Energy Materials Network
U.S. Department of Energy

HydroGEN
Advanced Water Splitting Materials

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

An Overview of HydroGEN:

A DOE Energy Materials Network, Aimed at Accelerating the R&D of Advanced Water Splitting Materials (AWSM)

H.N. Dinh, E.L. Miller, K. Randolph, A. Weber, A. McDaniel, R. Boardman, T. Ogitsu, and H. Colon-Mercado

Date: 11/8/2017

Venue: Fuel Cell Seminar, Long Beach, CA

Renewable Hydrogen Pathways Session

Website: https://www.h2awsm.org/

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

Energy Materials Network (EMN)

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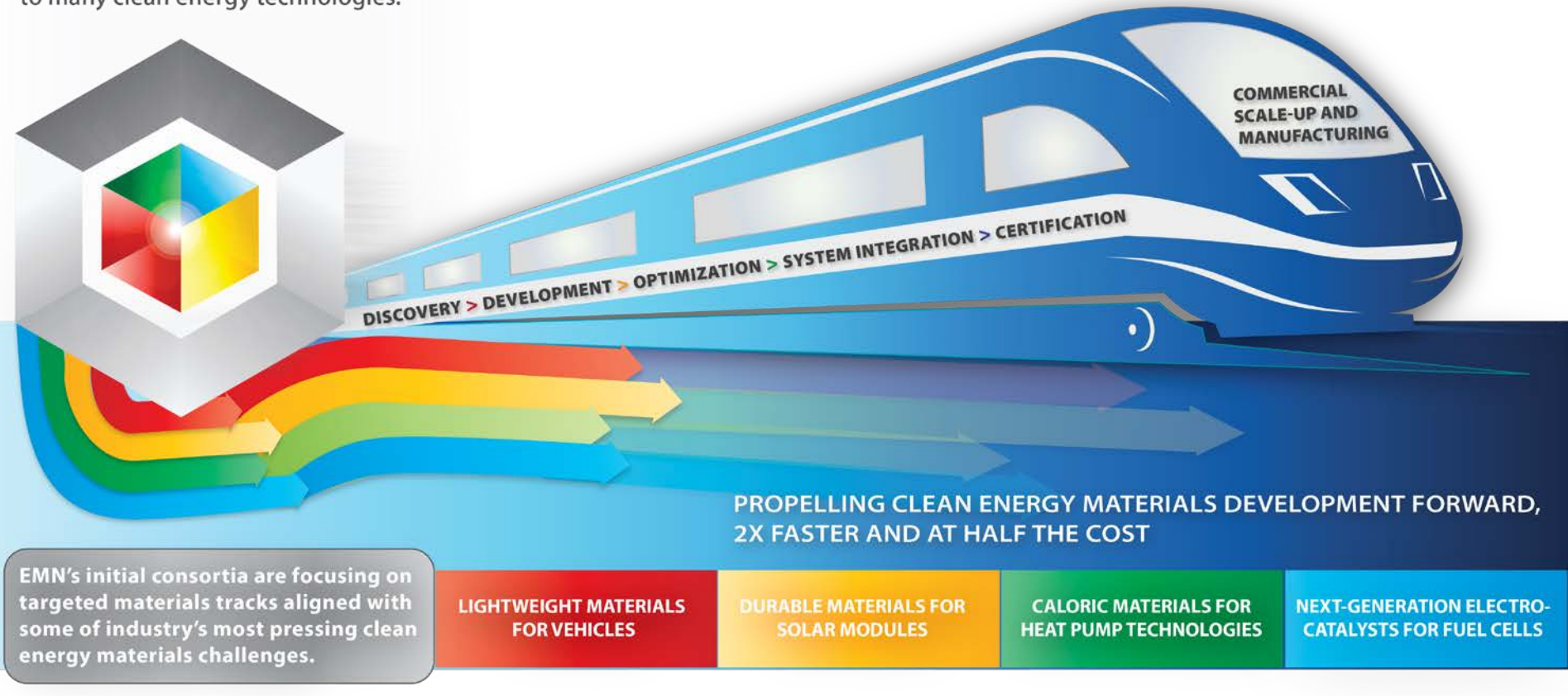
The Energy Materials Network (EMN) aims to dramatically decrease time-to-market for advanced materials that are critical to many clean energy technologies.

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.



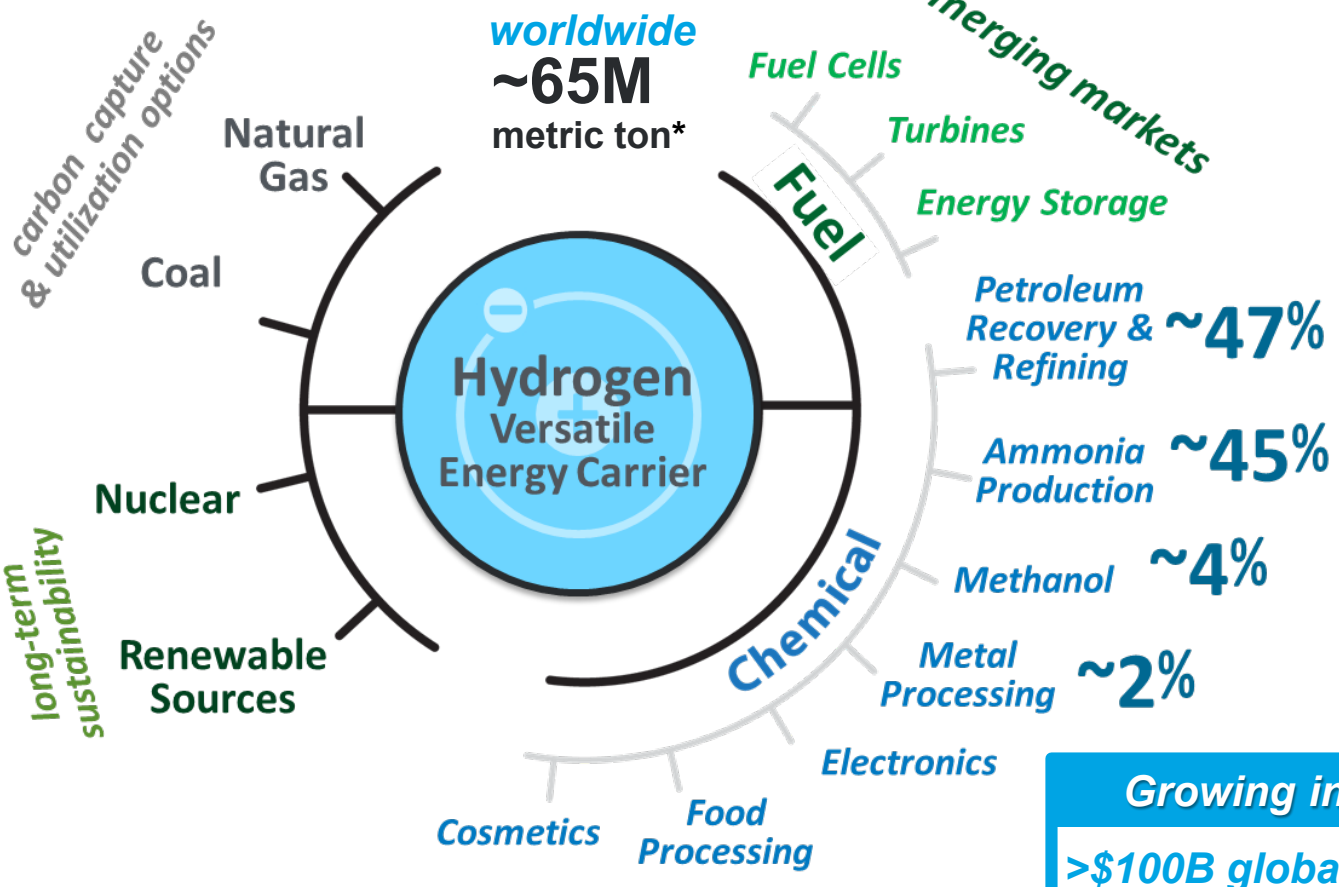
Current EMN Consortia Overview

Energy Materials Network
U.S. Department of Energy

CaloriCool CALORIC MATERIALS CONSORTIUM	Caloric materials for efficient cooling and heat pumping technologies.
ChemCatBio Chemical Catalysis for Bioenergy	Catalytic materials for commercial bioenergy applications
DuraMAT Durable Module Materials Consortium	Durable module materials that reduce the levelized cost of energy of photovoltaic systems.
LightMAT Lightweight Materials Consortium	Lightweight materials for automotive manufacturing.
ElectroCat Electrocatalysis Consortium	Platinum group metal-free catalysts for automotive fuel cells
HyMARC Hydrogen Materials Advanced Research Consortium	Hydrogen storage materials by providing capabilities and foundational understanding.
HydroGEN Advanced Water Splitting Materials	Advanced water splitting technologies for clean, sustainable hydrogen production.

Goal: Widespread H_2 Production & Delivery

Diverse Sources



Diverse Applications

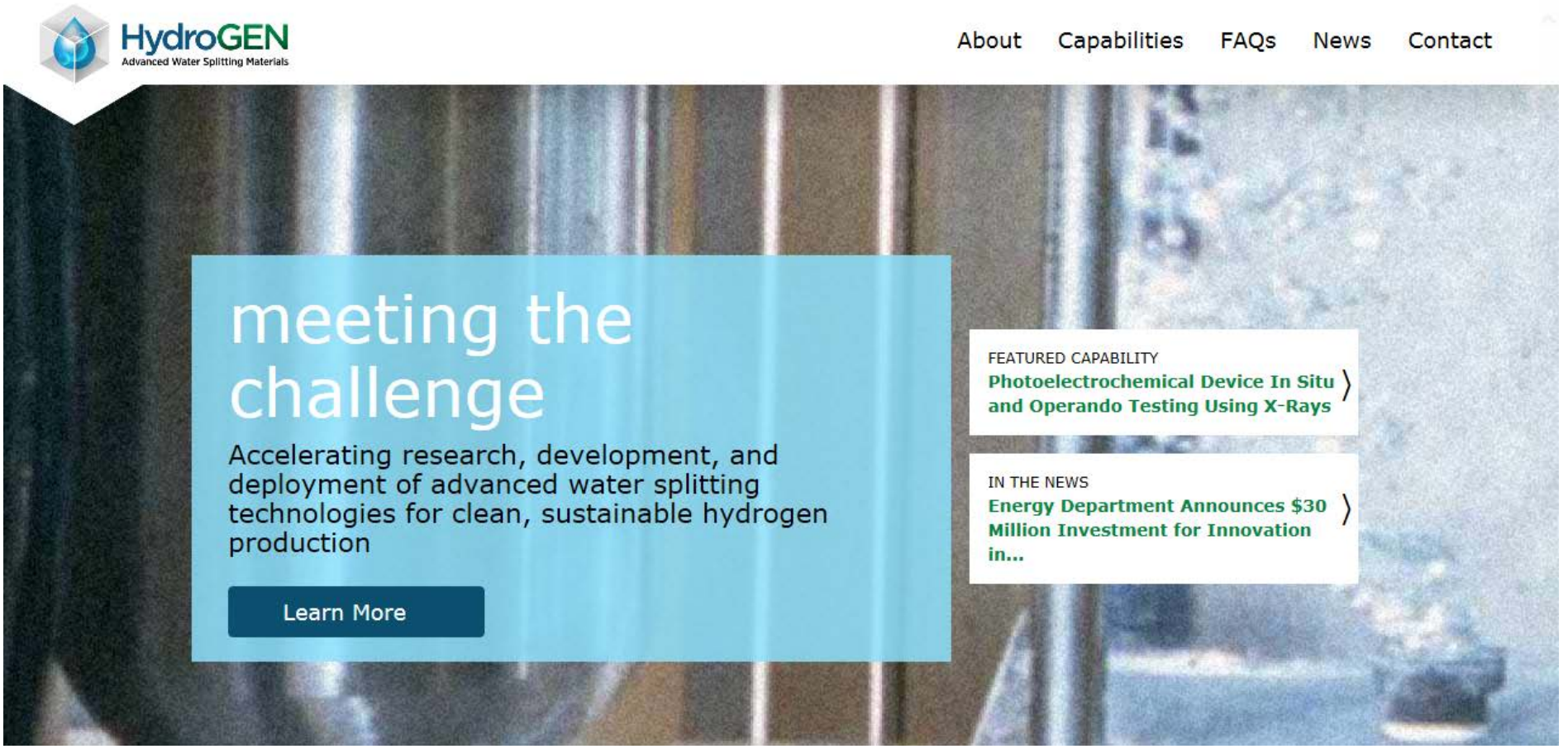
Growing industrial demand for H_2

>$100B global market and expanding

Hydrogen enables domestic energy & environmental security, with large-scale market potential & with job creation and economic growth opportunities

HydroGEN Consortium Launch

From drawing-board to consortium full deployment in 6 months!



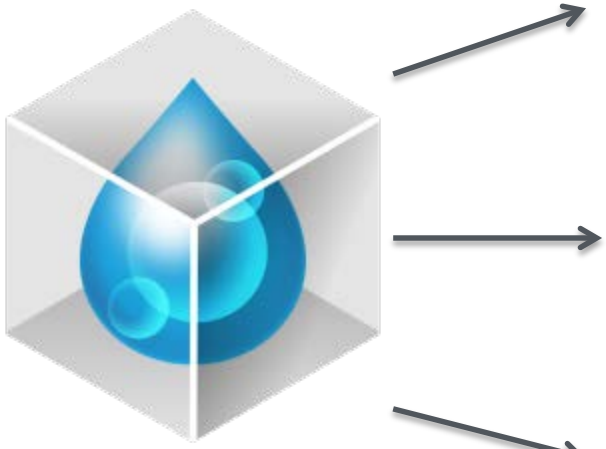
Visit the HydroGEN website at https://www.h2awsm.org

HydroGEN: Advanced Water-Splitting Materials (AWSM) Consortium

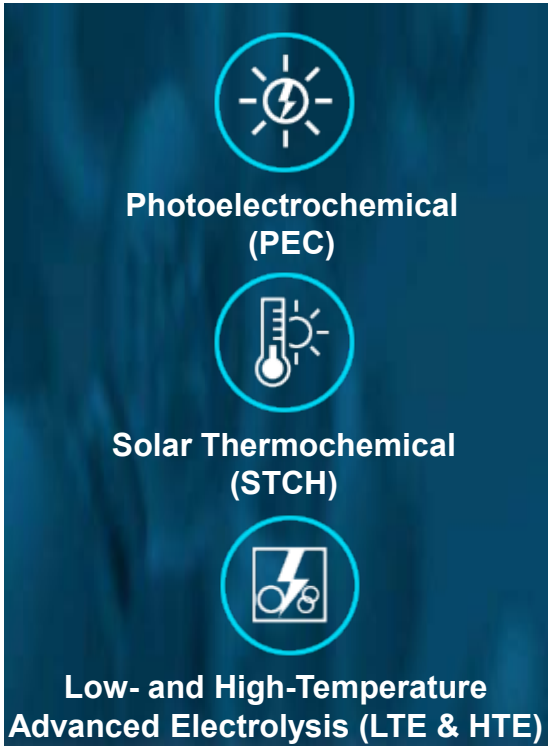
HydroGEN
Advanced Water Splitting Materials

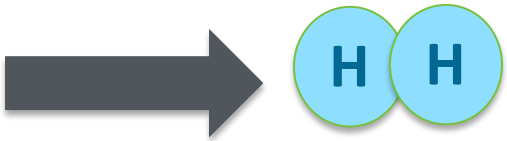
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
BERKELEY LAB
Sandia National Laboratories
INL
Idaho National Laboratory
Lawrence Livermore National Laboratory
SRNL

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



Water





Hydrogen

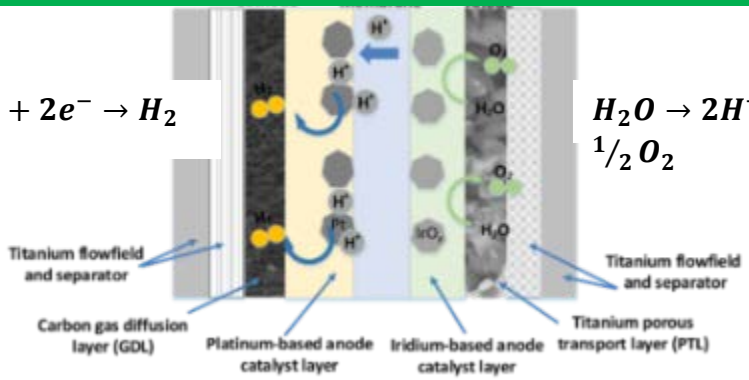
Website: www.h2awsm.org/

Cross-Cutting Multiple Advanced Water Splitting Material (AWSM) Technologies

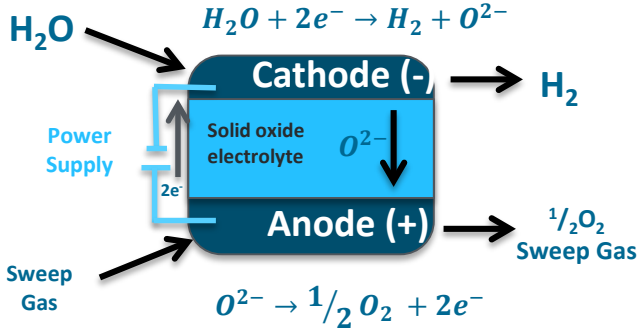
Polymer Electrolyte Membrane Electrolysis (LTE)

$2H^+ + 2e^- \rightarrow H_2$

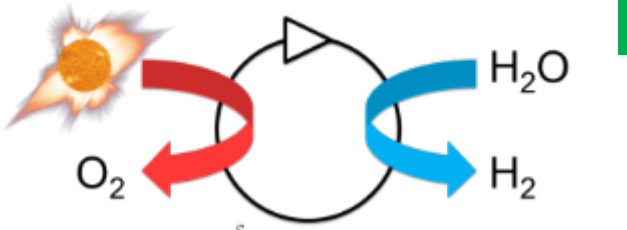
$H_2O \rightarrow 2H^+ + 2e^- + {}^1/_2\,O_2$



Solid Oxide Electrolysis (HTE)



Solar Thermochemical (STCH)

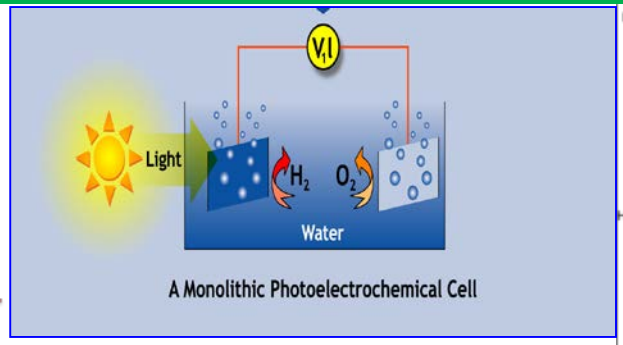


$MO_x \rightarrow MO_{x-\delta} + \frac{\delta}{2} O_2$ (1) Reduction

$MO_{x-\delta} + \delta \cdot H_2O \rightarrow MO_x + \delta \cdot H_2$ (2) Oxidation

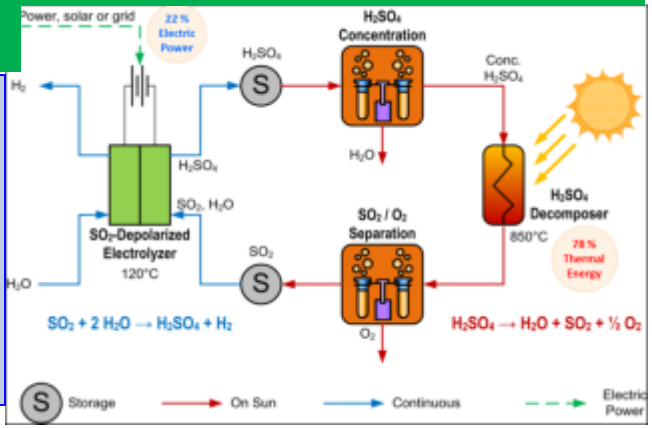
$\delta \cdot H_2O \rightarrow \frac{\delta}{2} O_2 + \delta \cdot H_2$ (3) Thermolysis

Photoelectrochemical (PEC)



A Monolithic Photoelectrochemical Cell

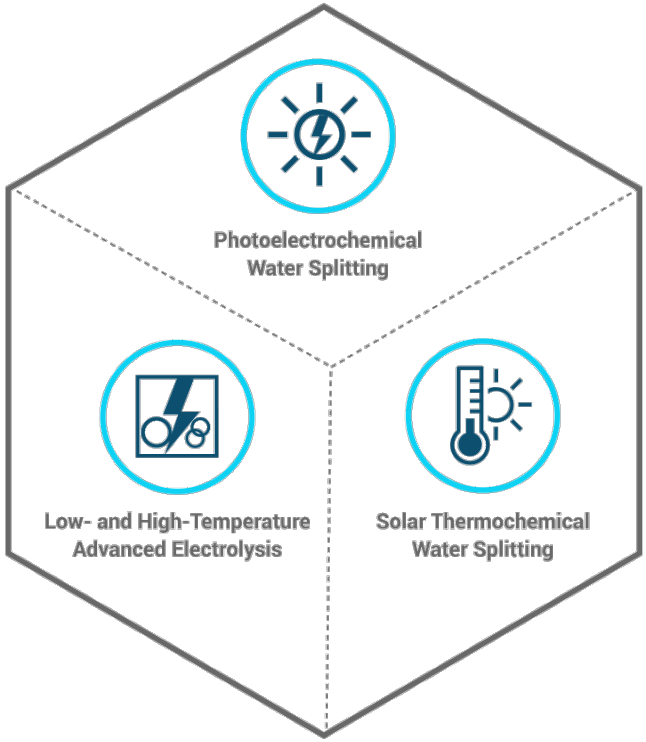
Hybrid Sulfur Cycle (HT)



Hybrid = Electrolysis + STCH

Cross-Cutting Technologies and Collaboration Can Enable Reduction in H_2 Production Cost

RD&D from different water splitting pathways is critical to reducing renewable H_2 production cost



Production target <$2/gge

H_2 Cost at Pump

<$4/gge

<$7/gge (early market)

Collaborations: HydroGEN Steering Committee

NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Huyen Dinh (Director)

BERKELEY LAB

Adam Weber (Deputy Director)

Sandia National Laboratories

Anthony McDaniel (Deputy Director)

INL
Idaho National Laboratory

Richard Boardman

Lawrence Livermore National Laboratory

Tadashi Ogitsu

SRNL
SAVANNAH RIVER NATIONAL LABORATORY

Héctor Colón-Mercado

Eric Miller and Katie Randolph, FCTO

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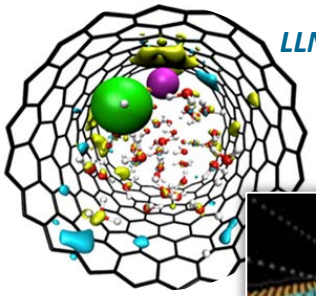
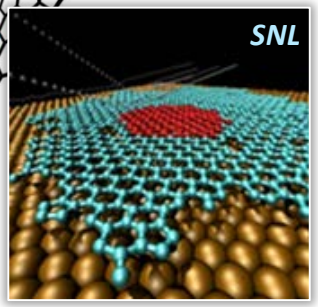
HydroGEN: Advanced Water-Splitting Materials (AWSM) Consortium

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

Materials Theory/Computation

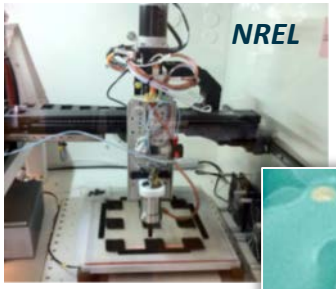


Bulk & interfacial models of aqueous electrolytes

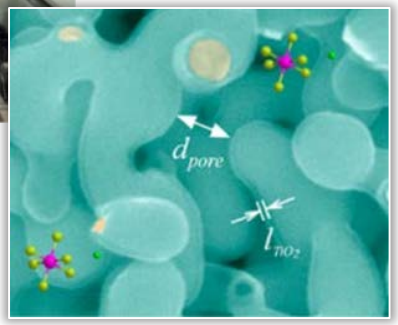


LAMMPS classic molecular dynamics modeling relevant to H_2O splitting

Advanced Materials Synthesis



High-throughput spray 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

Cross technology collaboration opportunities

Website: https://www.h2awsm.org/

HydroGEN Website – Enhanced Capability Search

LIST OF CAPABILITIES

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

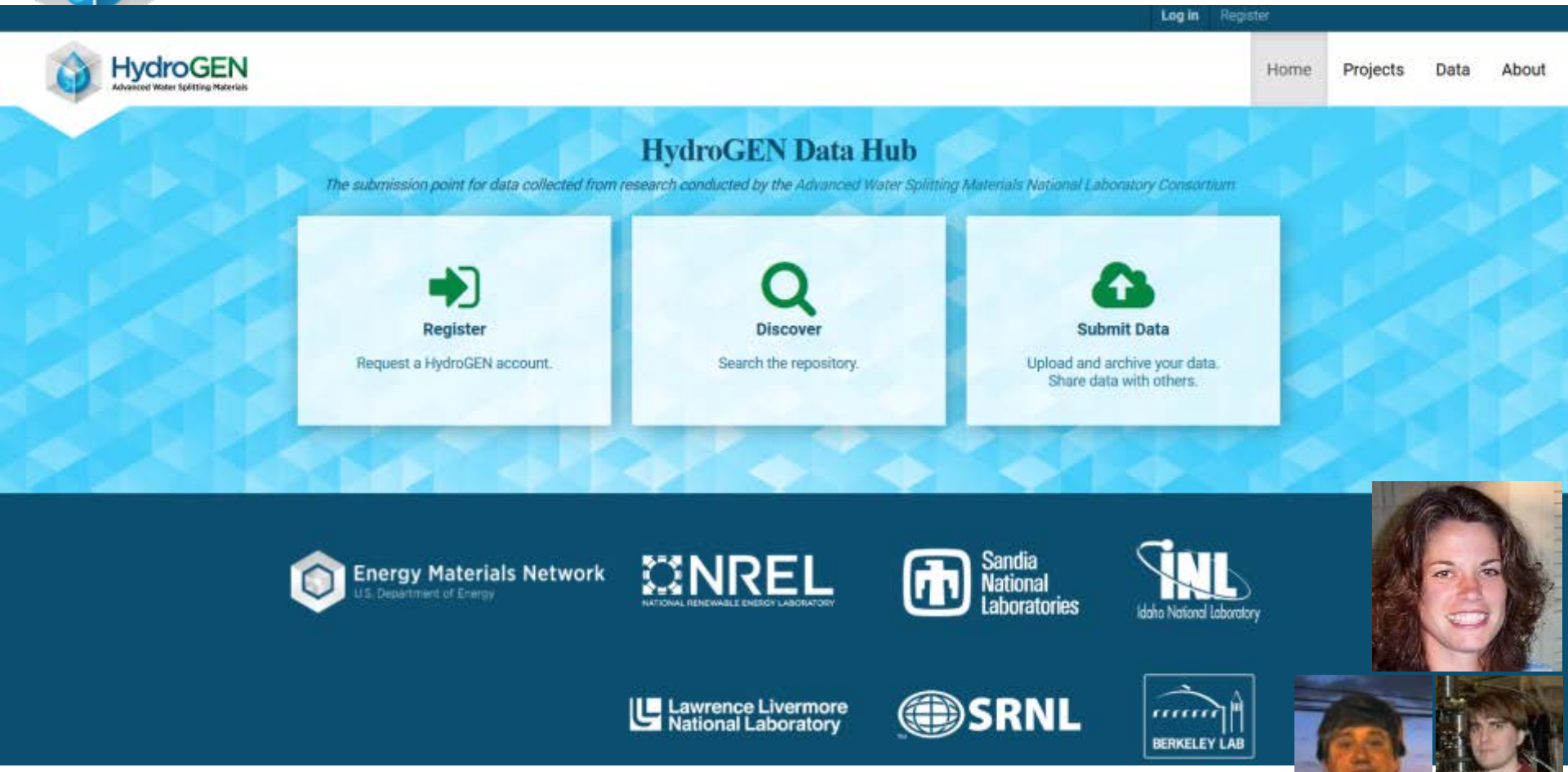
Showing 1 to 12 of 82 entries

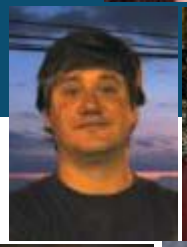
1 2 3 4 Next

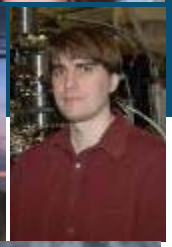
Ab Initio Modeling of Electrochemical Interfaces LLNL — PEC 1, LTE 2	Advanced Electron Microscopy SNL — HTE 1, LTE 1, PEC 1, STCH 1	Advanced Materials for Water Electrolysis at Elevated Temperatures INL — HTE 2
Advanced Water-Splitting Materials Requirements Based on Flowsheet Development and Techno-Economic A... SRNL — HT 1, HTE 1, STCH 2, LTE 3, PEC 3	Albany: Open-Source Multiphysics Research Platform SNL — HTE 1, LTE 1, PEC 1, STCH 1	ALD Based Surface Functionalization and Porosity Control LLNL — PEC 3
Analysis and Characterization of Hydrided Material Performance INL — HTE 2	Beyond-DFT Simulation of Energetic Barriers and Photoexcited Dynamics LLNL — PEC 2	Cascading Pressure Reactor SNL — STCH 1

https://www.h2awsm.org/index.html

HydroGEN Data Hub: Making digital data accessible







HydroGEN Data Hub Home Page (https://datahub.h2awsm.org/)

Technology Transfer Activities

Non-Disclosure Agreement (NDA)

- Information Disclosure

Intellectual Property Management Plan (IPMP)

- IP Protection

Materials Transfer Agreement (MTA)

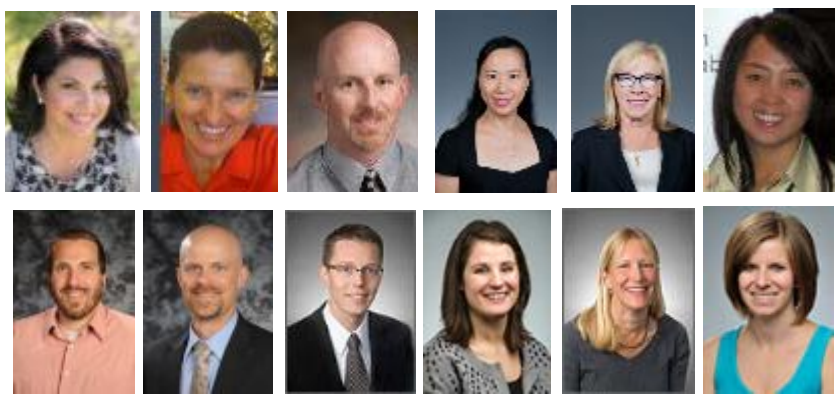
- Freedom to Operate

Cooperative Research and Development Agreement (CRADA)

- Collaboration (nearly complete)

➢ **Streamlined Access**

- ➢ Developed a catalog of pre-approved, mutual agreements between all consortium partners
- ➢ Facilitating rapid IP, NDA, and contract agreements

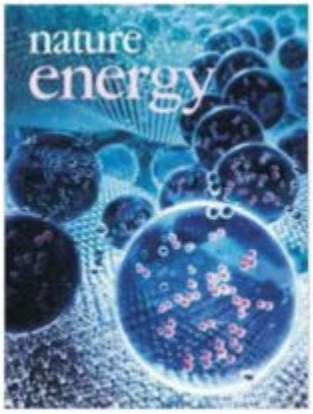


High Impact Publication

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

High Impact Publications & Patents

World-record Photoelectrolysis Efficiency with Inverted Metamorphic Multi-junction Semiconductors

Mass-spectrometer based Faradaic efficiency system

Protected Layer to Enhance Durability

- **Filed provisional patent on "PASSIVATING WINDOW AND CAPPING LAYER FOR PHOTOELECTROCHEMICAL CELLS."** on August 16, 2016 at the United States Patent & Trademark Office (USPTO) and has received Application No. 62/375,718.
- **Filed a non-provisional patent on "Devices and Methods for Photoelectrochemical water splitting"** March 23rd, 2016 based on our IMM for high efficiency work. United States Patent Application 20160281247. Awaiting examination.

High Impact Publications and Patent Applications

NEW HydroGEN Seedling Project

19 Proposals Selected, Negotiated, and Awarded

44 unique capabilities being utilized across 6 core labs

Advance Electrolysis (8)
LTE (5)
HTE (3)

PEC (5)

Benchmarking & Protocols (1)

STCH (5)
2-Step MO_x(4)
Hybrid cycle (1)

To learn more, check HydroGEN website or contact huyen.dinh@nrel.gov

HydroGEN EMN

Website: www.h2awsm.org/

HydroGEN
Advanced Water Splitting Materials

Core Labs

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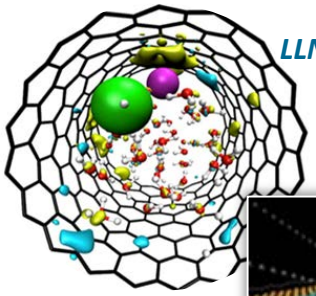
Comprising more than 80 unique, world-class capabilities/expertise in materials theory/computation, synthesis, and characterization & analysis:

Materials Theory/Computation



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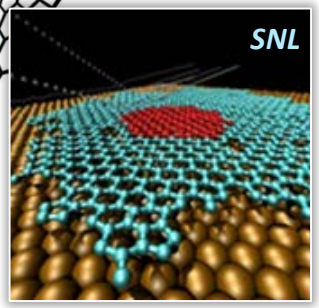

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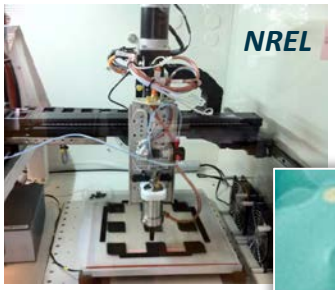

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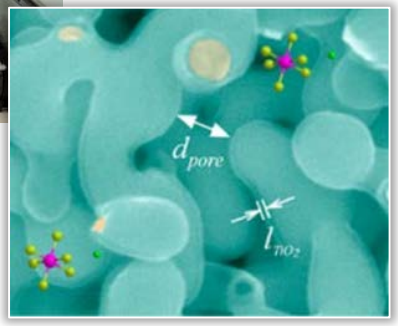

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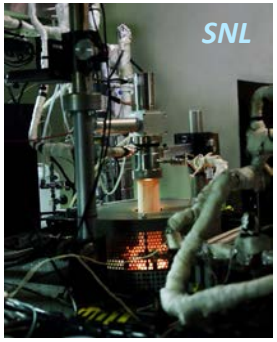

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TAP reactor for extracting quantitative kinetic data

HydroGEN is enabling innovative, world-class research of water-splitting materials and catalysts.

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DOE EERE Fuel Cell Technology Office Team

Eric Miller and Katie Randolph, (Leads)

David Peterson
James Vickers
Maxim Lyubovsky
Kim Cierpik-Gold

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

Acknowledgements

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HydroGEN
Advanced Water Splitting Materials

NREL Team

Huyen Dinh, Lead

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Adam Weber, Lead

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Ian Sharp
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Miquel Salmeron
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SRNL Team

Hector Colón-Mercado, Lead

Principal Investigators:

Maximilian Gorensek
Brenda Garcia-Diaz

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

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SNL Team

Anthony McDaniel, Lead Principal Investigators:

Mark Allendorf
Eric Coker
Bert Debusschere
Farid El Gabaly
Lindsay Erickson
Ivan Ermanoski
James Foulk
Cy Fujimoto
Fernando Garzon
Ethan Hecht
Reese Jones
Bryan Kaehr
David Littlewood
John Mitchell
Jeff Nelson
Peter Schultz
Randy Schunk
Subhash Shinde
Josh Sugar
Alec Talin
Alan Wright

LLNL Team

Tadashi Ogitsu, Lead Principal Investigators:

Sarah Baker
Monika Biener
Alfredo Correa Tedesco
Thomas Yong-Jin Han
Tae Wook Heo
Jonathan Lee
Miguel Morales-Silva
Christine Orme
Tuan Anh Pham
Christopher Spadaccini
Tony Van Buuren
Joel Varley
Trevor Willey
Brandon Wood
Marcus Worsley

INL Team

Richard Boardman, Lead Principal Investigators:

James O'Brien
Dong Ding
Rebecca Fushimi
Dan Ginosar
Ting He
Gabriel Ilevbare
Soe Lwin
Carl Stoots

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