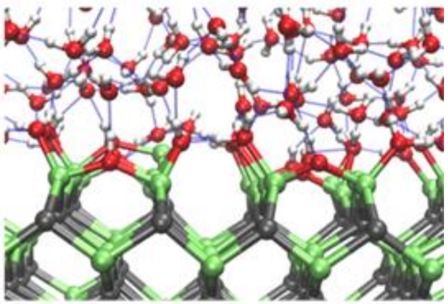
Stagnation flow reactor to evaluate kinetics of redox material at high-T

TAP reactor for extracting quantitative kinetic data

HydroGEN: Cross-Cutting Computational Capability

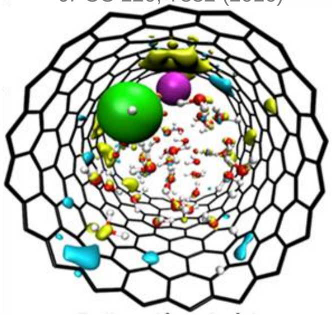
solid-liquid interfacial chemistry

JACS 135, 15774 (2013)



Ab-initio molecular dynamics of semiconductor-water and metal-water interfaces

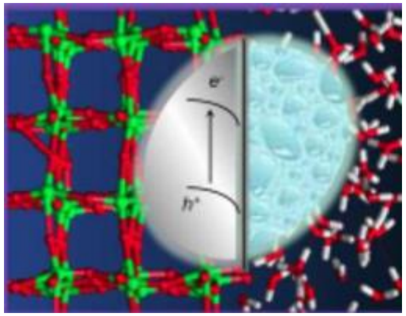
JPCC 120, 7332 (2016)



Bulk and interfacial properties of aqueous electrolytes

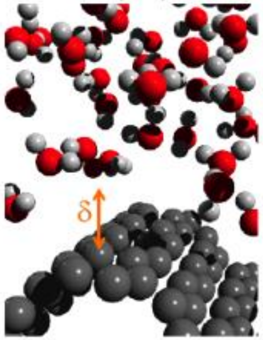
electronic properties of interfaces

JACS 136, 17071 (2014)



Electronic properties of electrode-electrolyte interfaces (from GW)

PRB 91, 12415 (2015)



Simulations under applied voltage bias or photo-bias

Cutting-edge theoretical modelling of electrochemical interfaces at LLNL includes 'excited states' estimations- Opening new opportunities in:

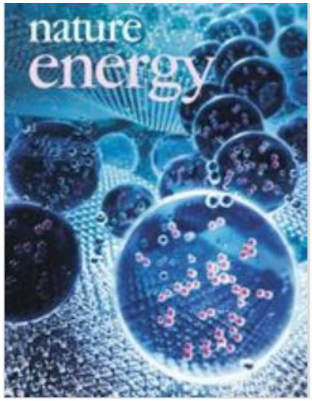
- Advanced computational models of electrolysis under voltage bias
- Ground-breaking analysis of PEC interfaces under photo-excitation
- New cross-cutting opportunities in R&D of fuel cells, batteries, etc.

HydroGEN: High-Impact Computational Research in Catalysis

nature energy

ARTICLES

PUBLISHED: 31 JULY 2017 | VOLUME: 2 | ARTICLE NUMBER: 17127



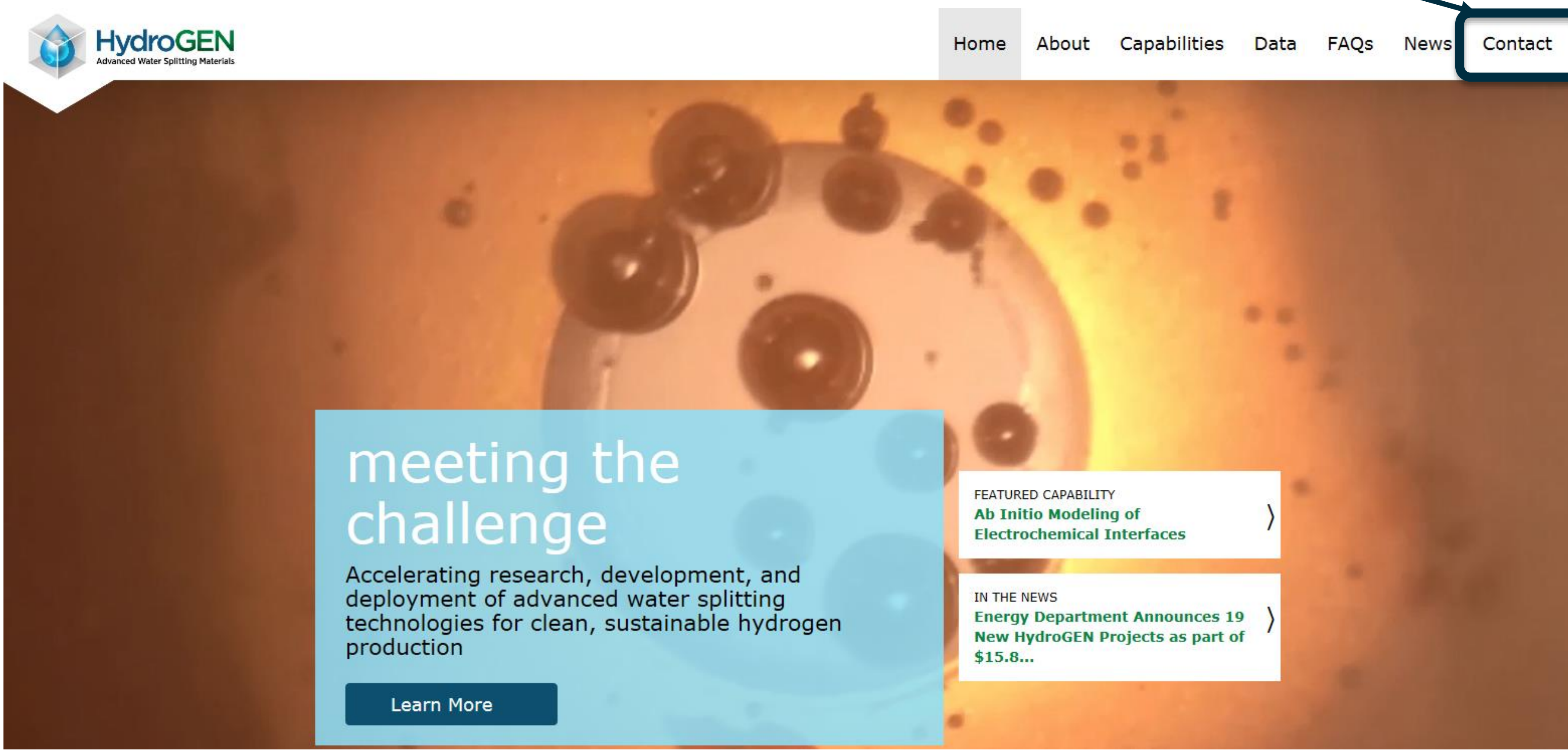
Self-optimizing, highly surface-active layered metal dichalcogenide catalysts for hydrogen evolution

Yuanyue Liu[1†‡], Jingjie Wu[1‡], Ken P. Hackenberg[1‡], Jing Zhang[1], Y. Morris Wang[2], Yingchao Yang[1], Kunttal Keyshar[1], Jing Gu[3], Tadashi Ogitsu[2], Robert Vajtai[1], Jun Lou[1], Pulickel M. Ajayan[1], Brandon C. Wood[2*] and Boris I. Yakobson[1*]

Steering Committee Member (Tadashi) owns a FCEV and chooses a unique license plate

Collaborate with HydroGEN!

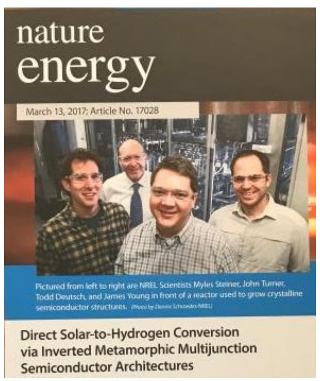
Visit **h2awsm.org** , **use the "Contact"** tab

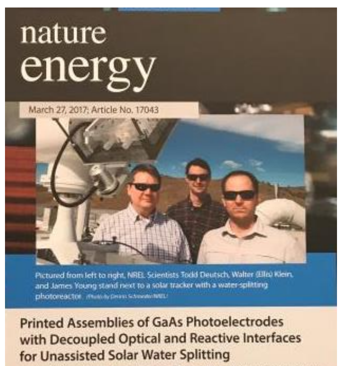


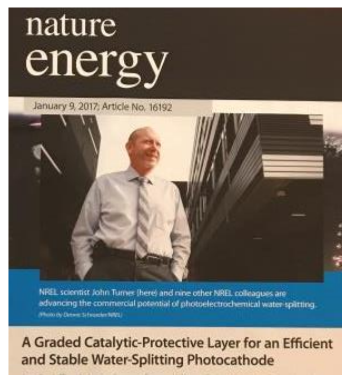
HydroGEN: High-Impact Research in Photoelectrochemistry

Achieving Record Performance

NREL set new record with III-V semiconductor PEC tandem cell: 3 *Nature Energy* publications.



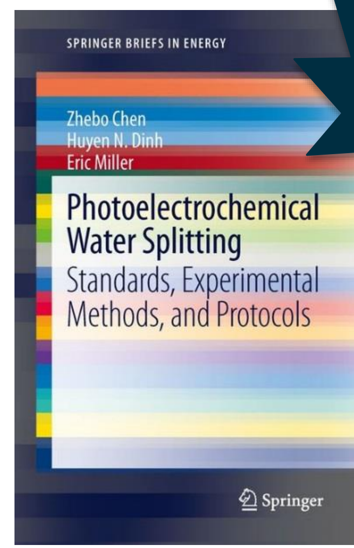




New PEC World Record Benchmarked at >16% STH

Addressing Benchmarking Needs

Technology advancement by publishing standards, protocols and reviews.



28,000 Downloads to date

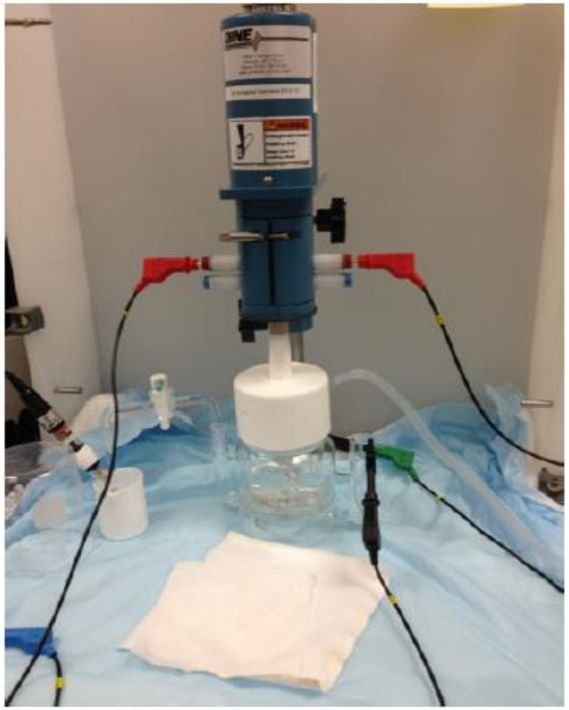
Technology Standards to Facilitate Research Progress

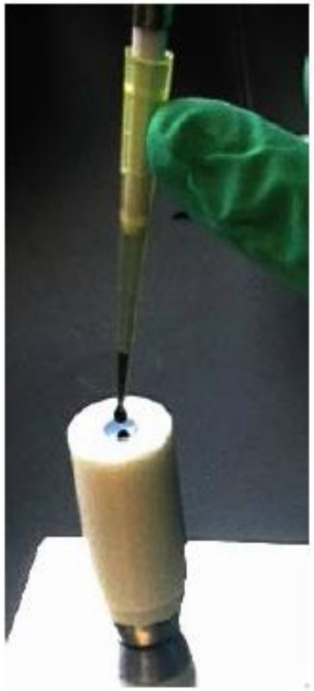
Raising the tide

Enablers
Example: Protocols

Catalyst Screening Challenge - RDE Variability

Need for more consistency in RDE measurements of catalyst activity

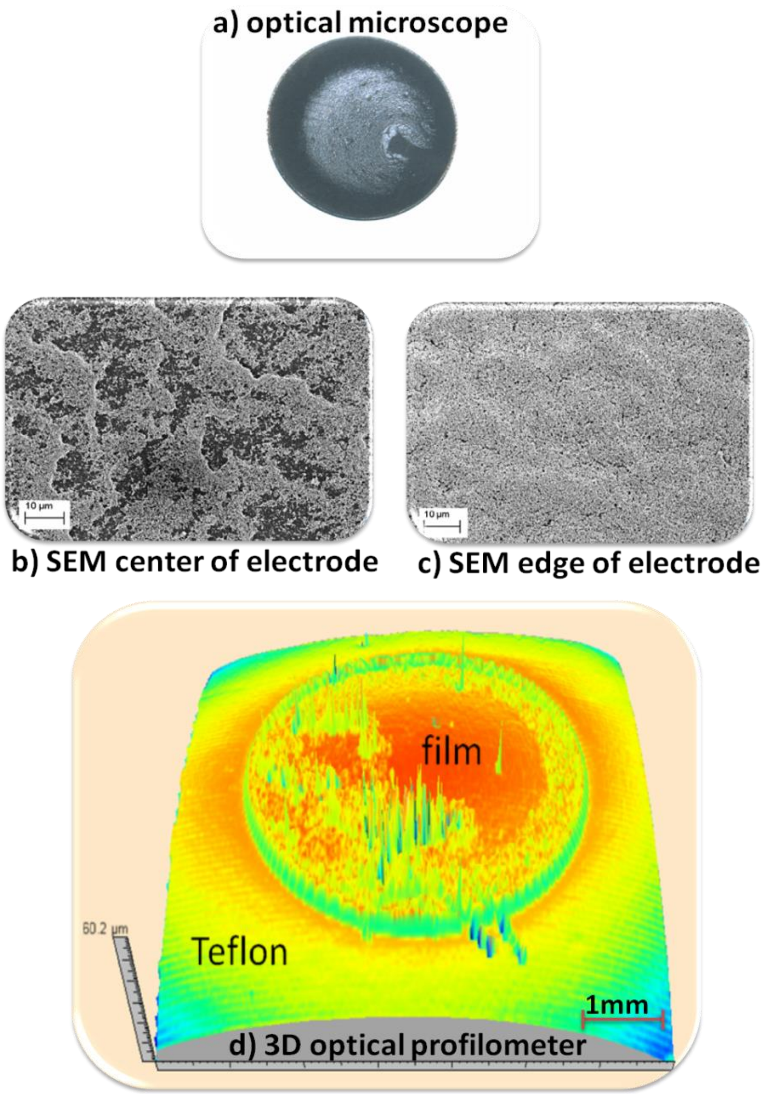




- MEA preparation and testing
  - Demanding, needs large amounts of catalyst
- Ex situ, rotating-disk electrode (RDE) measurements
  - Useful for determining electrocatalyst activity trends
- Variability of oxygen reduction reaction (ORR) activities reported in the literature for the same catalyst = **the need for a standardized method for using RDE to measure catalyst activity**

Acknowledgment: NRL

Example of Challenges in Technique

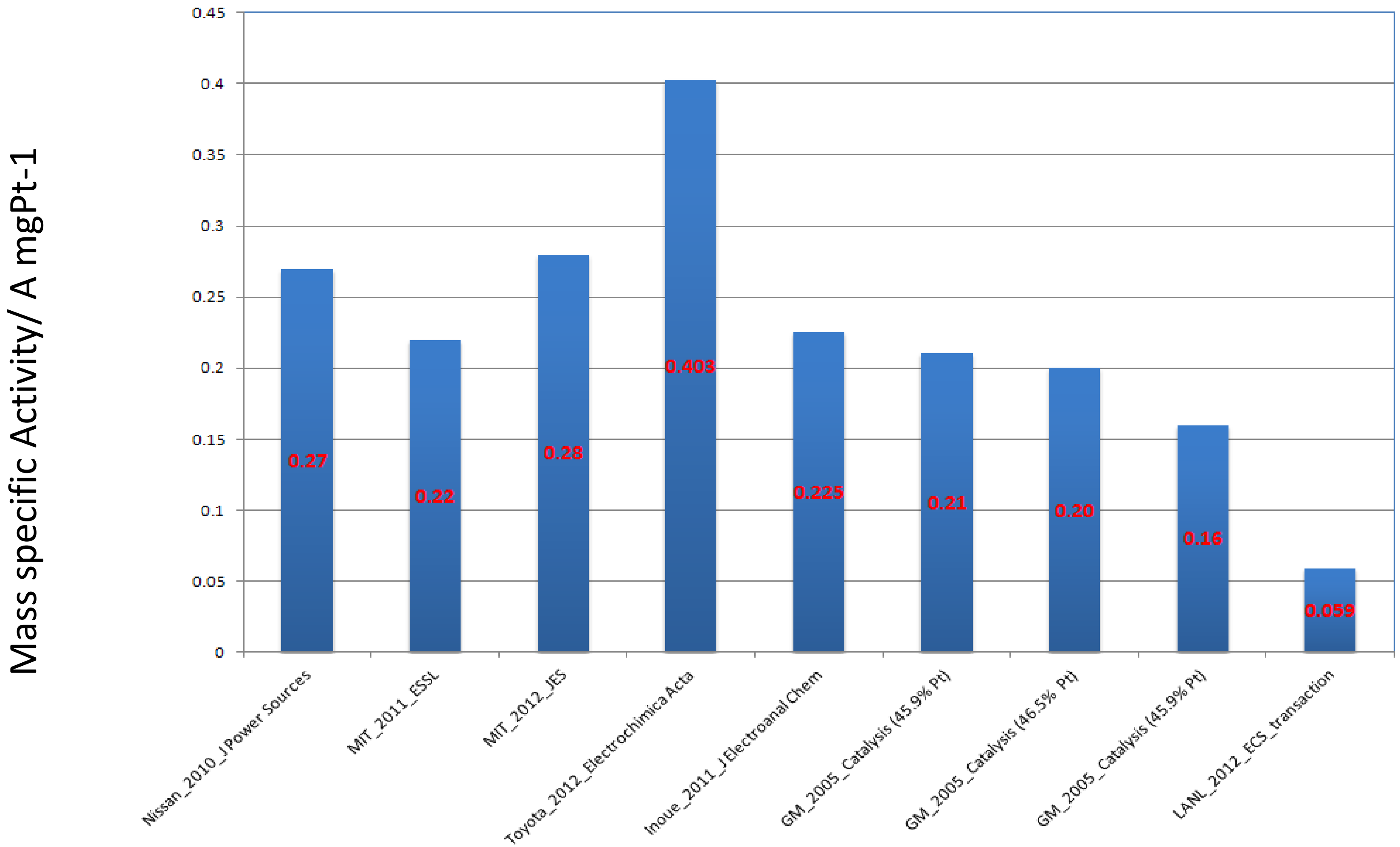


Stationary drying method thin-film morphology

- Fairly uniform on the edge of electrode
- Thinner region towards the center of electrode
- **Coffee ring structure at the edge**

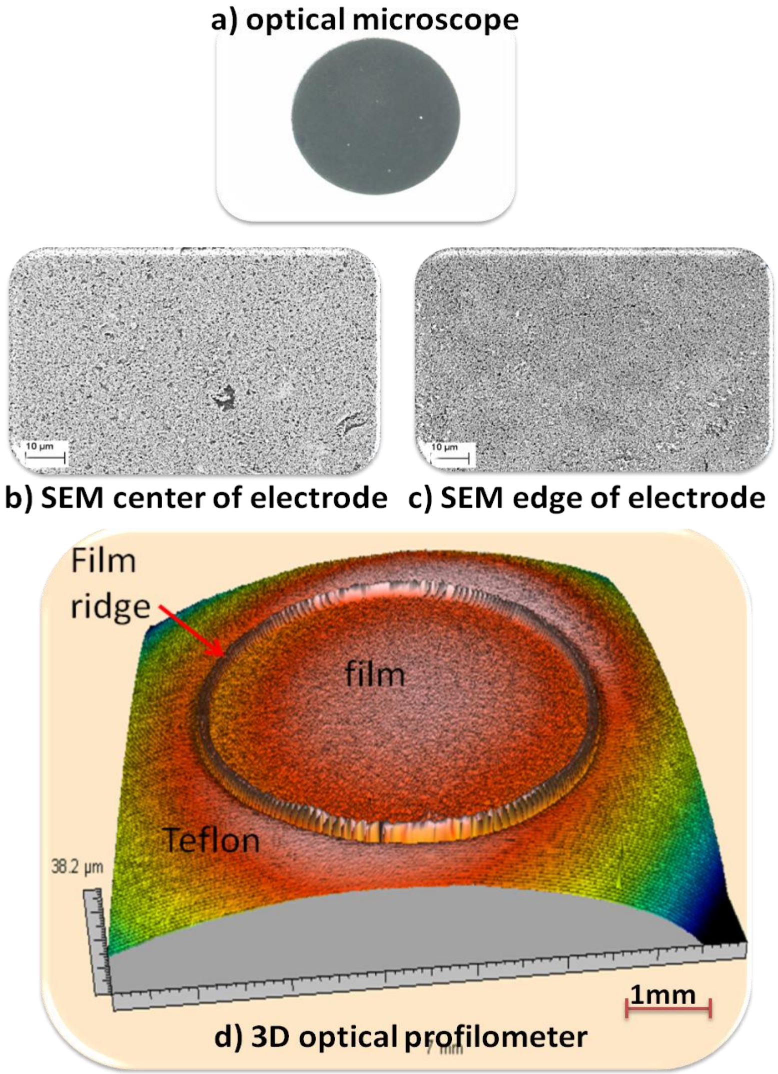
Y. Garsany, I.L. Singer, K.E. Swider-Lyons, S.S. Kocha, Impact of film drying procedures on the RDE characterization of Pt/VC electrocatalyst, J. Electroanal. Chem. 662 (2011) 396-406.

RDE Experimental Variability



ORR activity values reported in the literature for the same commercial Pt/C catalyst (Tanaka)

Technique Improvement



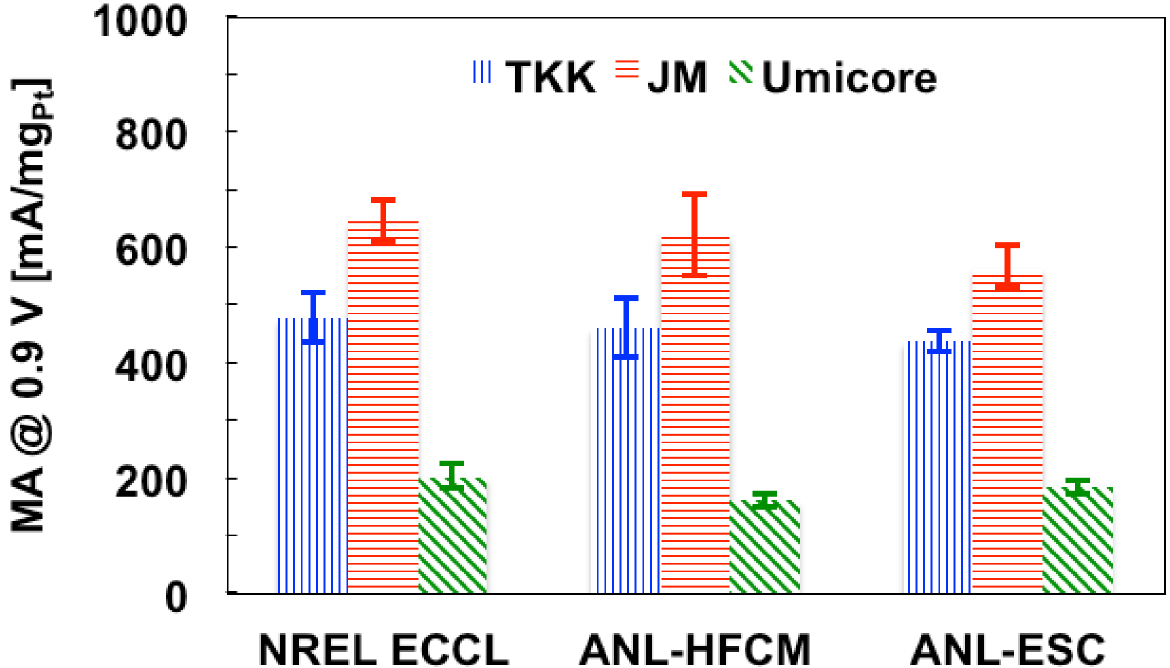
Rotational drying method thin-film morphology

- Very uniform over the entire surface
- **No Coffee ring structure visible**

Y. Garsany, I.L. Singer, K.E. Swider-Lyons, S.S. Kocha, Impact of film drying procedures on the RDE characterization of Pt/VC electrocatalyst, J. Electroanal. Chem. 662 (2011) 396-406.

RDE Testing Protocol and Best Practices Disseminated

Test protocol and best practices validated at NREL and ANL



Nafion-based Rotational Air Drying (N-RAD) most reliable method for routine screening

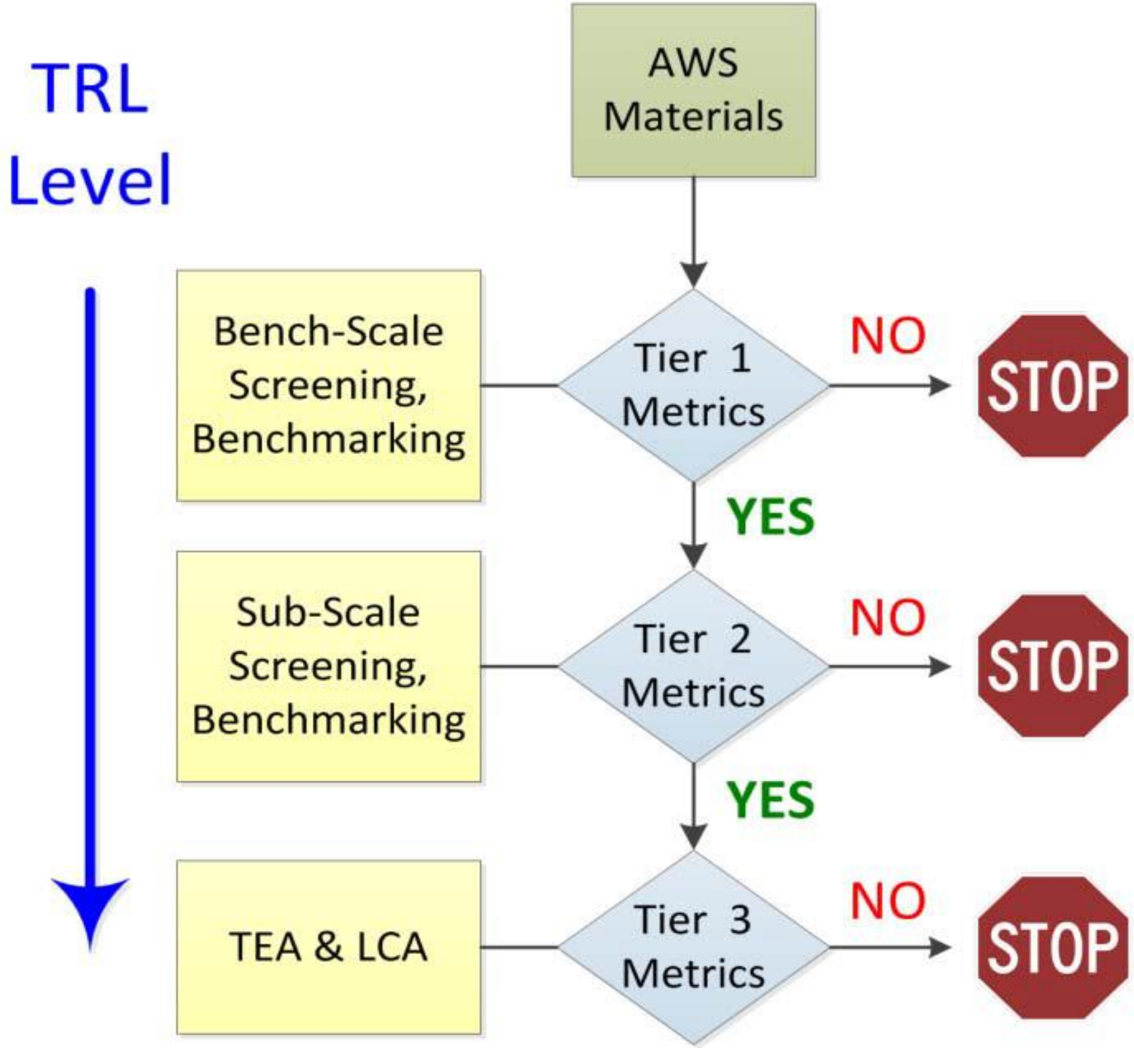
Kocha, Shyam S., Kazuma Shinozaki, Jason W. Zack, Deborah J. Myers, Nancy N. Kariuki, Tammi Nowicki, Vojislav Stamenkovic, Yijin Kang, Dongguo Li, and Dimitrios Papageorgopoulos. *"Best Practices and Testing Protocols for Benchmarking ORR Activities of Fuel Cell Electrocatalysts Using RDE."* ***Electrocatalysis (2017): 1-9. doi:10.1007/s12678-017-0378-6***

NEW EERE AWARD

Lab Collaboration with Industry on Protocols under HydroGEN

Proton, National Labs and other industry

Material Performance Metrics - Example



Consensus-based performance metrics offer neutral, unbiased process for down-selects

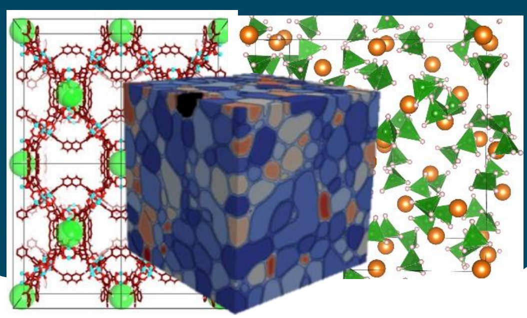
HyMARC Advanced Hydrogen Storage Materials

Provides **foundational understanding** of thermodynamics and kinetics to advance solid-state hydrogen storage materials

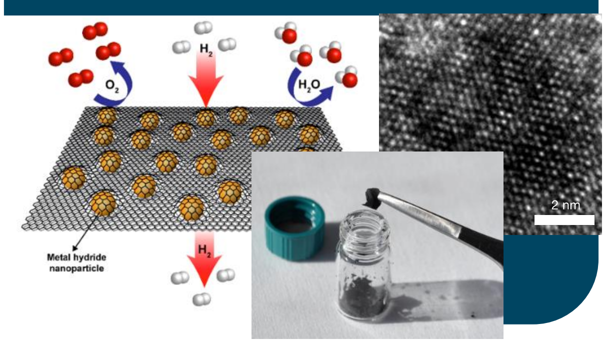
Delivers **community tools and capabilities:**

- High-throughput materials screening
- Surface, bulk, soft X-ray, synchrotron
- Probing nanoscale phenomena

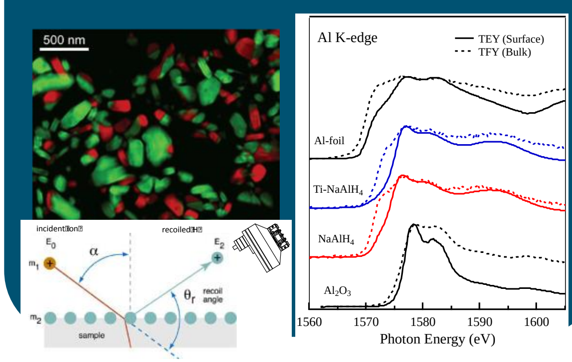
Theory, simulation, & data



Controlled synthesis



In situ characterization

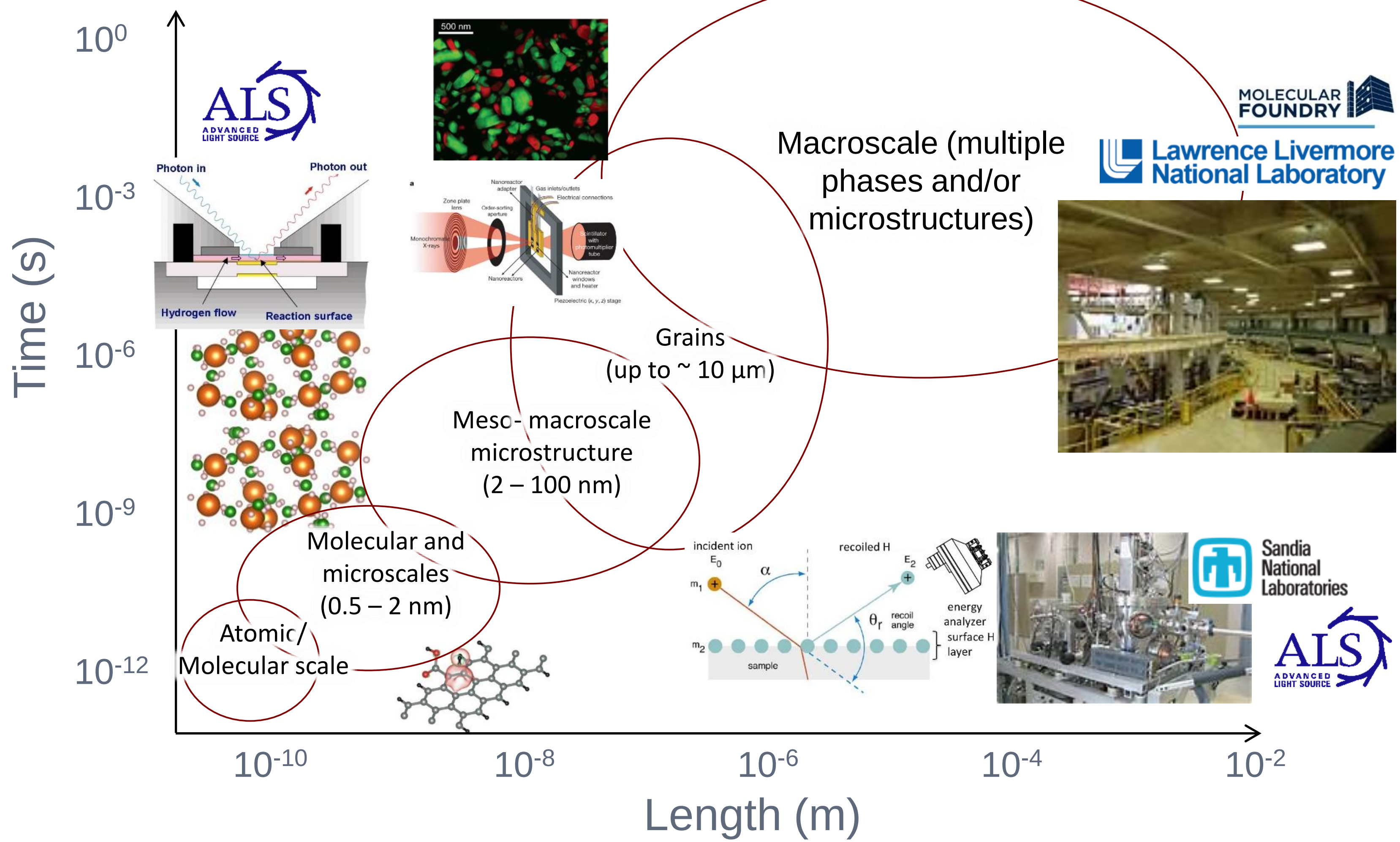


Collaborate with HyMARC!

Visit hymarc.org , use the "contact" tab

HyMARC Tackles Key Multiphysics/Multiscale Challenges

Extensive suite of state-of-the-art tools to probe bulk and surface chemistry, microstructure, phase composition

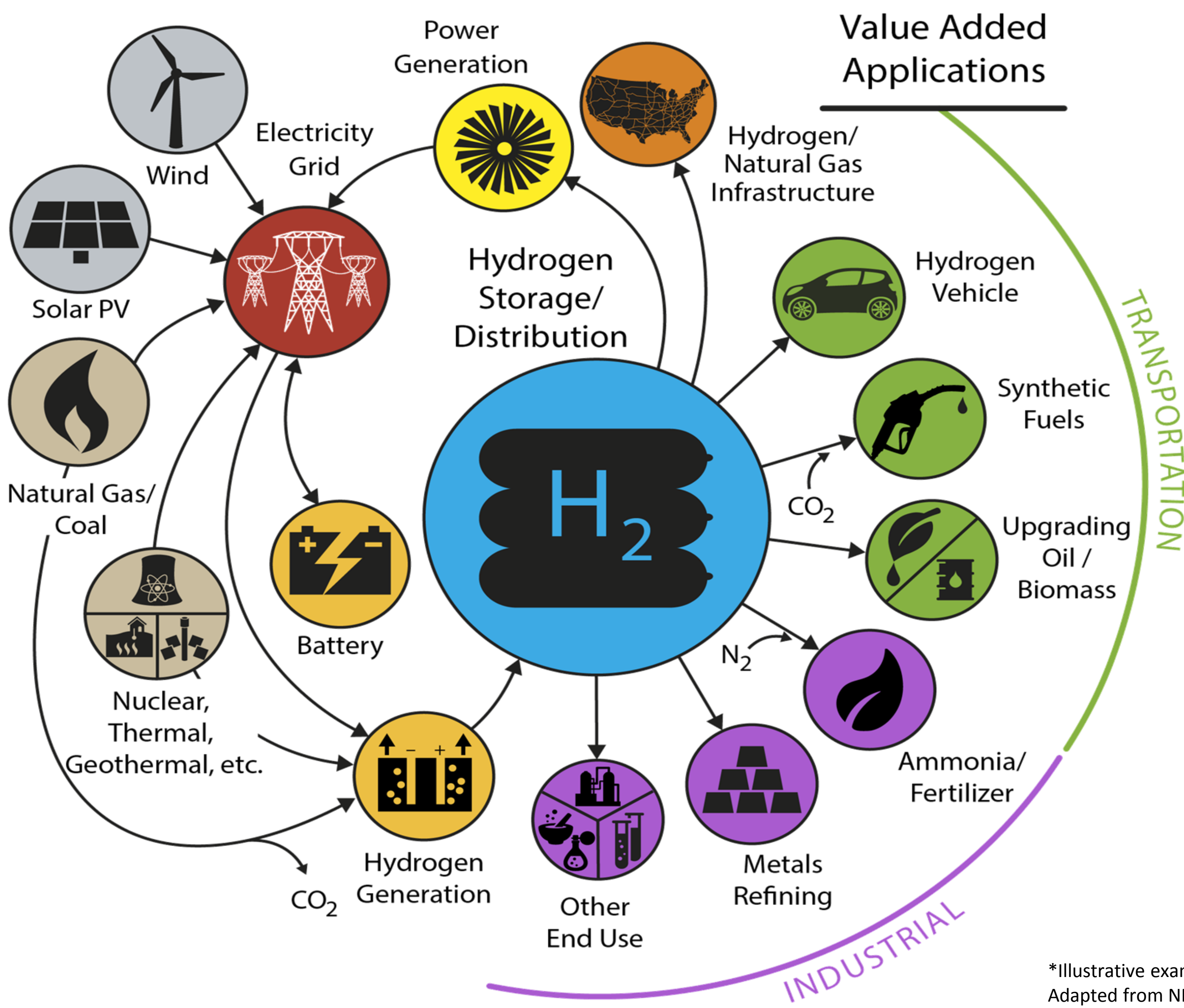


Electrochemistry to the rescue in other areas

- Studying bipolar plate corrosion
- Enabling lower cost and more durable plates
- Electrochemical compression
- Sensors, contaminant detectors
- Other ideas?

Key Areas Moving Forward

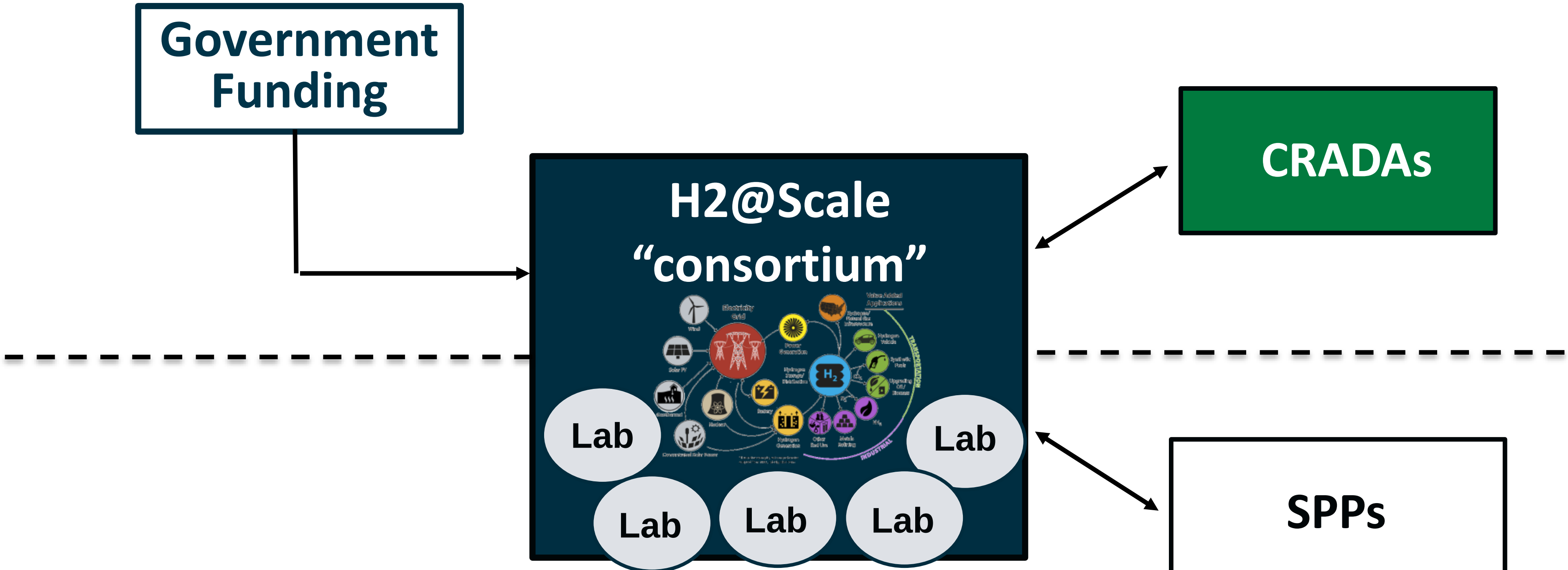
H2@Scale Energy System



*Illustrative example, not comprehensive
Adapted from NREL, Lab Big Idea Team

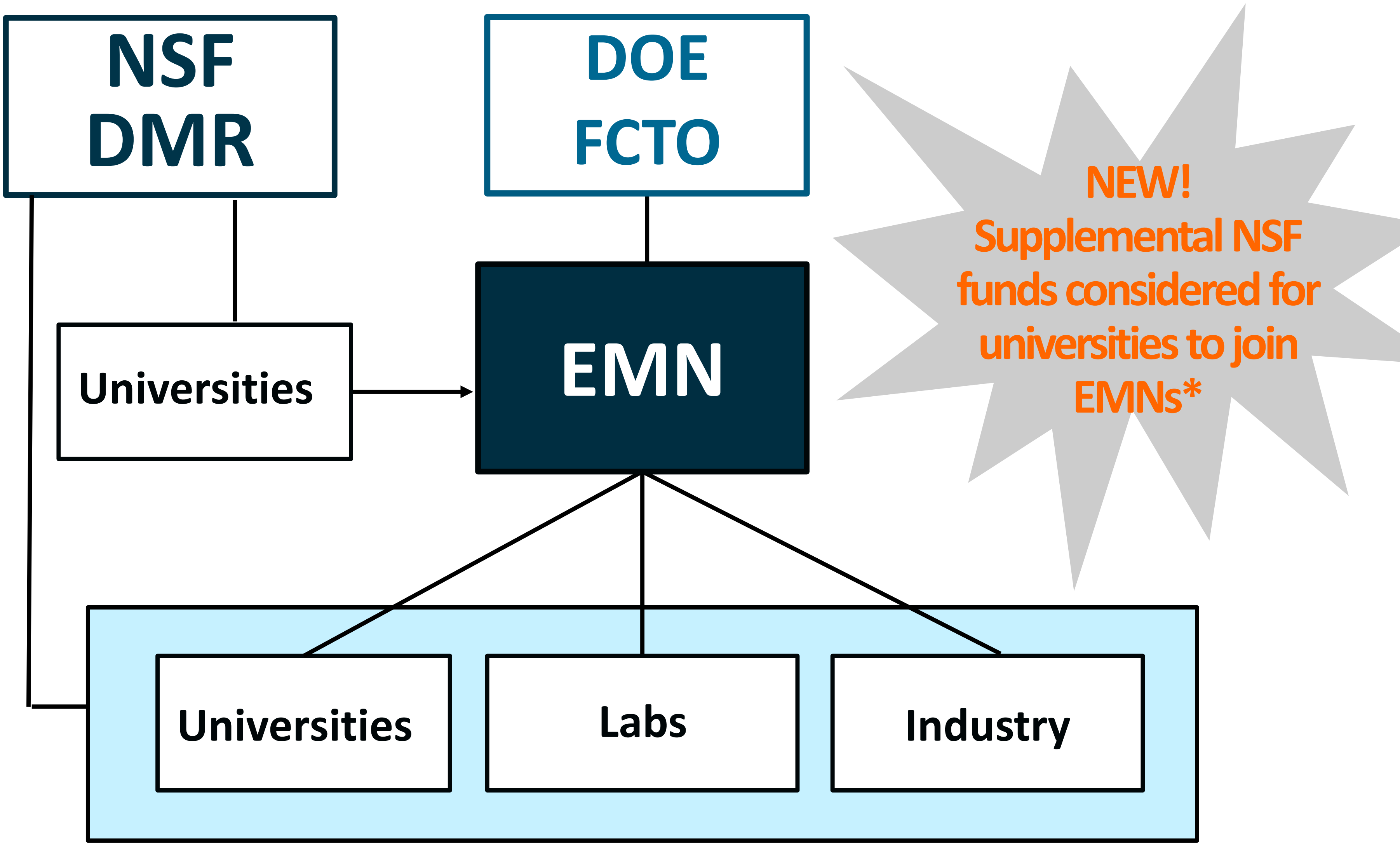
H2@Scale CRADA Call

- To leverage **lab capabilities and expertise to address challenges- materials R&D, analysis, safety R&D, etc.**
- **Round 1 closed Sept. 15 – stay tuned for winners and future rounds**



CRADA = Cooperative Research and Development Agreement
SPP- Strategic Partnership Project ('Work for Others')

Leveraging Funding- Example Pilot

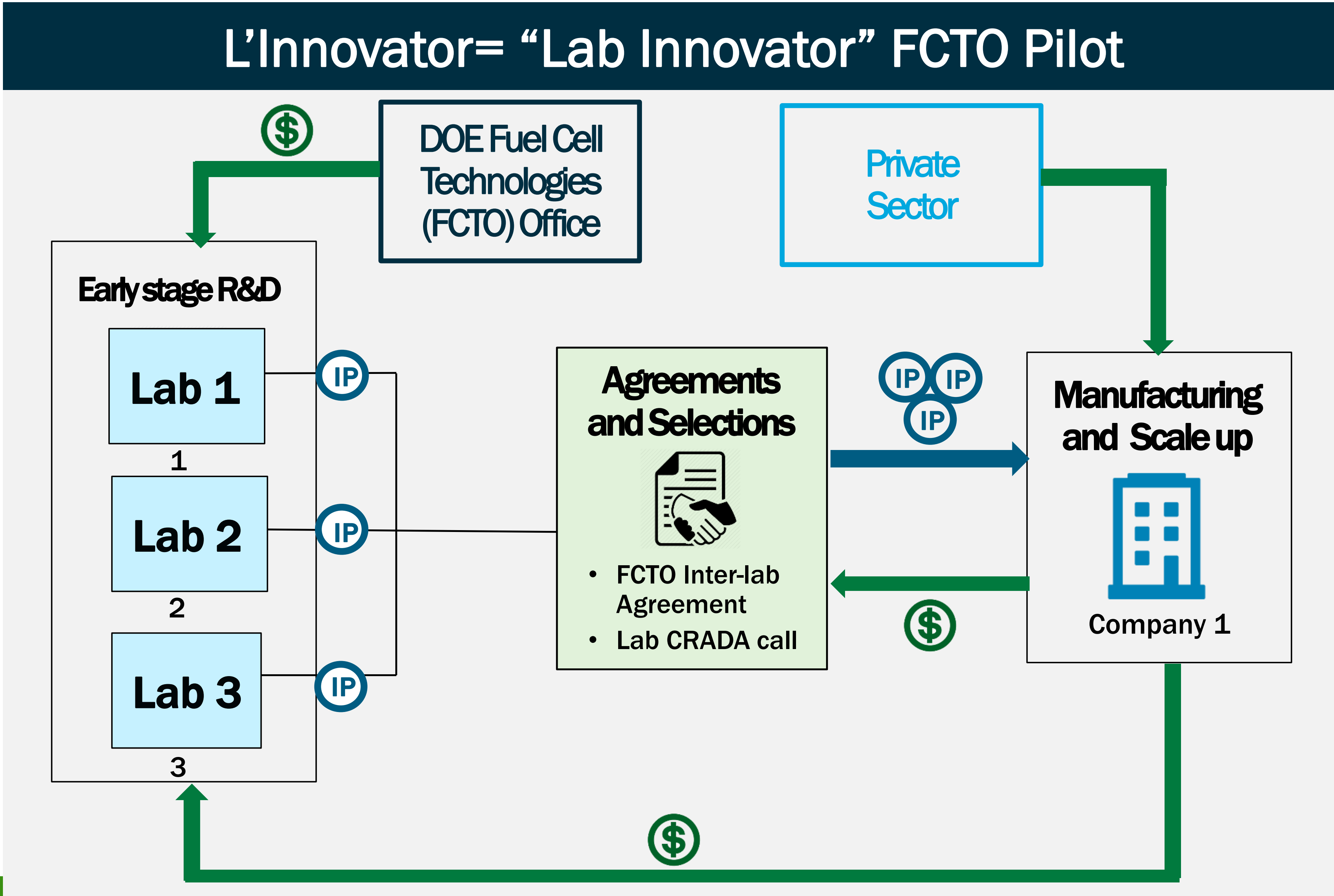


DMR- Division of Materials Research, NSF

FCTO- Fuel Cell Technologies Office, EERE, DOE

* Guidance to be provided by NSF DMR in upcoming 'Dear Colleague' communications

Leverage Private Sector to Accelerate Lab IP to Market



New Online Resources - we need your help!

Spread the word on

H_2 Safety Lessons Learned!

Share at regular team meetings

Provide feedback to FCTO and stakeholders

Find lessons learned at **H2tools.org**

Spread the word….

National Hydrogen & Fuel Cell Day | 10·08

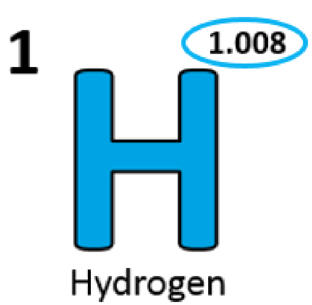
See Electrochemistry in Action while at ECS!

Celebrate Hydrogen & Fuel Cell Day on 10/8

(Held on its very own atomic-weight-day)

Ride-and-Learn

World's First Commercial Fuel Cell Cars



When: Monday, Oct 2, 12pm -2pm

Where: Outside the Maryland Ballroom doors – Gaylord National Convention Center

Thank You

Dr. Sunita Satyapal
Director
Fuel Cell Technologies Office
Sunita.Satyapal@ee.doe.gov

energy.gov/eere/fuelcells