U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

FCTO’s HydroGEN AWSM Energy Materials Network Overview Webinar

Huyen N. Dinh, National Renewable Energy Laboratory

This presentation does not contain any proprietary, confidential, or otherwise restricted information

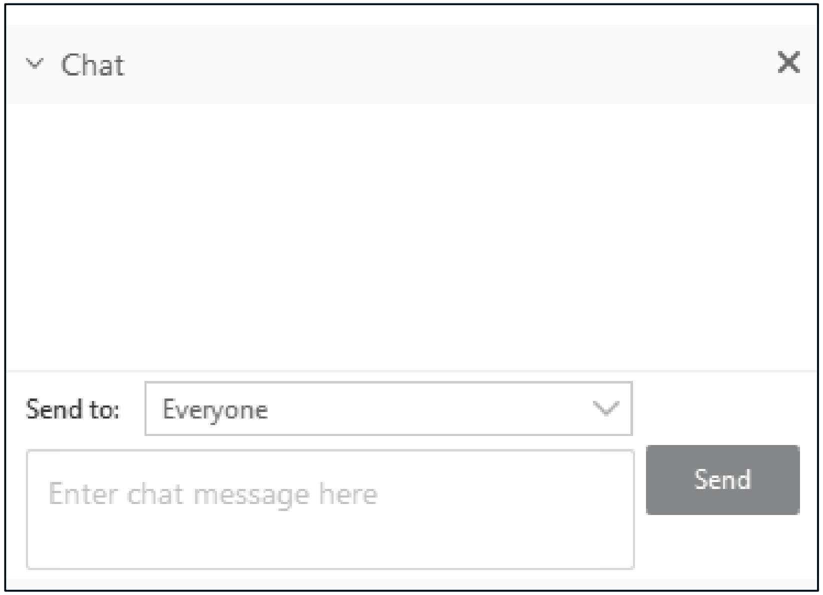
Fuel Cell Technologies Office Webinar

February 7, 2019

This presentation is part of the monthly webinar series provided by the U.S. Department of Energy's Fuel Cell Technologies Office (FCTO) within the Office of Energy Efficiency and Renewable Energy (EERE). Funding for research, development and innovation to accelerate progress in hydrogen and fuel cell technologies is provided by EERE FCTO.

During Q&A session:

Please type your questions to the chat box. **<u>Send to: (HOST)</u>**



Goals and Objectives of H_2 Fuel R&D at FCTO

FCTO Early-Stage R&D Areas

Fuel Cells

- PGM- free catalysts
- Durable MEAs
- Electrode performance

PGM = Platinum group metals
MEA = Membrane Electrode Assembly

Hydrogen

- Production pathways
- Delivery components
- Advanced materials for storage

H_2 Production

- Enable **H_2 production at < $2/kg** utilizing diverse, domestic feedstocks

H_2 Delivery

- Reduce the cost of **delivery and dispensing to $5/kg by 2025 and ultimately $2/kg**

H_2 Storage

- Enable **$8/kWh for on-board H_2 storage cost**

HydroGEN consortium supports early stage R&D in H_2 production

Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

For more information & Engagement with HydroGEN

Go to www.h2awsm.org

For capability node lists and descriptions, technology transfer agreements and currently funded project info

When a FOA is open, first engagement should go through h2awsm@nrel.gov

To identify and discuss capability node(s) of interest

NREL National Renewable Energy Laboratory | Berkeley Lab | Sandia National Laboratories | INL Idaho National Laboratory | Lawrence Livermore National Laboratory | SRNL

Consortium Services

How do I find the right resource to accelerate a solution to my materials challenge?

How do I engage with the National Labs quickly and effectively?

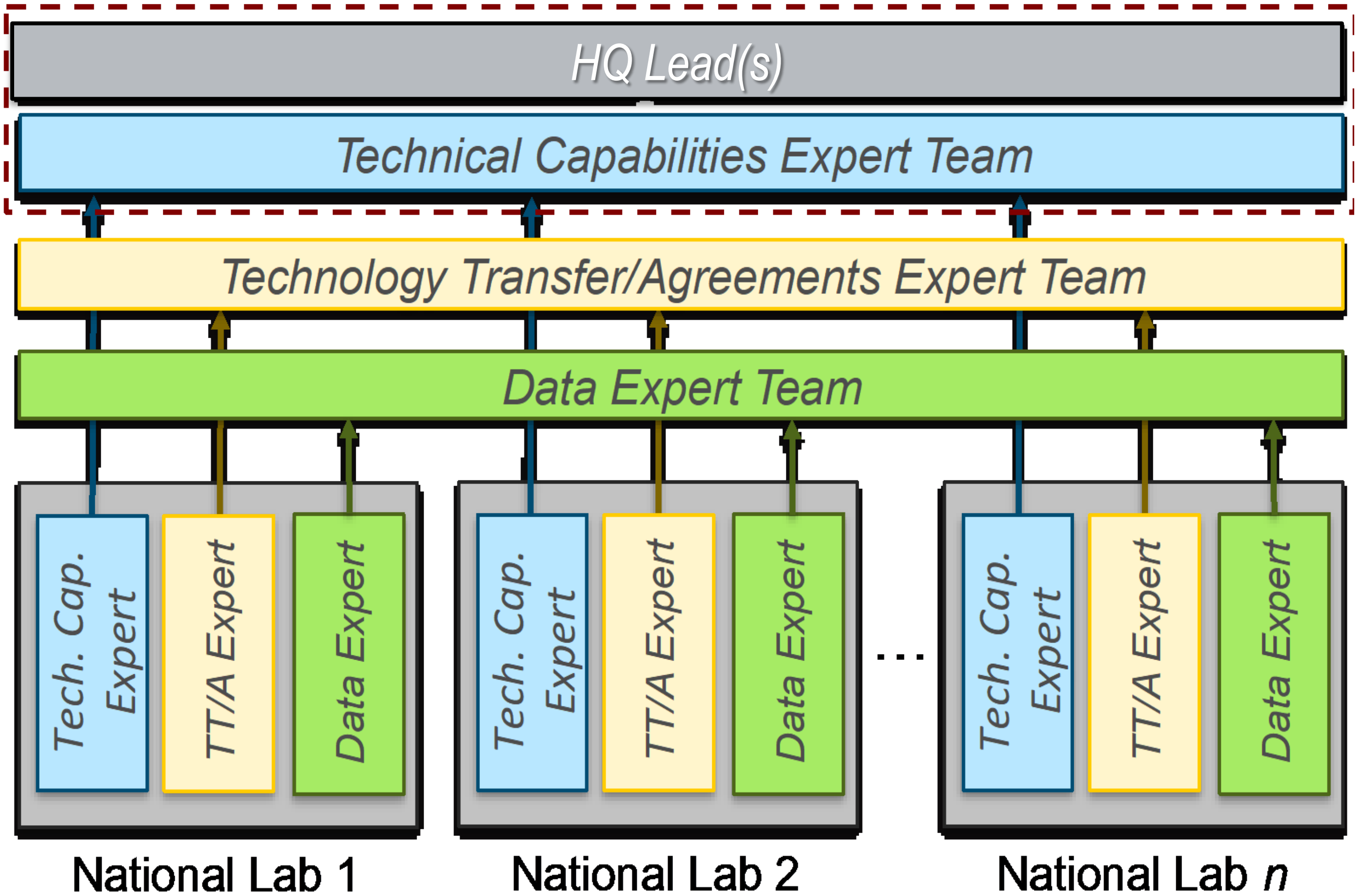
The EMN offers a common yet flexible R&D consortium model to address key materials challenges in specific high-impact clean energy technologies aimed at accelerating the tech-to-market process

Consortium Requirements

Energy Materials Network
U.S. Department of Energy

- **World Class Materials Capability Network:** *Create and manage a **unique, accessible set of capabilities** within the DOE National Laboratory system.*
- **Clear Point of Engagement:** *Provide a **single point-of-contact** and concierge to direct interested users (e.g. industry research teams) to the appropriate laboratory capabilities, and to **facilitate efficient access**.*
- **Data and Tool Collaboration Framework:** ***Capture data, tools, and expertise** developed at each node such that they can be **shared and leveraged** throughout the EMN and **in future programs**. Establish data repositories and, where appropriate, distribute data to the scientific community and public. Accelerate learning and development through data analysis using advanced informatics tools.*
- **Streamlined Access:** *Facilitate **rapid completion of agreements** for external partners, and aggressively pursue approaches to reduce non-technical burden on organizations seeking to leverage the EMN for accelerated materials development.*

Consortium Steering Teams

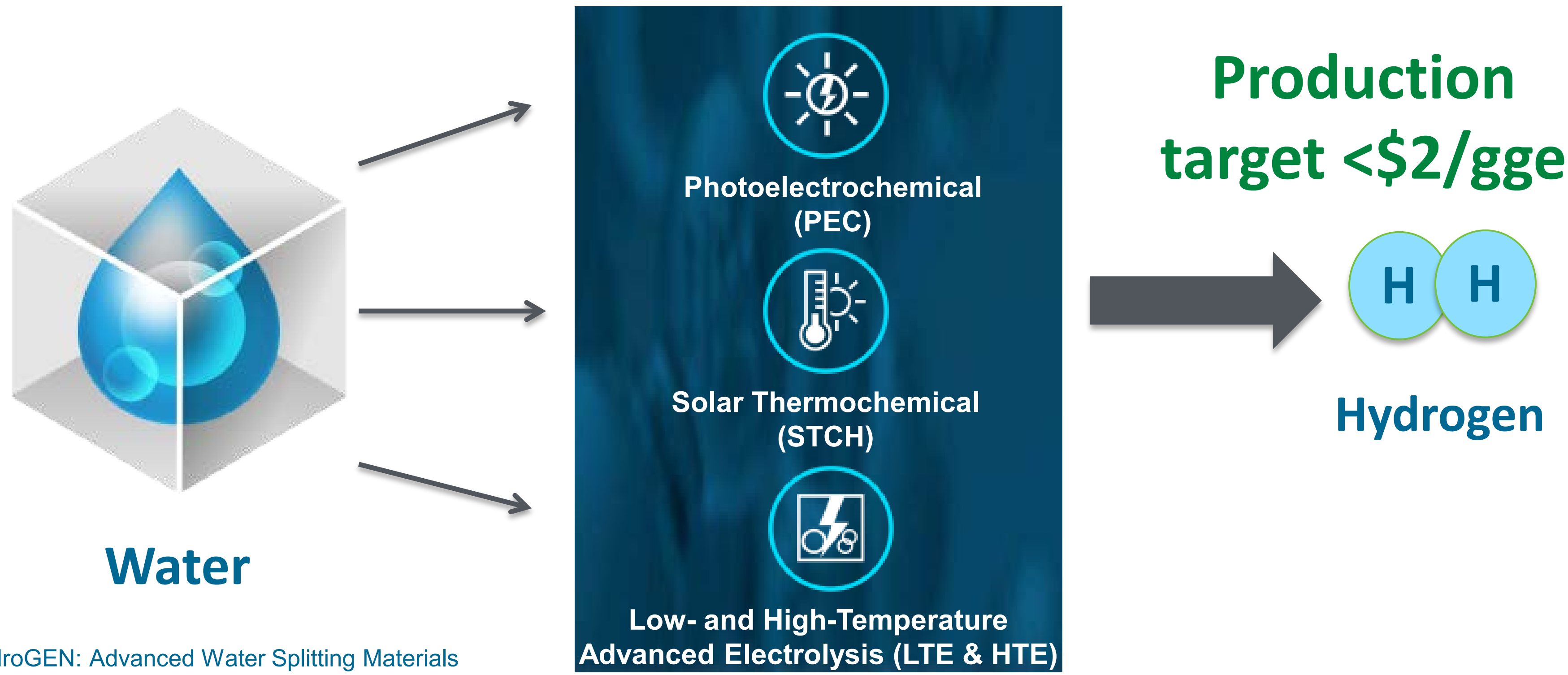


Advanced Water-Splitting Materials (AWSM)

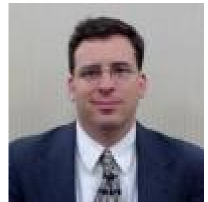
AWSM Consortium Six Core Labs:

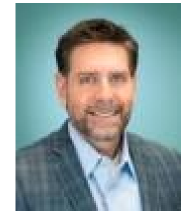
NREL National Renewable Energy Laboratory
Berkeley Lab
Sandia National Laboratories
INL Idaho National Laboratory
Lawrence Livermore National Laboratory
SRNL

Accelerating R&D of innovative materials critical to advanced water splitting technologies for clean, sustainable, and low cost H_2 production, including:



HydroGEN Steering Committee





Huyen Dinh (Director)

Adam Weber (Deputy Director)

Anthony McDaniel (Deputy Director)

Richard Boardman

Tadashi Ogitsu

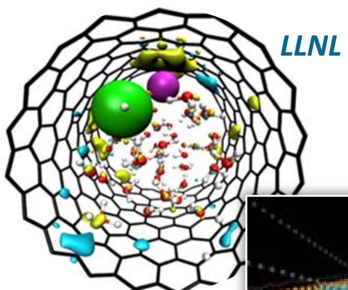
Donald Anton

Eric Miller and Katie Randolph, DOE-EERE-FCTO

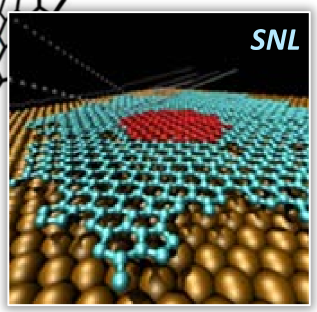
HydroGEN-AWSM Consortium

Comprising more than 80 unique, world-class capabilities/expertise in:

Materials Theory/Computation

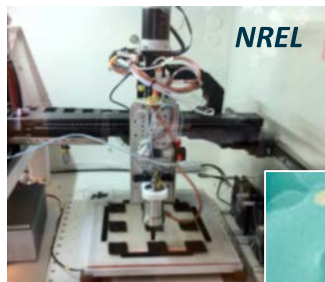


Bulk & interfacial models of aqueous electrolytes

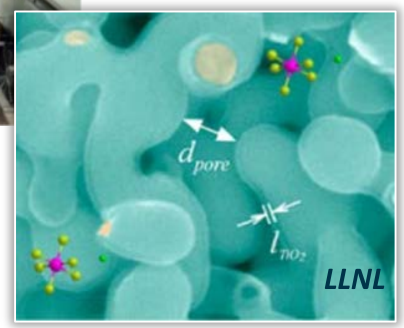


LAMMPS classic molecular dynamics modeling relevant to H_2O splitting

Advanced Materials Synthesis



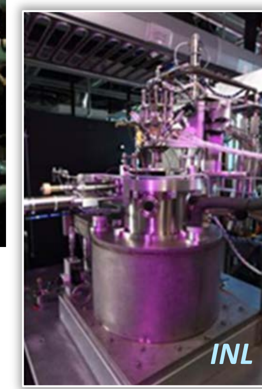
High-throughput spray system for electrode fabrication



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 fosters cross-cutting innovation using theory-guided applied materials R&D to advance all emerging water-splitting pathways for hydrogen production

Capability Nodes on the User-Friendly Node Search Engine for Stakeholders

Search

Reset filtering

CAPABILITY CLASS

- Analysis
- Benchmarking
- Characterization
- Computational Tools and Modeling
- Data Management
- Material Synthesis
- Process and Manufacturing Scale-Up
- System Integration

WATER-SPLITTING TECHNOLOGY

High-Temperature Electrolysis

- HTE 1
- HTE 2
- HTE 3

Low-Temperature Electrolysis

- LTE 1
- LTE 2
- LTE 3

Photoelectrochemical

- PEC 1
- PEC 2
- PEC 3

Solar Thermochemical

- STCH 1
- STCH 2
- STCH 3

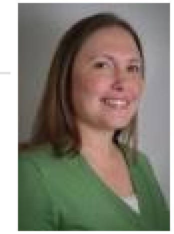
Hybrid Thermochemical

- HT 1
- HT 2
- HT 3

Node Readiness Categories

NATIONAL LABORATORY

- Idaho National Laboratory (INL)
- Lawrence Berkeley National Laboratory (LBNL)
- Lawrence Livermore National Laboratory (LLNL)
- National Renewable Energy Laboratory (NREL)
- Sandia National Laboratories (SNL)
- Savannah River National Laboratory (SRNL)



Show

12

Apply

Reset

Showing 1 to 12 of 82 entries

1 2 3 4 Next

Ab Initio Modeling of Electrochemical Interfaces	LLNL	PEC 1, LTE 2
Advanced Electron Microscopy	SNL	HTE 1, LTE 1, PEC 1, STCH 1
Advanced Materials for Water Electrolysis at Elevated Temperatures	INL	HTE 2

https://www.h2awsm.org/capabilities

HydroGEN FOA-Awarded Projects

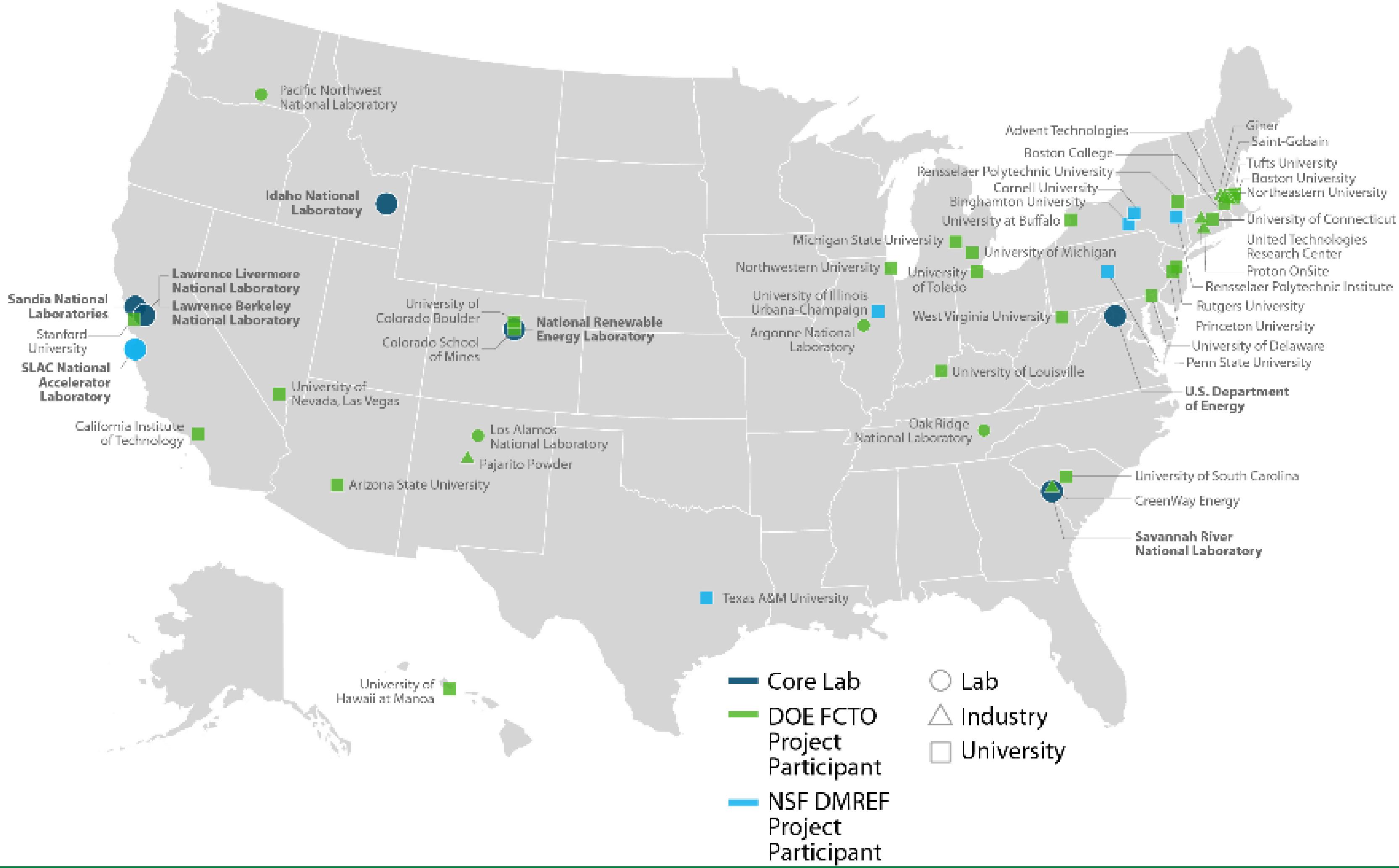
21 proposals selected, negotiated, and awarded

44 unique capabilities being utilized across six core labs

Advanced Electrolysis (10)	PEC (5)	STCH (5)
LTE (5) HTE (5)	Benchmarking & Protocols (1)	2-Step MO_x (4) Hybrid cycle (1)

National Innovation Ecosystem

11 Labs **7** Companies **30** Universities **2** Funding Agencies



HydroGEN is vastly collaborative and focused on early-stage R&D

A Balanced AWSM R&D Portfolio

Low Temperature Electrolysis (LTE) (5 Projects)

PEME Component Integration

PEM Electrolysis

- PGM-free OER and HER catalyst
- Novel AEM and Ionomers
- Electrodes

AEM Electrolysis

High Temperature Electrolysis (HTE) (5 Projects)

- Degradation mechanism at high current density operation
- Nickelate-based electrode & scalable, all-ceramic stack design

O^{2-} conducting SOEC

- High performing and durable electrocatalysts
- Electrolyte and electrodes
- Low cost electrolyte deposition

H^{+} conducting SOEC

Photoelectrochemical (PEC) (5 Projects)

- III-V and Si-based semiconductors
- Chalcopyrites
- Thin-film/Si
- Protective catalyst system
- Tandem cell

Semiconductors

- PGM-free catalyst
- Earth abundant catalysts
- Layered 2D perovskites
- Tandem junction

Perovskites

Solar Thermochemical (STCH) (5 Projects)

- Computation-driven discovery and experimental demonstration of STCH materials
- Perovskites, metal oxides

STCH

- Solar driven sulfur-based process (HyS)
- Reactor catalyst material

Hybrid Thermochemical

PEME = proton exchange membrane electrolysis;
AEME = alkaline exchange membrane electrolysis

PGM = platinum group metal
Solid oxide electrolysis cells: SOEC

Low Temperature Electrolysis (45 Nodes)

Low Temperature Electrolysis (LTE)
- **Proton Exchange Membrane (PEM)**
- **Alkaline Exchange Membrane (AEM)**

13 nodes used by current LTE projects

LTE Node Labs

Idaho National Laboratory (INL)

Berkeley Lab

NREL – National Renewable Energy Laboratory

Lawrence Livermore National Laboratory

Support through:

Personnel
Equipment
Expertise
Capability
Materials
Data

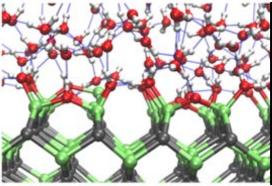
LTE Projects

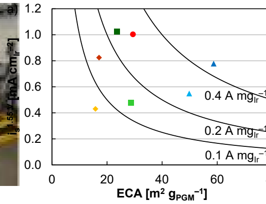
Proton OnSite / nel – number one by nature – Your source for all things hydrogen

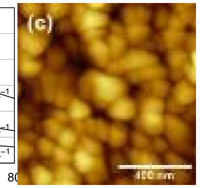
Argonne National Laboratory

Northeastern University – Center for Renewable Energy Technology

Los Alamos National Laboratory – Est. 1943 (2)







High Temperature Electrolysis (39 Nodes)

High Temperature Electrolysis (HTE)
- Oxygen Conducting SOEC (o-SOEC)
- Proton Conducting SOEC (p-SOEC)

6 nodes used by current HTE projects

HTE Node Labs

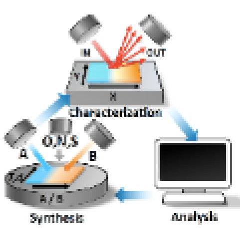
Idaho National Laboratory (INL)
Berkeley Lab
NREL – National Renewable Energy Laboratory
Lawrence Livermore National Laboratory

Support through:

Personnel
Equipment
Expertise
Capability
Materials
Data

HTE Projects

United Technologies Research Center
UCONN
Northwestern
West Virginia University
Saint-Gobain – Saint-Gobain Research North America



Photoelectrochemical Water Splitting (56 Nodes)

PEC: Photoelectrochemical (PEC) Water Splitting

17 nodes used by current PEC projects

PEC Node Labs

Idaho National Laboratory

BERKELEY LAB

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Lawrence Livermore National Laboratory

Support through:

Personnel
Equipment
Expertise
Capability
Materials
Data

PEC Projects

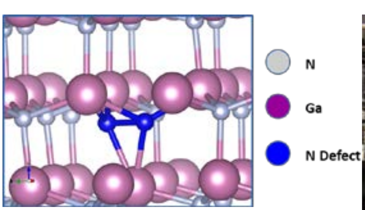
THE STATE UNIVERSITY OF NEW JERSEY RUTGERS

University of Hawai'i

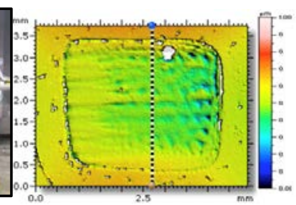
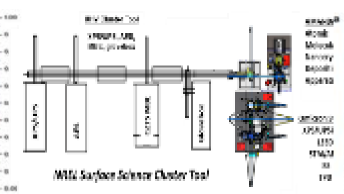
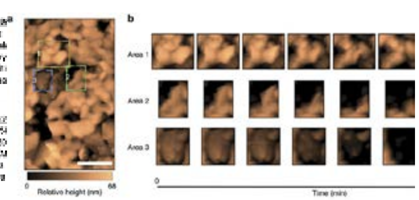
University of Michigan

Stanford University

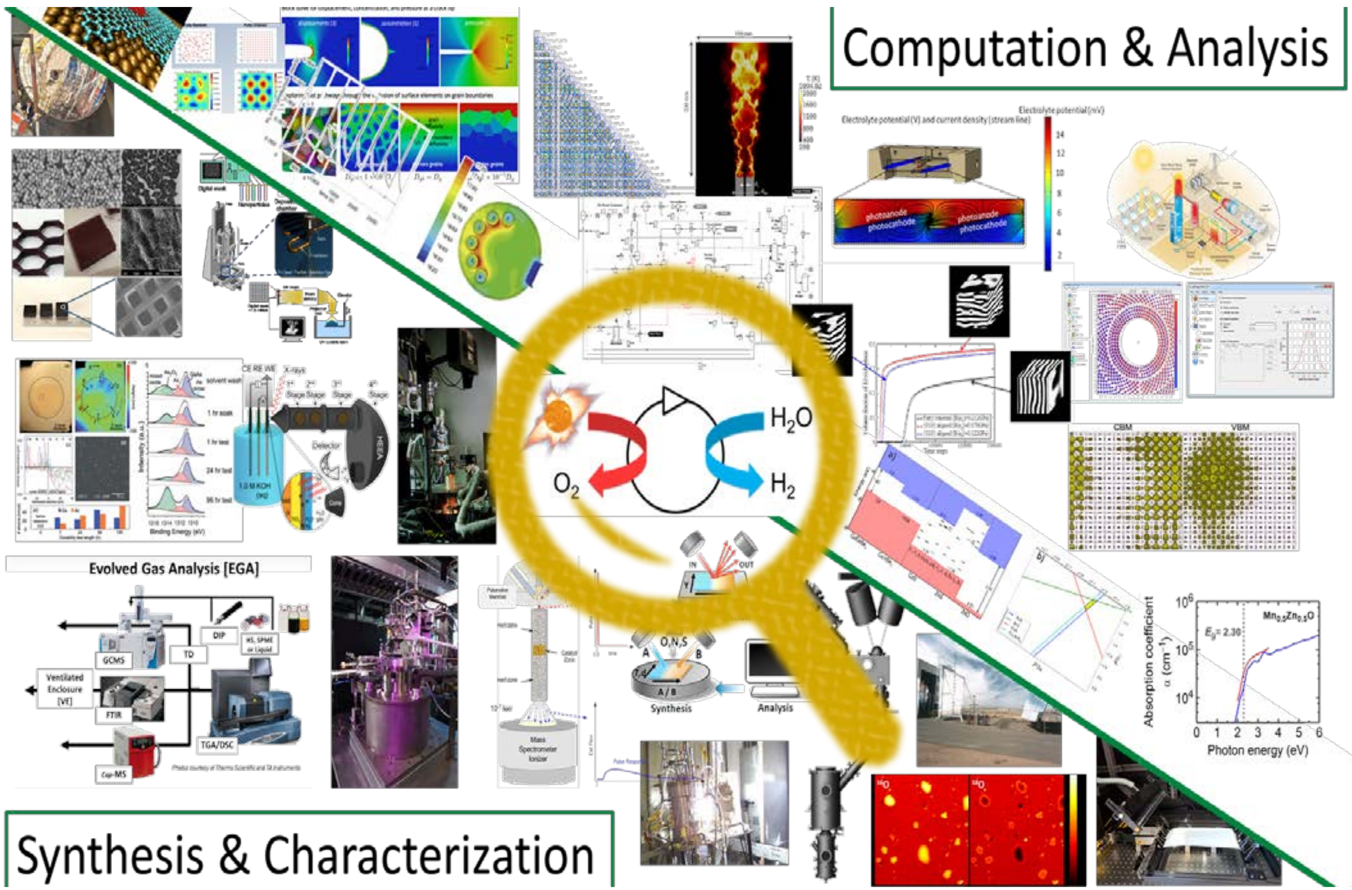
Los Alamos National Laboratory EST. 1943





Solar and Hybrid Thermochemical (39 Nodes)



STCH Projects

Arizona State University

Northwestern

Greenway Energy LLC

Engineering consultant in Aiken County, South Carolina

11 nodes from 5 National Labs supporting 5 STCH projects

Sandia National Laboratories

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Lawrence Livermore National Laboratory

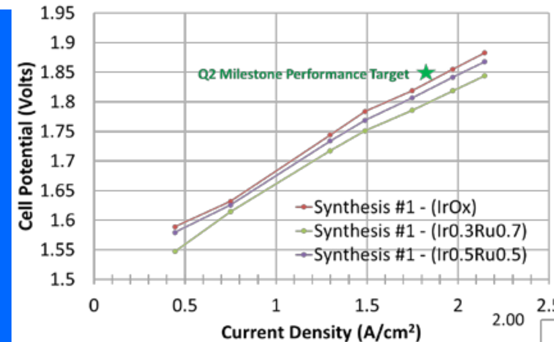
INL Idaho National Laboratory

SRNL SAVANNAH RIVER NATIONAL LABORATORY

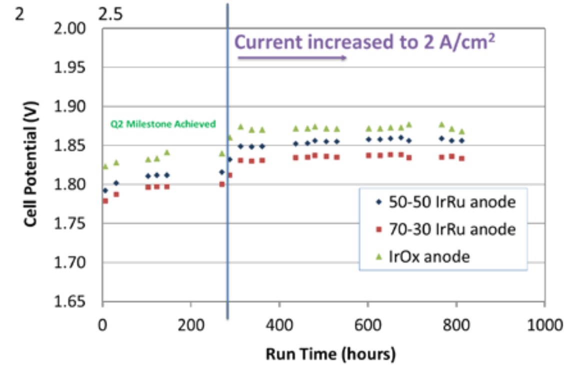
HydroGEN Collaborative R&D Technical Highlights

Low Temperature Electrolysis (LTE)

NREL's contributed towards **Proton Onsite** achievement of **1.8 V at 2.0 A/cm²**, and **800 h PEM electrolysis durability at 2 A/cm²**, operating at 80°C and 30 bar. Proton's improved cell efficiency **is a step towards achieving its PEM water electrolysis cell efficiency goal of 43 kWh/kg** (1.7 V at 90°C) and at a cost of $2/kg H_2, a significant improvement over the state-of-the-art cell efficiency of 53 kWh/kg.

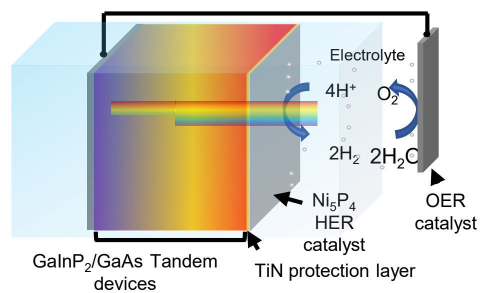


PROTON ON SITE
nel number one by nature
YOUR SOURCE FOR ALL THINGS HYDROGEN

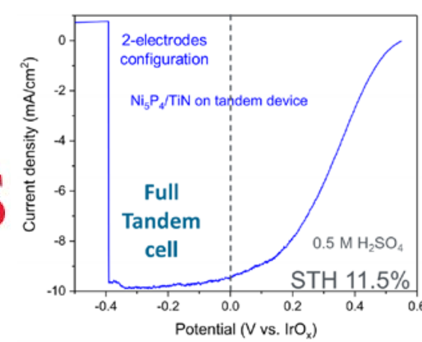


Photoelectrochemical (PEC) Water Splitting

NREL's high performance photoabsorber ($GaInP_2/GaAs$), integrated with **Rutgers' PGM-free electrocatalysts** ($LiCoO_2$ and Ni_5P_4) and protection layer (TiN), achieved a solar-to-hydrogen efficiency of **11.5%** for unassisted water splitting, on par performance with conventional PGM electrocatalysts (PtRu).



RUTGERS

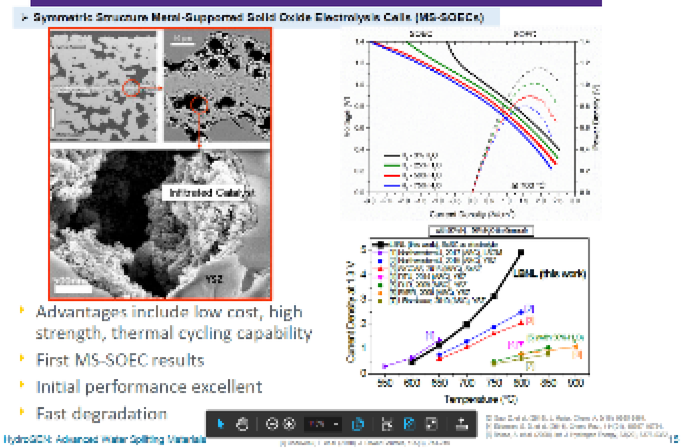


HydroGEN Collaborative R&D Technical Highlights

High Temperature Electrolysis (HTE)

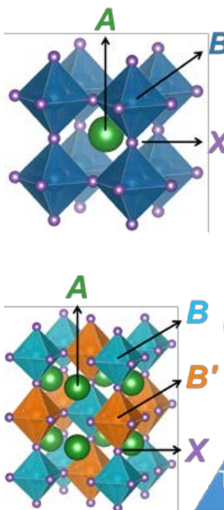
Using Northwestern University catalyst, YSZ electrolyte ($(ZrO_2)_{0.92}(Y_2O_3)_{0.08}$), and LBNL Metal-Supported Solid Oxide Cell and INL Advanced HTE testing nodes, the collaboration **demonstrated a metal-supported SOEC for the first time in electrolysis mode, with the highest performance** for oxygen-conducting type electrolysis cells to-date and promising stability.

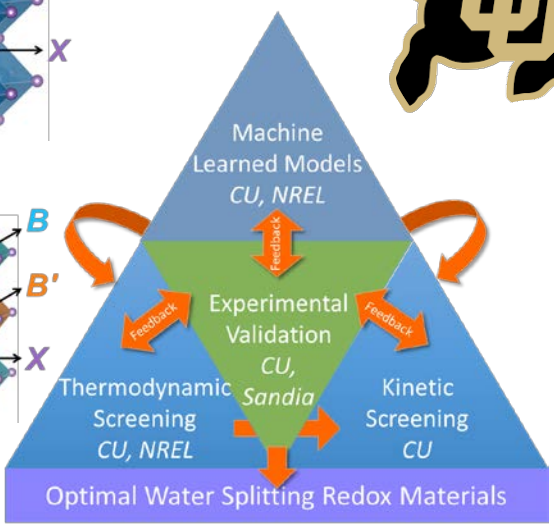
Northwestern



Solar Thermochemical (STCH) Water Splitting

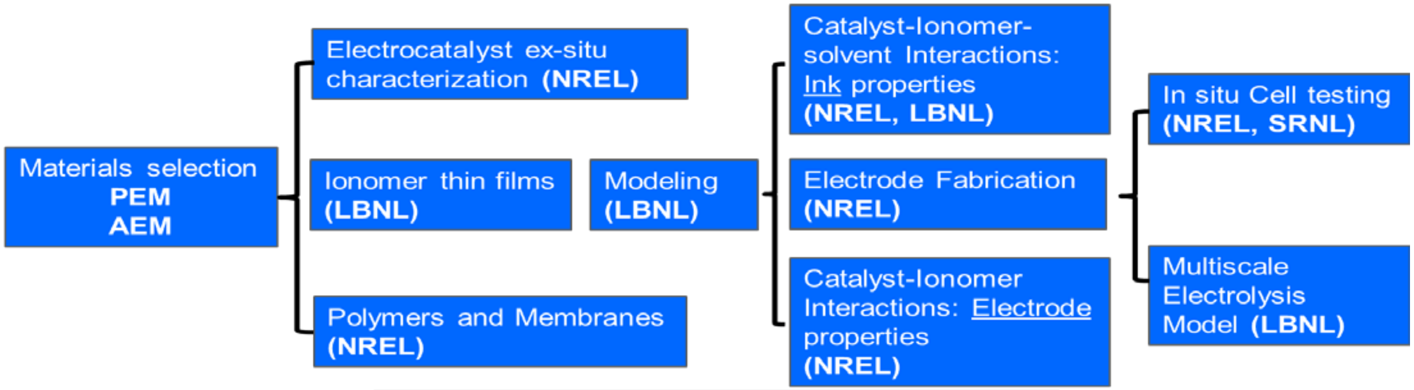
The University of Colorado Boulder, with NREL's DFT node, was able to develop and apply machine learning (ML) to accelerate STCH materials discovery, **identifying several hundred stable STCH perovskites** from over 1.1 million possible candidates, with **92% accuracy**. SNL's stagnation flow reactor and High-Temperature XRD nodes are used to **experimentally validate** water splitting kinetics and crystal structures for a select number of materials, providing critical feedback to **develop rapid kinetic screening techniques of materials**.

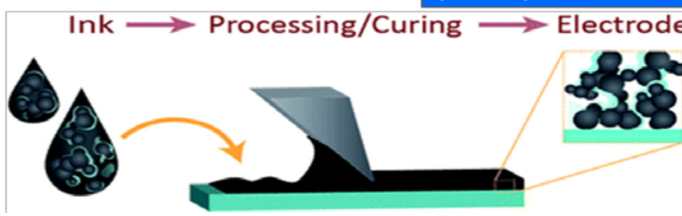




Five New Collaborative "Supernodes" Developed to Accelerate AWSM R&D

1. LTE/Hybrid Supernode : Linking Low Temperature Electrolysis (LTE)/Hybrid Materials to Electrode Properties to Performance (NREL, SRNL, LBNL; 8 Nodes)

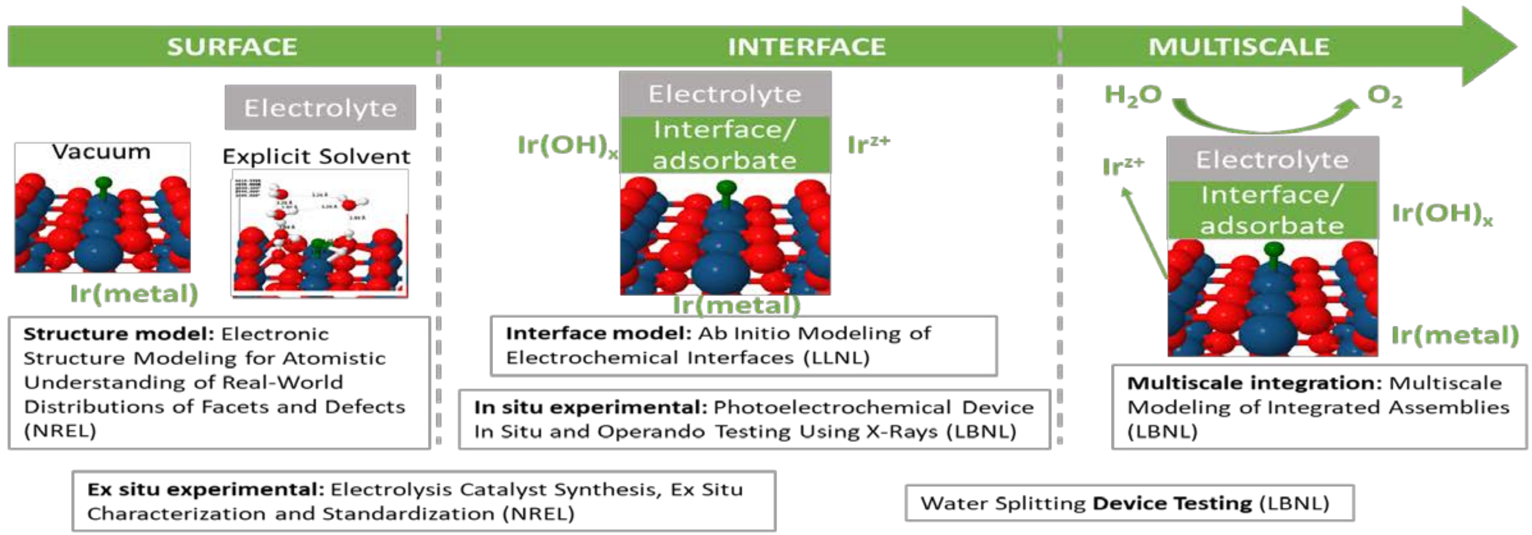




Outcome: *Better integration between ex-situ and in-situ performance, more relevant ex-situ testing, and improved material specific component development to achieve optimized electrolyzer cell performance and durability.*

Five New Collaborative "Supernodes" Developed to Accelerate AWSM R&D

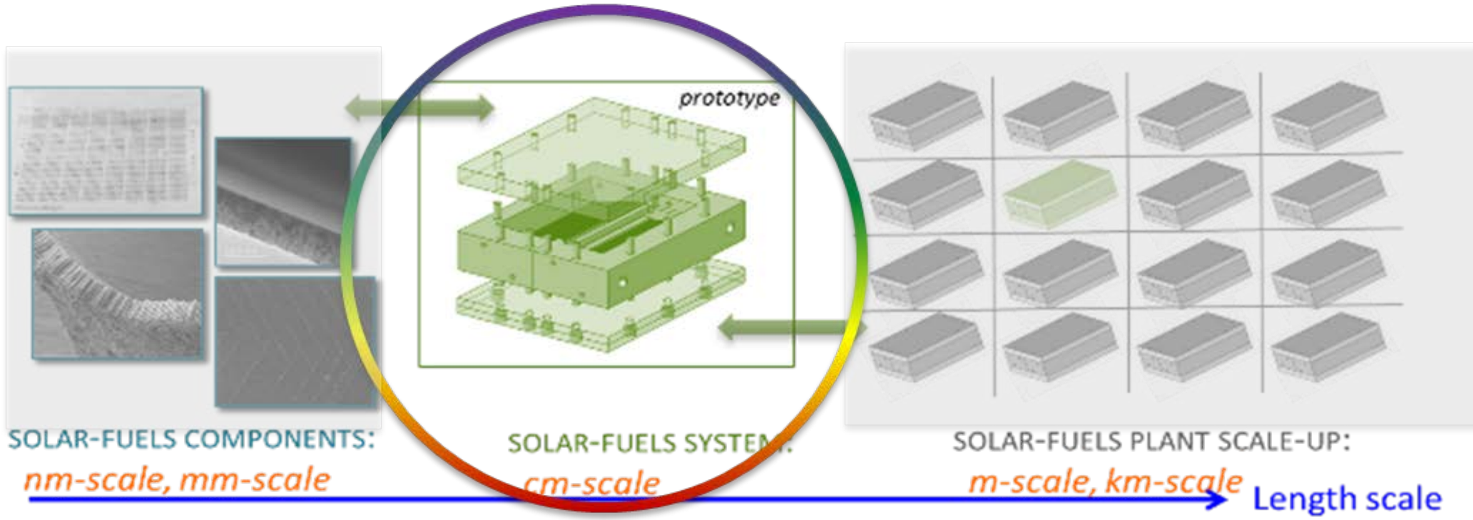
2. OER Supernode : Understanding OER Across pH Ranges Through Multiscale, Multi-Theory Modeling (LBNL, LLNL, NREL; 6 Nodes)



***Outcome**: Address knowledge gaps about OER and demonstrate a multiscale multi-theorymethodology.*

Five New Collaborative "Supernodes" Developed to Accelerate AWSM R&D

3. PEC Supernode : Emergent Degradation Mechanisms with Integration and Scale Up of PEC Devices (NREL, LBNL; 7 Nodes)



***Outcome**: Understand integration issues and emergent degradation mechanisms of PEC devices at relevant scale, and demonstrate an integrated and durable 50 cm^2 PEC panel.*

Five New Collaborative "Supernodes" Developed to Accelerate AWSM R&D

4. HTE Supernode : Supernode Capability to Characterize HTE Electrode Microstructure Evolution (INL, NREL, LBNL, LLNL; 6 Nodes)

Processing ⇔ Structure ⇔ Properties ⇔ Performance

Cell Fabrication

Catalyst Infiltration

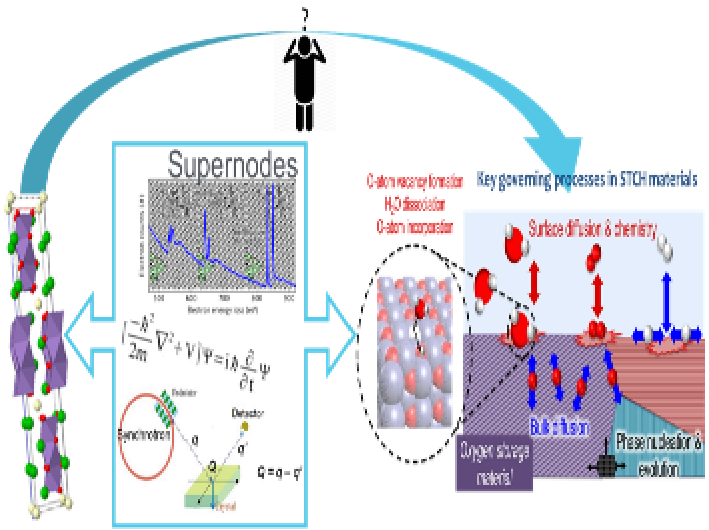
Analysis

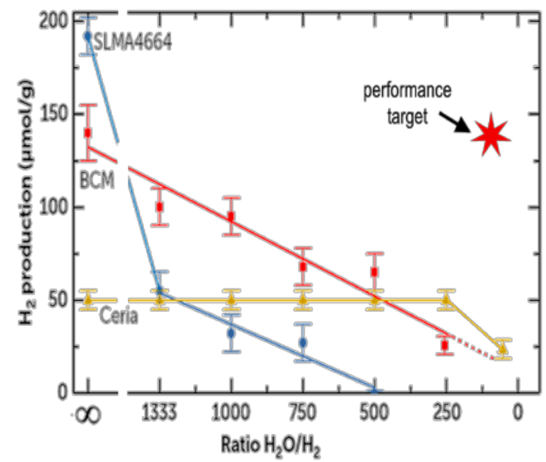
Measurements

Outcome: *A deeper understanding of HTE electrode microstructure evolution as a function of local solid-oxide composition and operating conditions to develop more active, longer-life electrodes.*

Five New Collaborative "Supernodes" Developed to Accelerate AWSM R&D

5. STCH Supernode : Develop Atomistic Understanding of the Layered Perovskite $Ba_4CeMn_3O_{12}$ (BCM) and its Polytypes (SNL, NREL, LLNL; 7 Nodes)





***Outcome**: A comprehensive understanding of Mn's local structure in BCM will lead to novel pathways for modifying and improving STCH perovskites.*

4 New NSF DMREF / DOE EERE HydroGEN EMN Projects

NSF DMREF PSU LTE

PennState

Membrane Databases – New Schema and Dissemination

Recipient Penn State University (PI: Michael A. Hickner)

Subs National Institute of Standards and Technology/NIST (PI: Debra Audus) and Rensselaer Polytechnic Institute/RPI (PI: Chulsung Bae)

HydroGEN Node Experts

National Renewable Energy Laboratory:

- Shaun Alia
- Guido Bender
- Kristin Munch
- Bryan Pivovar

NSF DMREF CSM STCH

High Temperature Defects: Linking Solar Thermochemcial and Thermoelectric Materials

Recipient Colorado School of Mines (PI: Eric Toberer and Vladan Stevanovic)

Subs University of Illinois Urbana-Champaign (PI: Elif Ertikin) and SLAC National Accelerator Laboratory (PI: Michael Toney)

HydroGEN Node Experts

National Renewable Energy Laboratory:

- Robert Bell
- David Ginley
- Stephan Lany
- Philip Parilla

NSF DMREF PSU PEC

PennState

Experimental Validation of Designed Photocatalysts For Solar Water Splitting

Recipient Penn State University (PI: Ismaila Dabo and Raymond E. Schaak)

Subs Cornell University (PI: Héctor D. Abruña)

HydroGEN Node Experts

National Renewable Energy Laboratory:

- Todd Deutsch
- James Young

NSF DMREF UB PEC

University at Buffalo
The State University of New York

Collaborative Research: A Blueprint for Photocatalytic Water Splitting: Mapping Multidimensional Compositional Space to Simultaneously Optimize Thermodynamics and Kinetics

Recipient University at Buffalo (PI: David Watson)

Subs Texas A&M University (PI: Sarbajit Banerjee) and Binghamton University (PI: Louis Piper)

HydroGEN Node Experts

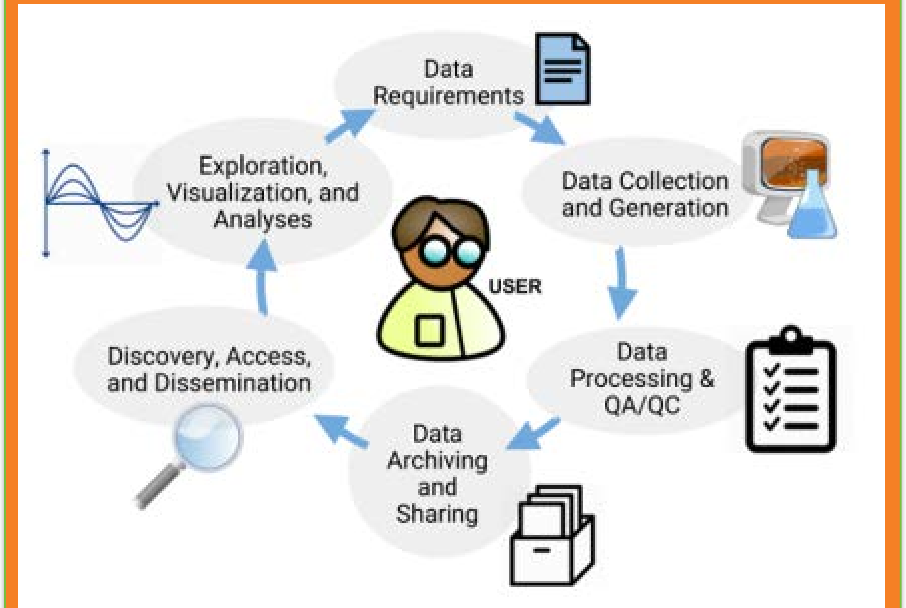
Lawrence Berkeley National Laboratory

- Jinghua Guo
- David Prendergast

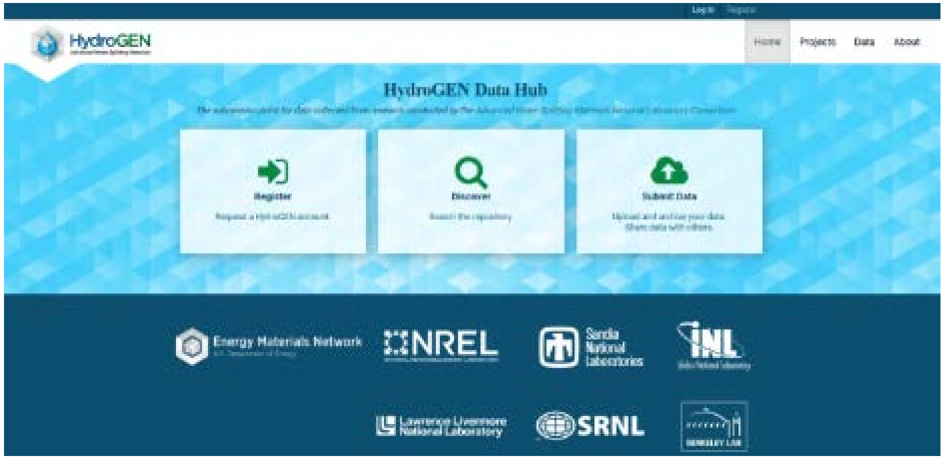
HydroGEN Data Hub: Making digital data accessible

A Researcher Centric Approach

The HydroGEN Data Hub currently has >170 users, >4050 files



https://datahub.h2awsm.org/



Data Hub implemented in May 2017

- Secure project space for team members
- View and download project data
- Metadata tools to support advanced search
- Data plug-ins for visualization and graphing of data

Technology Transfer Agreements (TT/A)

Non-Disclosure Agreement (NDA)
- Information Disclosure

Intellectual Property Management Plan (IPMP)
- IP Protection

Materials Transfer Agreement (MTA)
- Freedom to Operate

Cooperative Research and Development Agreement (CRADA)
- Collaboration

➢ **Streamlined Access**

- ✓ **Four** standard, pre-approved TT/A between all consortium partners
- ✓ Executed all 21 project NDAs and 2 MTAs

https://www.h2awsm.org/working-with-hydrogen

Working with HydroGEN: Testimonials

Tom Jaramillo, principal investigator on a HydroGEN seedling project, talks about how the capabilities and expertise of the HydroGEN Advanced Water Splitting Materials consortium can help researchers working on hydrogen technologies.

Useful HydroGEN-Related Links

- 2016 HydroGEN Webinars (good capability descriptions)
  - HydroGEN Consortium Overview, Part 1 of 3: Photoelectrochemical (PEC) Water Splitting
  - HydroGEN Consortium Overview, Part 2 of 3: Electrolysis
  - HydroGEN Consortium Overview, Part 3 of 3: Solar Thermochemical (STCH) Hydrogen Production
- 2017 HydroGEN-FOA Awarded Project Kick-Off Presentations
- 2018 HydroGEN EMN AMR Presentations and Posters
- HydroGEN Website
  - Technology Transfer Agreement Types
  - Video testimonial
- HydroGEN Data Hub
- DOE EERE Energy Materials Networks

Acknowledgements

Energy Materials Network
U.S. Department of Energy

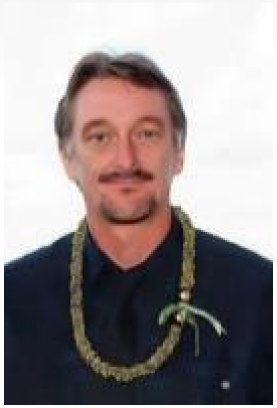
HydroGEN
Advanced Water Splitting Materials

This work was fully supported by the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Office (FCTO).

Katie Randolph

David Peterson

James Vickers



Eric Miller

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
Fuel Cell Technologies Office

NREL | BERKELEY LAB | Sandia National Laboratories | INL Idaho National Laboratory | Lawrence Livermore National Laboratory | SRNL

Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

For more information & Engagement with HydroGEN

Go to www.h2awsm.org

For capability node lists and descriptions, technology transfer agreements and currently funded projects

When a FOA is open, first engagement should go through h2awsm@nrel.gov

To identify and discuss capability node(s) of interest

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

Acknowledgements

Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Authors

Guido Bender
Huyen Dinh
Nemanja Danilovic
Adam Weber

LTE Project Leads

Kathy Ayers
Chris Capuano
Hoon Chung
Yu Seung Kim
Di-Jia Liu
Sanjeev Mukerjee

Research Teams

University of Delaware
Argonne National Laboratory
University at Buffalo The State University of New York
Rensselaer
Pajarito Powder
Advent
Proton OnSite nel number one by nature YOUR SOURCE FOR ALL THINGS HYDROGEN
Giner
Northeastern University Center for Renewable Energy Technology
Tufts University School of Engineering
Oak Ridge National Laboratory
Los Alamos National Laboratory EST. 1943

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

Acknowledgements

Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Node Experts

Dong Ding
Michael Tucker
Zhiwen Ma
James O'Brien
Carl Stoots
Andriy Zakutayev

HTE Project Leads

Scott Barnet
Tianli Zhu
Prabhakar Singh
Xingbo Liu
John Pietras

Research Teams

United Technologies Research Center
UCONN
West Virginia University
Northwestern
Saint-Gobain Research North America
Pacific Northwest National Laboratory
ElectroChem Ventures

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

Acknowledgements

Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Authors

Adam Weber
Todd Deutsch
Nemanja Danilovic
Huyen Dinh

PEC Project Leads

Eric Garfunkel
Tom Jaramillo
Nicolas Gaillard
Zetian Mi
Aditya Mohite

Research Teams

University of Hawaiʻi Mānoa
UNLV University of Nevada Las Vegas
Los Alamos National Laboratory Est. 1943
Leland Stanford Junior University 1891
Rutgers
University of Louisville
The University of Michigan 1817

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

Acknowledgements

Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

Authors

Anthony McDaniel
Huyen Dinh

STCH Project Leads

Claudio Corgnale
Charles Musgrave
Ryan O'Hayre
Ellen Stechel
Chris Wolverton

Node Experts

Eric Coker
Bert Debusschere
David Ginley
Daniel Ginosar
Max Gorensek
Tae Wook Heo
Stephan Lany
Zhiwen Ma
Anthony McDaniel
Genevieve Saur
Andriy Zakutayev

Research Teams

Greenway Energy LLC
Engineering consultant in Aiken County, South Carolina

Northwestern

Colorado School of Mines 1874

Arizona State University

University of South Carolina

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

Save the Date and Sign up for Our Newsletter

All relevant DOE offices and other federal agencies working on hydrogen and fuel cell technologies at Annual Merit Review (AMR)

2019 AMR – April 29 – May 1

Crystal City, VA

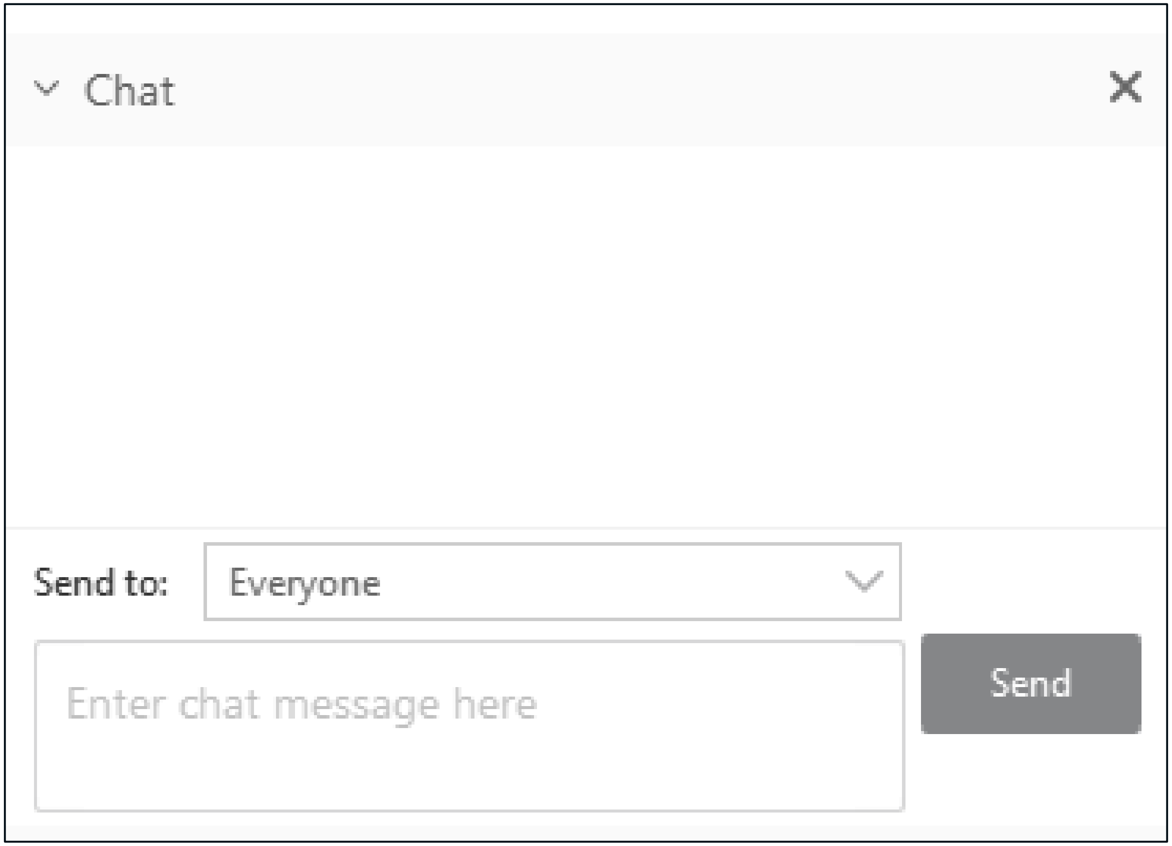
www.hydrogen.energy.gov

Sign up to receive hydrogen and fuel cell news and updates

www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-newsletter

Question and Answer

- Please type your questions to the chat box. **Send to: (HOST)**



Thank you

Eric Miller
Eric.miller@ee.doe.gov

Eric Parker
DOEFuelCellWebinars@ee.doe.gov

Huyen Dinh
Huyen.Dinh@nrel.gov

hydrogenandfuelcells.energy.gov

Backup Slides

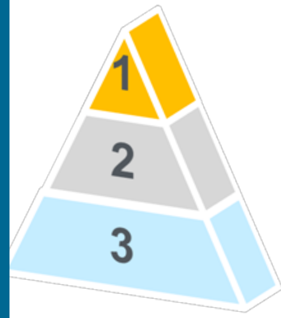
HydroGEN Capability Nodes

Node evaluation criteria:

1. **Relevant** to HydroGEN water splitting pathways
2. **Available** resources and associated expert(s) to support the capability and available to external stakeholders
3. **Unique** to the national laboratory system; comprise expertise, tools, and techniques

- **Other Considerations:**
  - **Node readiness category**

Node Readiness Category (NRC) Chart



Node is **fully developed** and has been used for AWSM research projects

Node requires **some development** for AWSM

Node requires **significant development** for AWSM

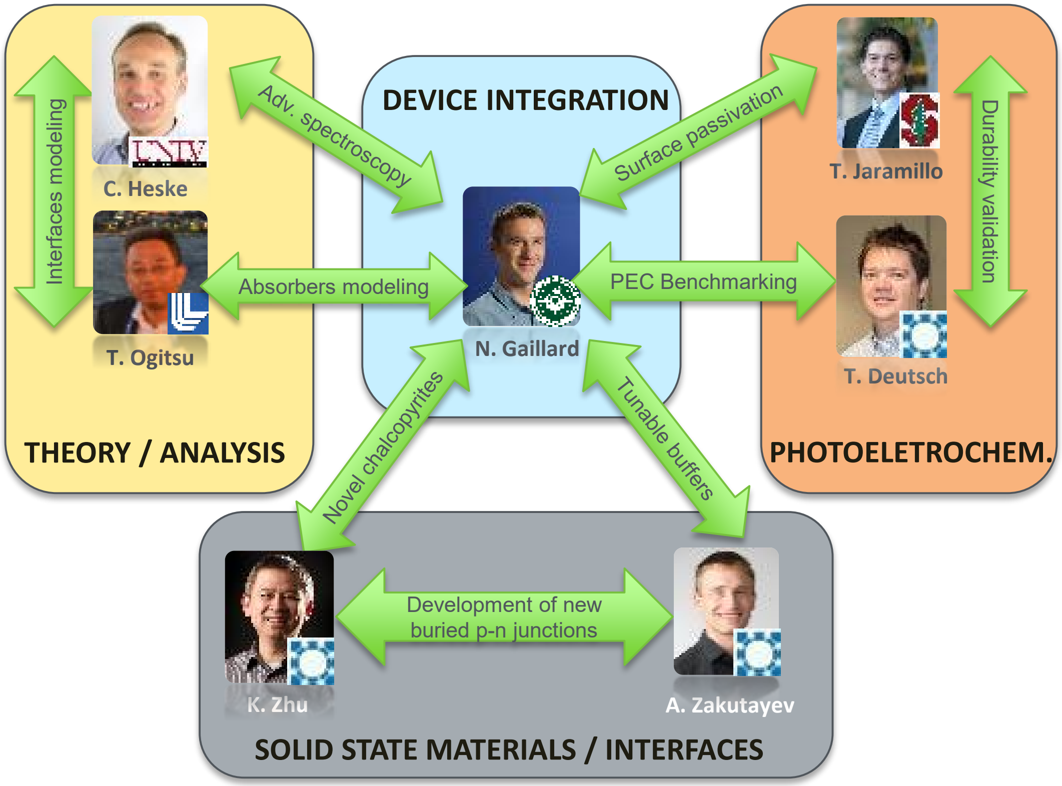
- Nodes comprise tool, technique, and expertise including uniqueness
- Category refers to availability, readiness and relevance to AE and not necessarily the expense and time commitment

Capability nodes are regularly updated and new ones are added

Collaboration Example: U Hawaii/HydroGEN Node Interactions

Academia-EMN Node interaction

Integrated Theory, Analysis, Synthesis and Testing



Computational Materials Diagnostics and Optimization Node (T. Ogitsu).

- **Role:** theoretical modeling of novel materials.
- **Benefit to this program:** defines synthesis conditions and thermodynamic stability of chalcopyrite candidates.

I-III-VI Compound Semiconductors for Water-Splitting Node (K. Zhu)

- **Role:** synthesis of high-purity material systems.
- **Benefit to this program:** “ideal” vacuum-based chalcopyrites used to test alloying/doping strategies.

High-Throughput Thin Film Combinatorial Capabilities Node (A. Zakutayev)

- **Role:** develop n-type buffers with tunable ‘energetics’
- **Benefit to this program:** accelerates material discovery for improved interfaces.

Corrosion Analysis of Materials Node (T. Deutsch)

- **Role:** supports development of surface passivation against photo-corrosion.
- **Benefit to this program:** provide access to unique instrumentation to identify corrosion mechanisms.

HydroGEN Benchmarking: Advanced Water Splitting Technologies Project

Best Practices in Materials Characterization

PI: Kathy Ayers, Proton OnSite (LTE)
Co-PIs: Ellen B. Stechel, ASU (STCH);
Olga Marina, PNNL (HTE);
CX Xiang, Caltech (PEC)
Consultant: Karl Gross

Accomplishments:

- 4 AWSM Questionnaires
- 4 AWSM Test Frameworks
- 2 Benchmarking Newsletters
- 2 Working Group Meetings
- 3 Conference Presentations
- > 80 Capability Nodes Assessed

- *Develop standardized best practices for characterizing and benchmarking AWSMs*
- *Foundation for accelerated materials RD&D for broader AWS community*
- *Extensive collaboration and engagement with HydroGEN steering committee, node subject matter experts, and broad water splitting community*

Development of Best Practices in Materials Characterization and Benchmarking: Critical to accelerate materials discovery and development