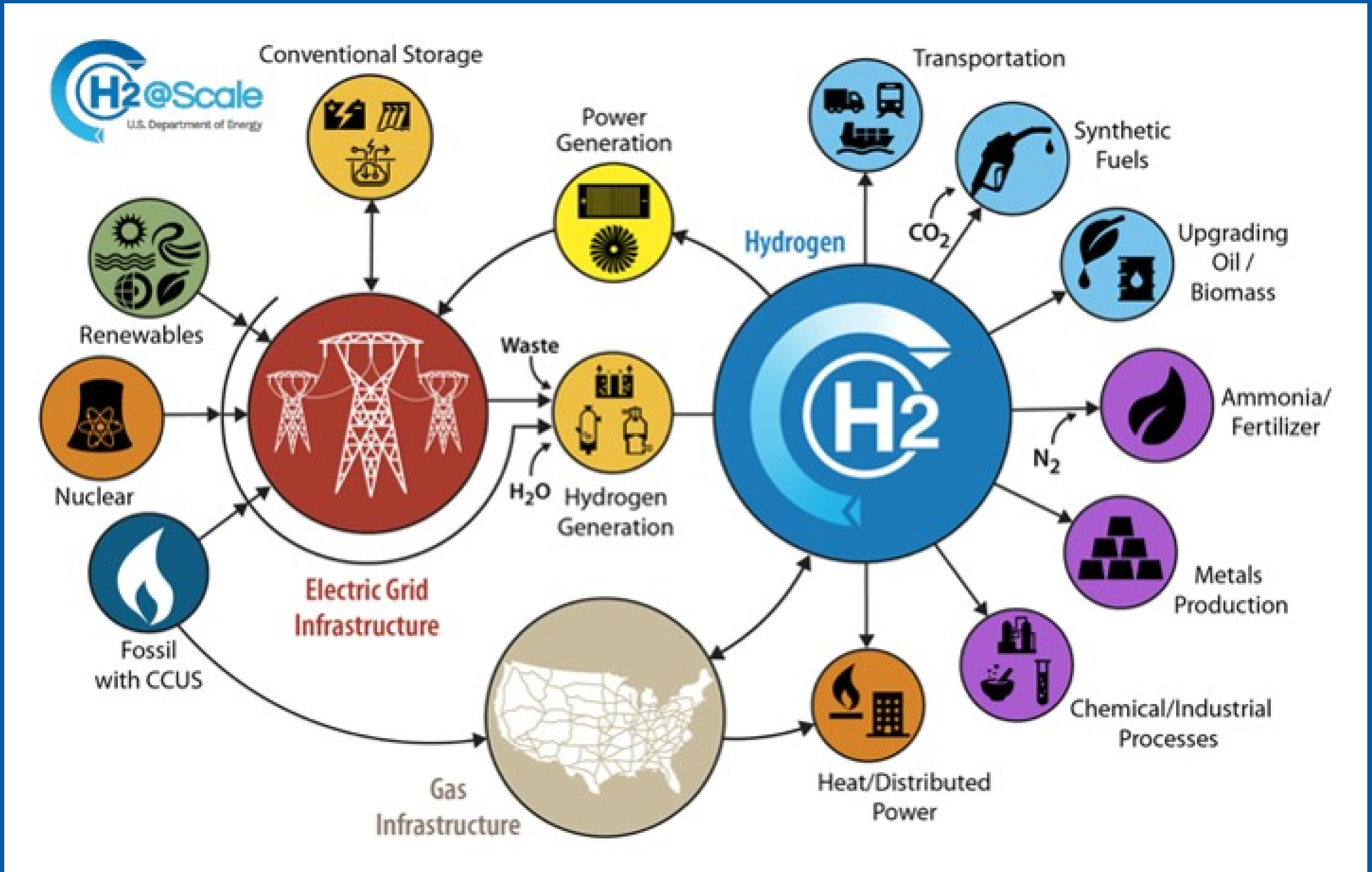
Renewable Hydrogen: A Key Enabler for the Energy Transformation



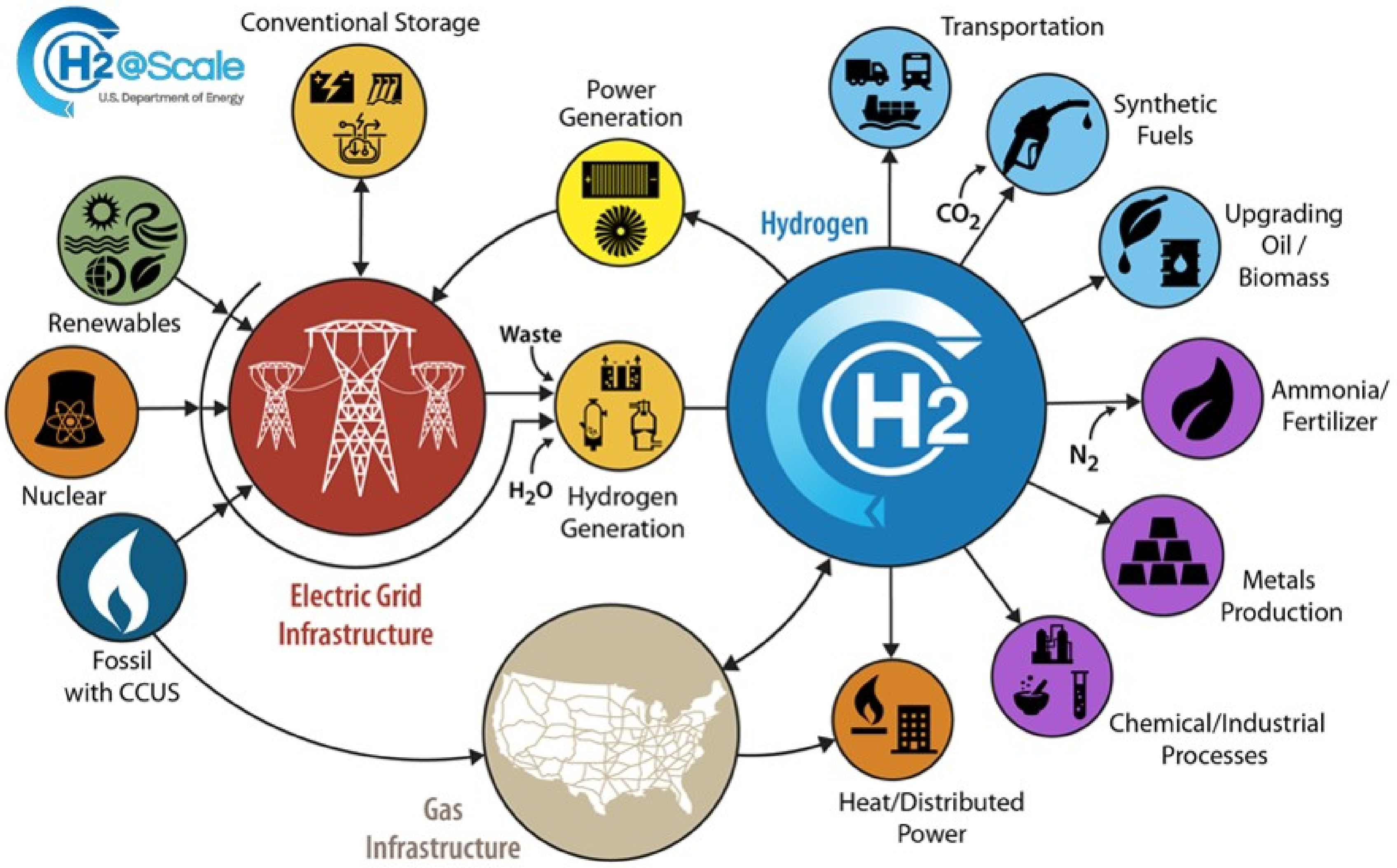
Bill Tumas
Associate Lab Director
Materials, Chemical and Computational Sciences
National Renewable Energy Laboratory—NREL

Keith Wipke, Bryan Pivovar, Mark Ruth, Huyen Dinh, Jennifer Kurtz, Kevin Harrison, Randy Cortright

International Conference on Hydrogen
Global Energy Cooperation Center (GECC)
Ministry of Foreign Affairs in the Republic of Korea

September 30, 2021

H2@Scale



Link clean energy and and chemicals for a wide range of applications

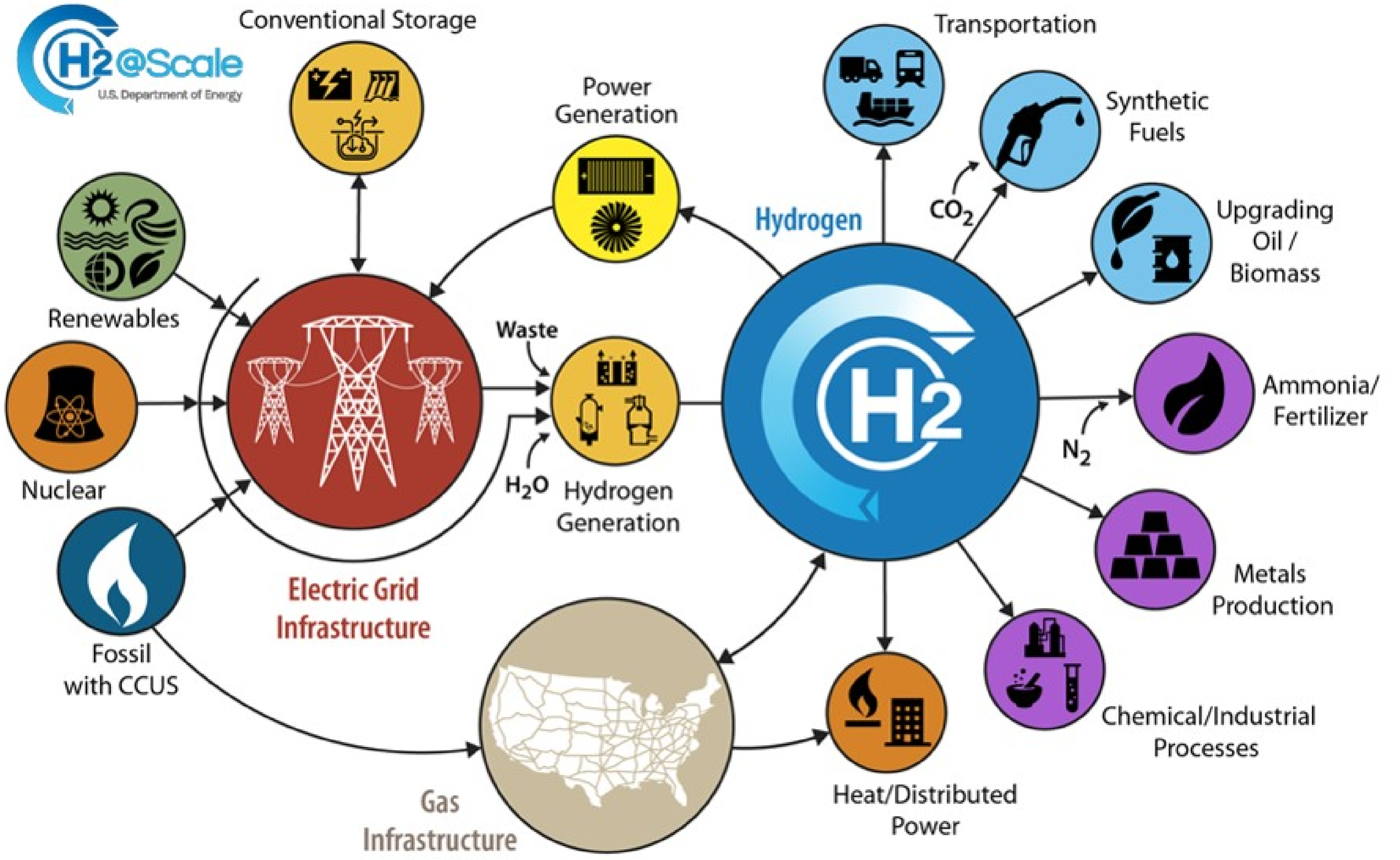
transportation, grid, industry, buildings, agriculture (cross-sector coupling)

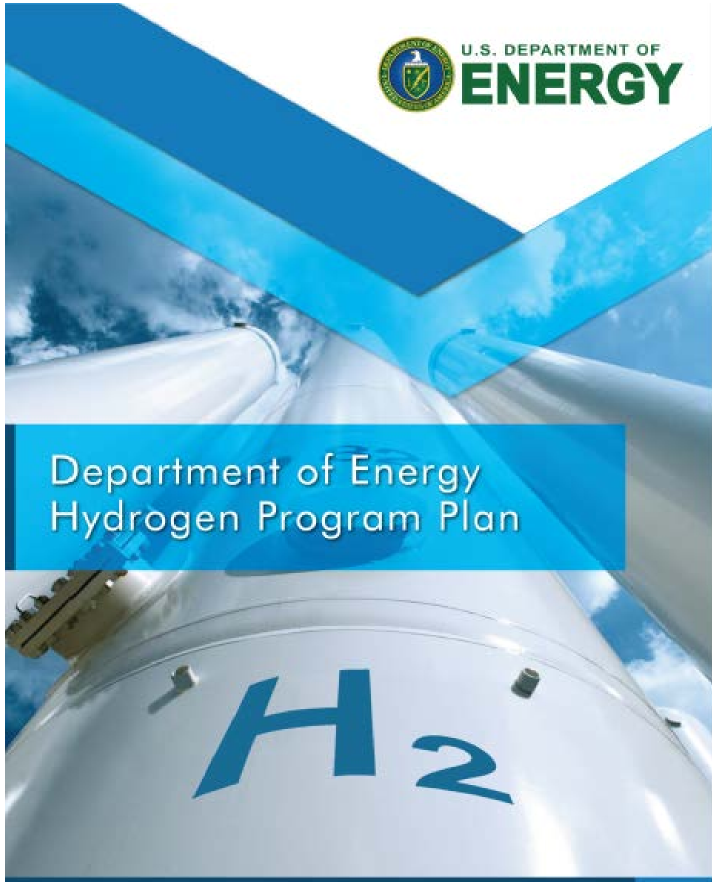
- Grid firming/integration
- Long-term energy storage
- Feedstock and fuel
- Transportation
- Low-carbon energy dense fuels
- Chemicals, materials, products
- Electrification of industrial processes
- Reactive capture and conversion of CO_2

MAKE, STORE, MOVE, and USE

https://www.energy.gov/eere/fuelcells/h2scale

H2@Scale

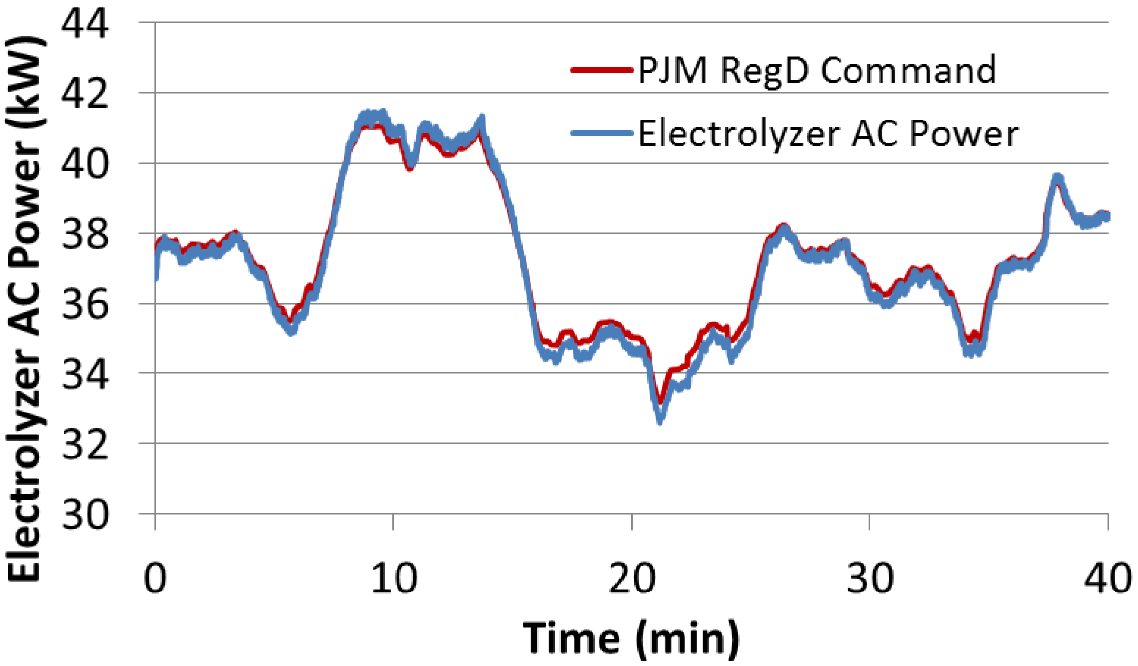




www.hydrogen.energy.gov

https://www.energy.gov/eere/fuelcells/h2scale

H_2 for Grid Integration and Support



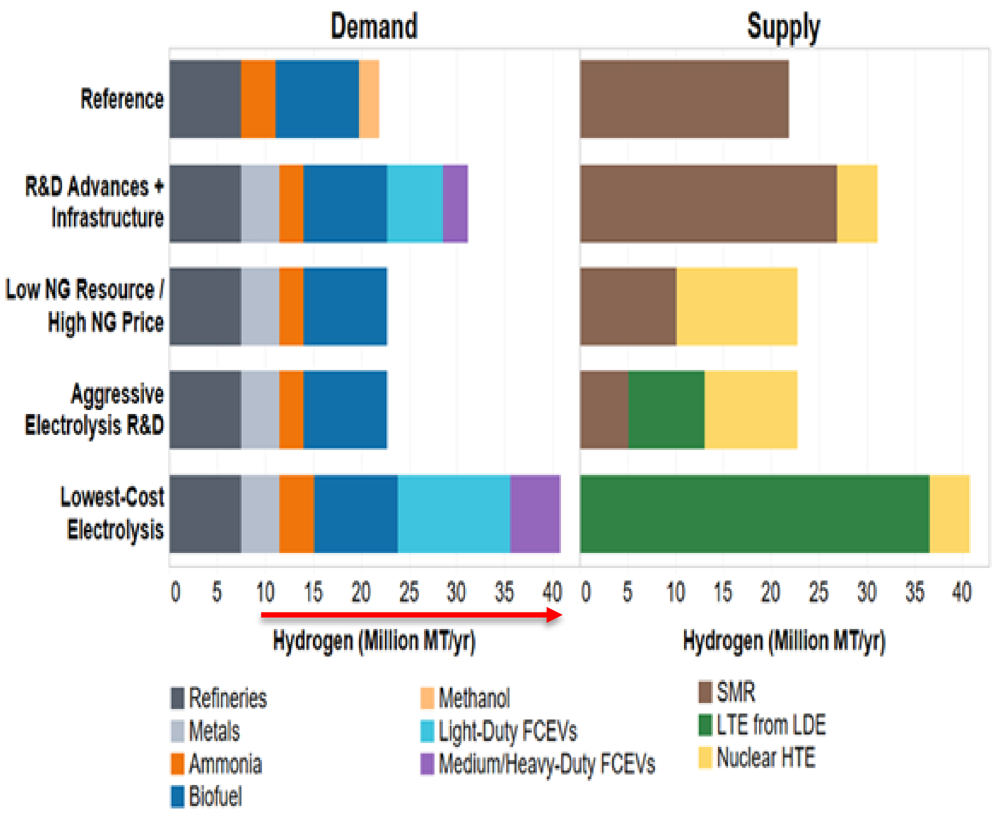
Supporting grid stability

- **Typical utility profile to validate performance**
- **System response, not just stack**
- **120 kW PEM stack operating on NREL's electrolyzer stack test bed**
- **Flexible demand side management tool could be used to provide frequency response service**

Electrolyzer systems are flexible electrical loads that can help stabilize the electricity grid and enable higher penetrations of renewable electricity

Analysis of Technical & Economic Potential of H2@Scale

Application	Serviceable Consumption Potential (MMT/yr)	2015 Market for On-Purpose H2 (MMT/yr)
Refineries and the chemical processing industry (CPI) [a]	7	6
Metals	12	0
Ammonia	4	3
Biofuels	9	0
Synthetic hydrocarbons	14	1
Natural gas supplementation	16	0
Seasonal energy storage for the electricity grid	15	0
Industry and Storage Subtotal	**77**	**10**
Light-duty fuel cell electric vehicles (FCEVs)	21	0
Medium- & Heavy-Duty FCEVs	8	0
Transportation Fuel Subtotal	**29**	**0**
Total	**106**	**10**

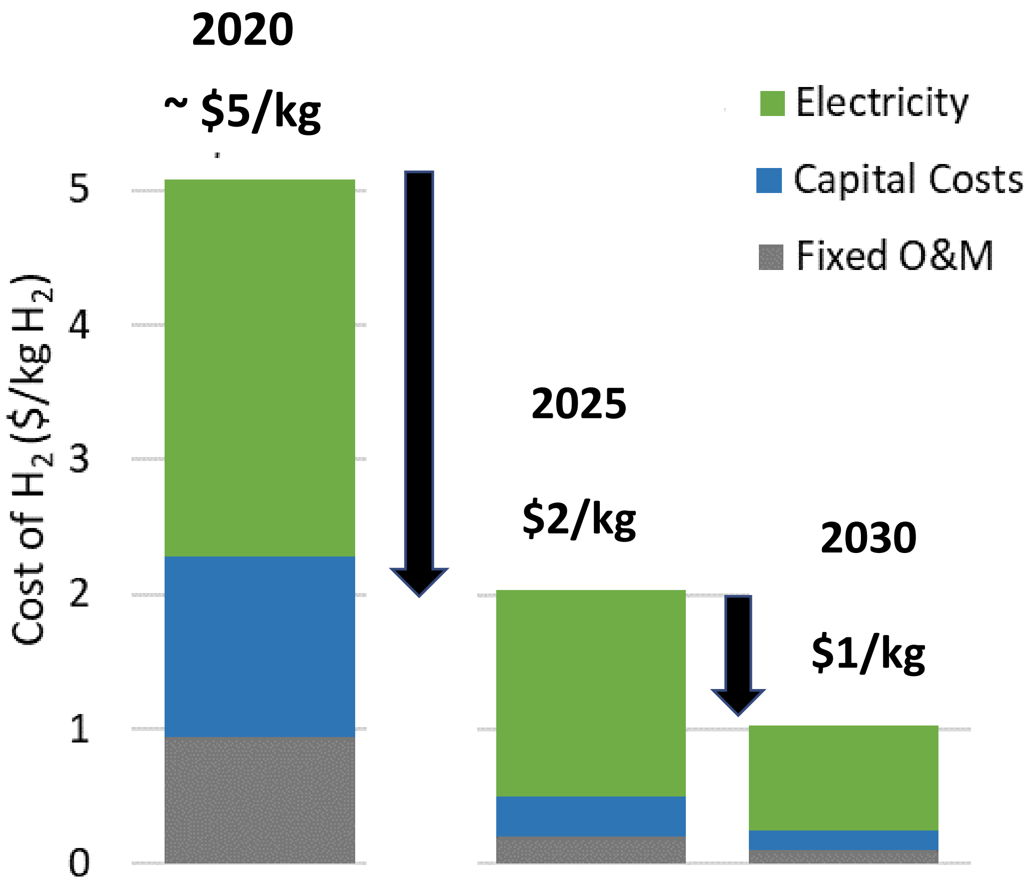


Reference (Oct. 2020): https://www.nrel.gov/docs/fy21osti/77610.pdf

Hydrogen Shot: "1 1 1"
$1 for 1 kg in 1 decade for clean hydrogen

Energy earthshots U.S. Department of Energy | Hydrogen

Example: Cost of Clean H_2 from Electrolysis



One of several pathways

- Reduce electricity cost from >$50/MWh to
  - $30/MWh (2025)
  - $20/MWh (2030)
- Reduce capital cost >80%
- Reduce operating & maintenance cost >90%

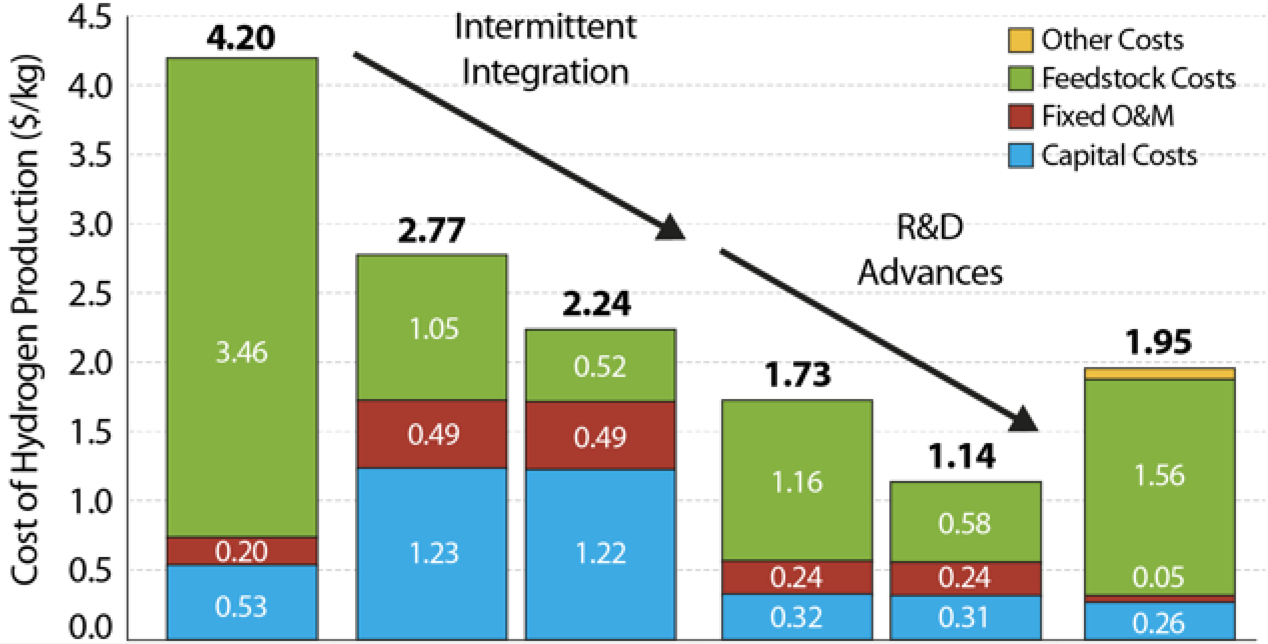
All pathways for clean hydrogen included: Thermal conversion w/ CCS, advanced water splitting, biological approaches, etc.

2020 Baseline: PEM low volume capital cost ~$1,500/kW, electricity at $50/MWh. Need less than $300/kW by 2025, less than $150/kW by 2030 (at scale)

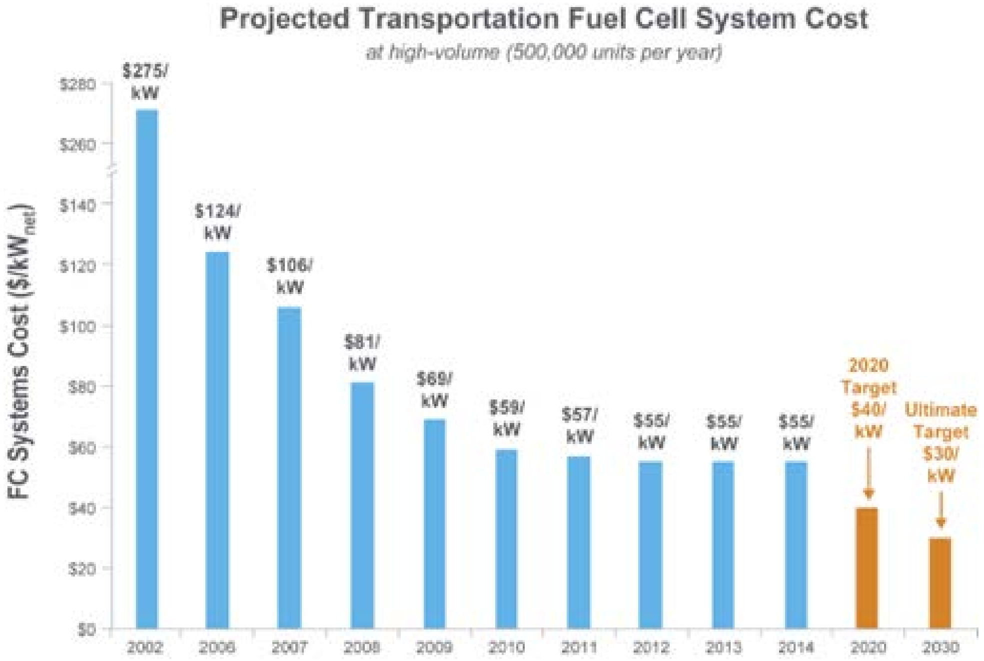
from Sunita Satyapal, DOE-EERE HFTO, June 2021

https://www.energy.gov/eere/fuelcells/hydrogen-shot

Pathway to Economical Generation of H_2 by Electrolysis

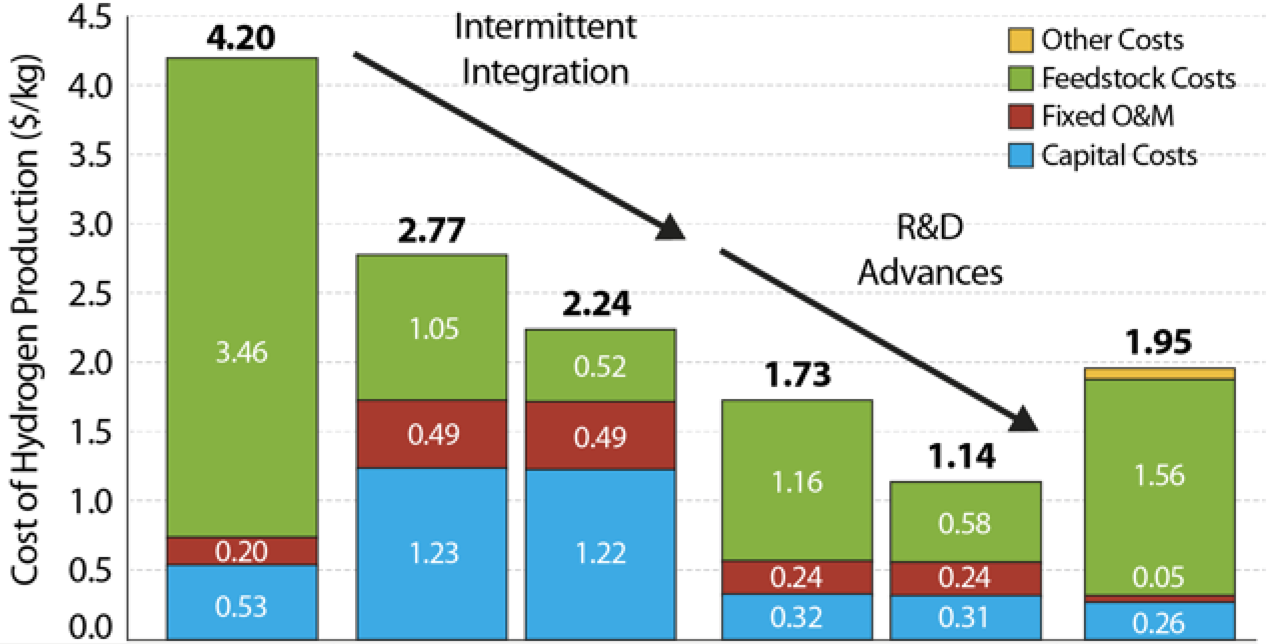


Capacity Factor	97%	40%		40%		0.9
Cost of Electricity	¢6.6/kWh	¢2/kWh	¢1/kWh	¢2/kWh	¢1/kWh	
Capital Cost	$400/kW	$400/kW		$100/kW		
Efficiency (LHV)	66%	66%		60%		
	Electrolyzer					SMR



M. Ruth et al. https://www.nrel.gov/docs/fy19osti/72740.pdf
Also: https://irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction

Pathway to Economical Generation of H_2 by Electrolysis



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Research and Development Needs

Electrocatalysts
- Improved performance and durability
- Thrift/replace precious metals

Membranes
- Resistance to differential pressures/cycling
- Alkaline systems (AEM)

Durability/Testing
- Degradation mechs; accelerated testing
- Bankability

Cell/Electrode Layer
- Impact of operating conditions
- Electrode structure/performance
- Manufacturing/Scale-up

Bipolar Plates/Porous transport layers
- Structure/performance; Corrosion

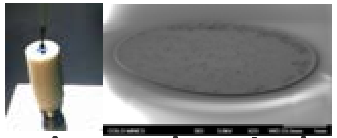
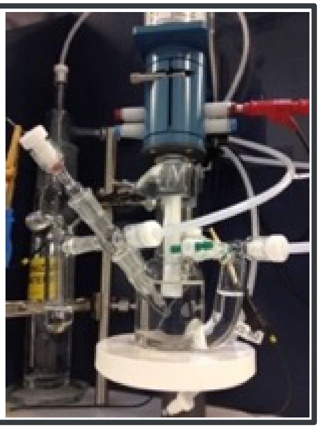
Manufacturing/Scale-up
- Learning curves

Balance of Plant
- Power supplies, inverters; DC systems
- High temperature compatible materials
- Impact of operating conditions

M. Ruth et al. https://www.nrel.gov/docs/fy19osti/72740.pdf

From Powders to Power—Fundamental Science to Large-Scale Testing

NREL Transforming ENERGY

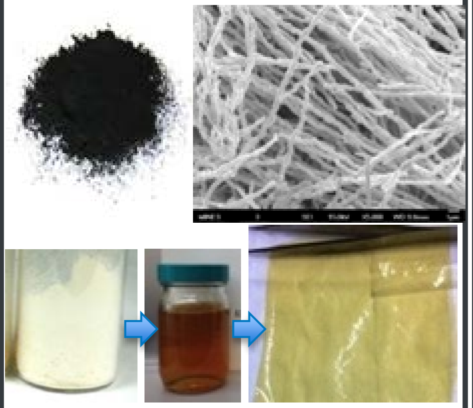
Electrochemical Characterization:
RDE & RRDE stations for Mass & Specific Activity, ECA, ORR; EQCMB, Seiras

Roll-to-roll manufacturing:
Micro-gravure coating, Slot die coating

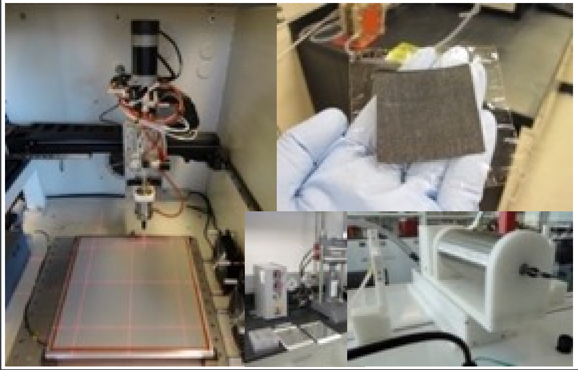
Manufacturing Lab
QC Diagnostic Development, Areal characterization, Roll-to-roll demonstration

Powders → Power

Material Synthesis:
Catalyst & Membrane Development



MEA integration
Coating, Spraying, Painting, Electrospinning, Lamination, Hot Press Transfer, Edge protection



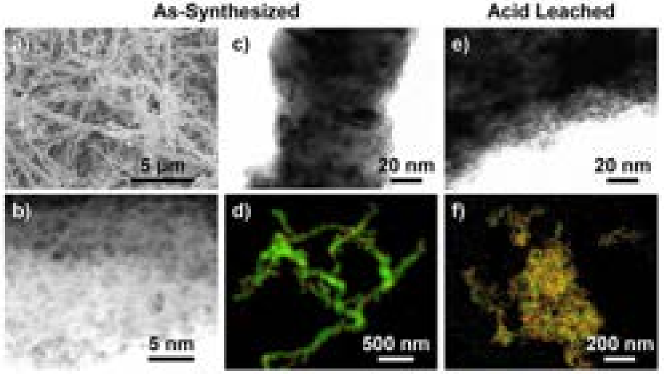
Performance and Durability Evaluation
In-situ Diagnostics, PEMFC, AEMFC, Electrolyzer; Single Cell, Stacks, Spatial

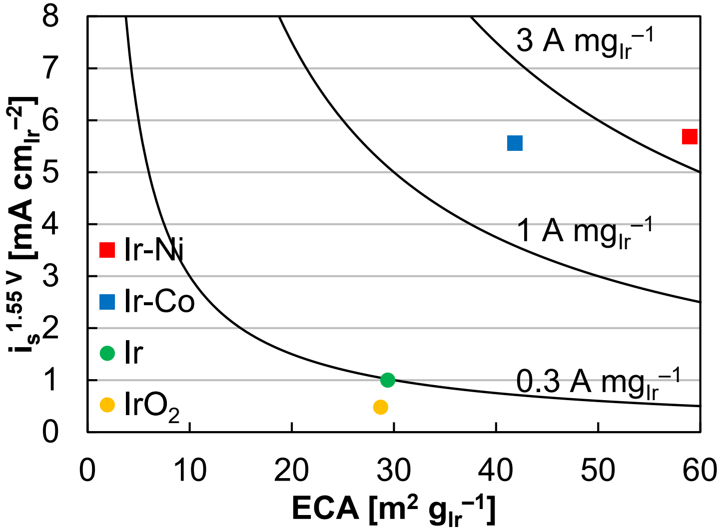
Systems Integration

Systems-focus ANALYSIS-driven R&D

Catalyst Development for Water Electrolysis

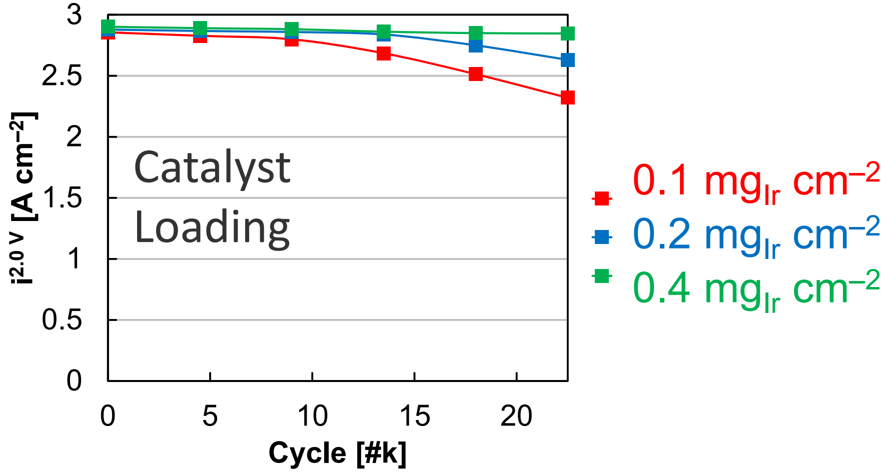
Thrifting Iridium oxygen evolution catalysts for PEM electrolyzers



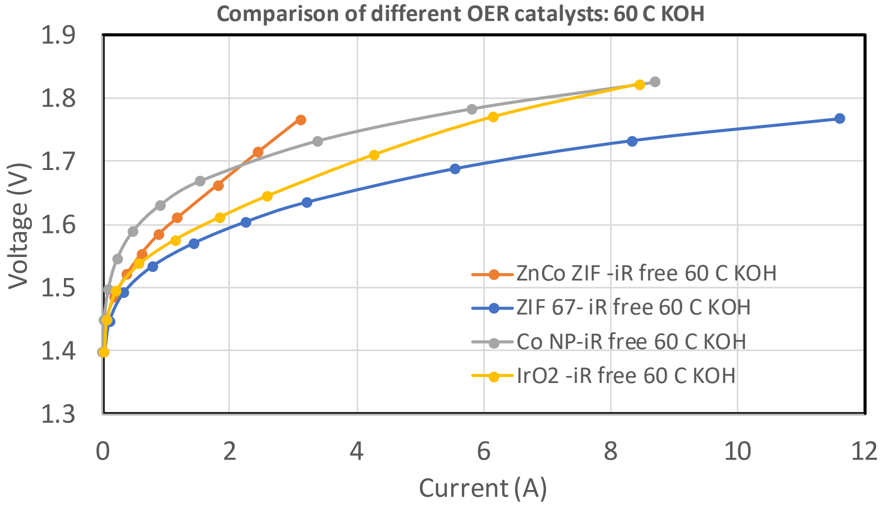


ACS Catal. **2018**, 8, 2111–2120

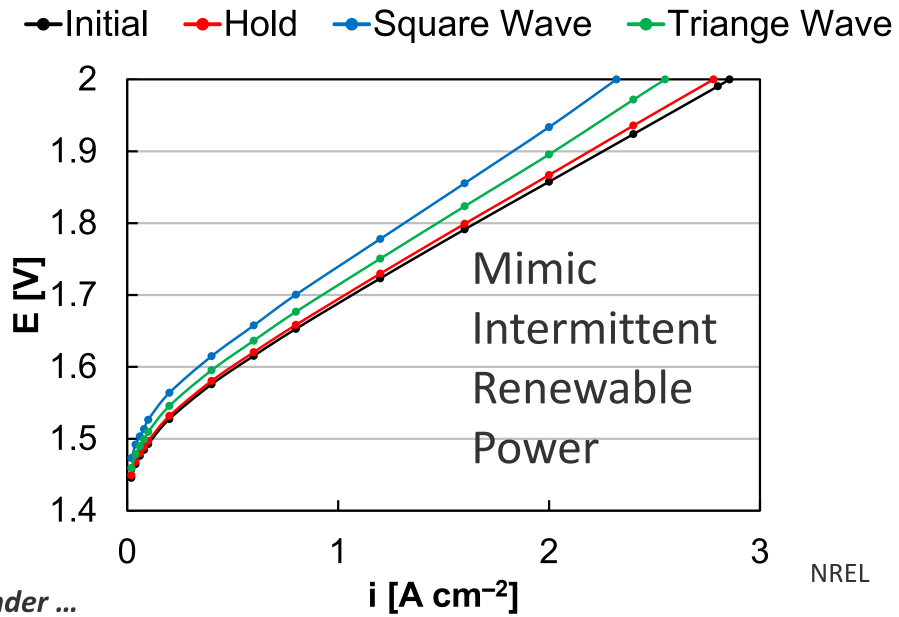
Durability Studies



PGM-free catalysts outperform Iridium oxygen evolution catalysts in AEM electrolyzers



https://www.hydrogen.energy.gov/pdfs/review18/tv146_alia_2018_p.pdf, **2018**



NREL: Pivovar, Wipke, Neale, Dinh, Alia, Bender …

H2NEW Consortium: H2 from Next-generation Electrolyzers of Water

A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable & efficient electrolyzers to achieve <$2/kg H_2

- Launched in FY21
- Both low- and high-temperature electrolyzers
- $50M over 5 years

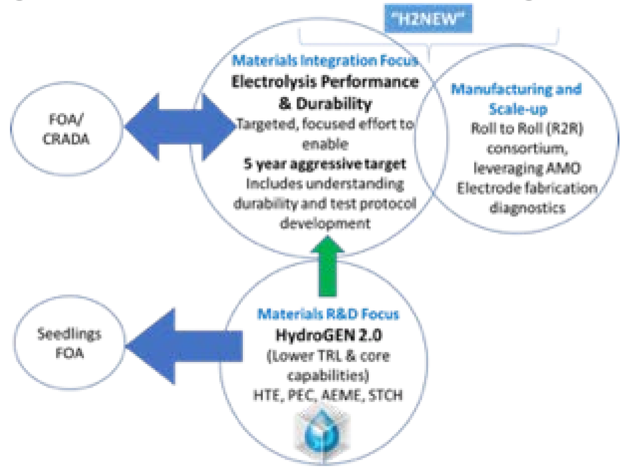
National Lab Consortium Team

NREL – National Renewable Energy Laboratory
INL – Idaho National Laboratory
Argonne National Laboratory
Berkeley Lab
Pacific Northwest National Laboratory
Los Alamos National Laboratory
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
NETL – National Energy Technology Laboratory

Clear, well-defined stack metrics to guide efforts.

Draft Electrolyzer Stack Goals by 2025		
	LTE PEM	HTE
Capital Cost	$100/kW	$100/kW
Elect. Efficiency (LHV)	70% at 3 A/cm^2	98% at 1.5 A/cm^2
Lifetime	80,000 hr	60,000 hr

The focus is not new materials but addressing components, materials integration, and manufacturing R&D



Durability/lifetime is most critical, initial, primary focus of H2NEW

- Limited fundamental knowledge of degradation mechanisms.
- Lack of understanding on how to effectively accelerate degradation processes.
- Develop and validate methods and tests to accelerate identified degradation processes to be able to evaluate durability in a matter of weeks or months instead of years.
- National labs are ideal for this critical work due to existing capabilities and expertise combined with the ability to freely share research findings.

B. Pivovar et al.

H2NEW's Approach to Addressing LTE Durability

Operando cell studies

- ✓ Determine key stressors accelerating degradation
- ✓ Identify relevant degradation mechanisms at the component level

Ex situ component studies

Membrane

- ✓ Limits of durability and the impact of different membrane chemistry
- ✓ Variables: Side chain, equivalent weight, pre-aging, reinforcements, recombination layers and/or radical scavenging
- ✓ Impact of seal area/edges, pressure

Accelerated Stress Tests

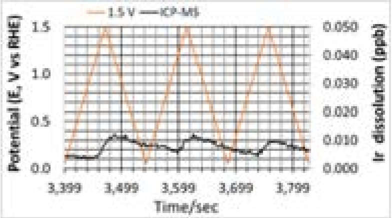
- ✓ Orders of magnitude acceleration of component degradation rates
- ✓ Assess cost and durability trade-offs, accelerate materials development, MEA integration, and optimal operating strategies for LTEs

Understanding → Understanding and Evaluation → Solutions

2025
80,000 h
2.24 µV/h
0.5 mg_{PGM}/cm^2

- ✓ Quantify losses associated with different operating conditions
- ✓ Propose and demonstrate degradation mitigation measures

Catalyst



- ✓ Aqueous electrochemical cell coupled with ICP-MS
- ✓ Potential and potential profile dependence of the dissolution of anode catalysts
- ✓ Correlation with oxidation state

Mitigation Strategies

- ✓ Develop and implement operational, materials, and cell design-based degradation mitigation strategies
- ✓ Coordinate with AST development, technoeconomic analysis, and cell fabrication tasks

In-cell Diagnostics:
I-V curves, impedance spectroscopy, cyclic voltammetry, fluoride emission

→ Voltage loss breakdown/modeling

→ ***Ex situ* component characterization:**
SEM, TEM, X-ray spectroscopy, scattering, tomography

Consortia are an Important Part of DOE Strategy for Green Hydrogen Challenges

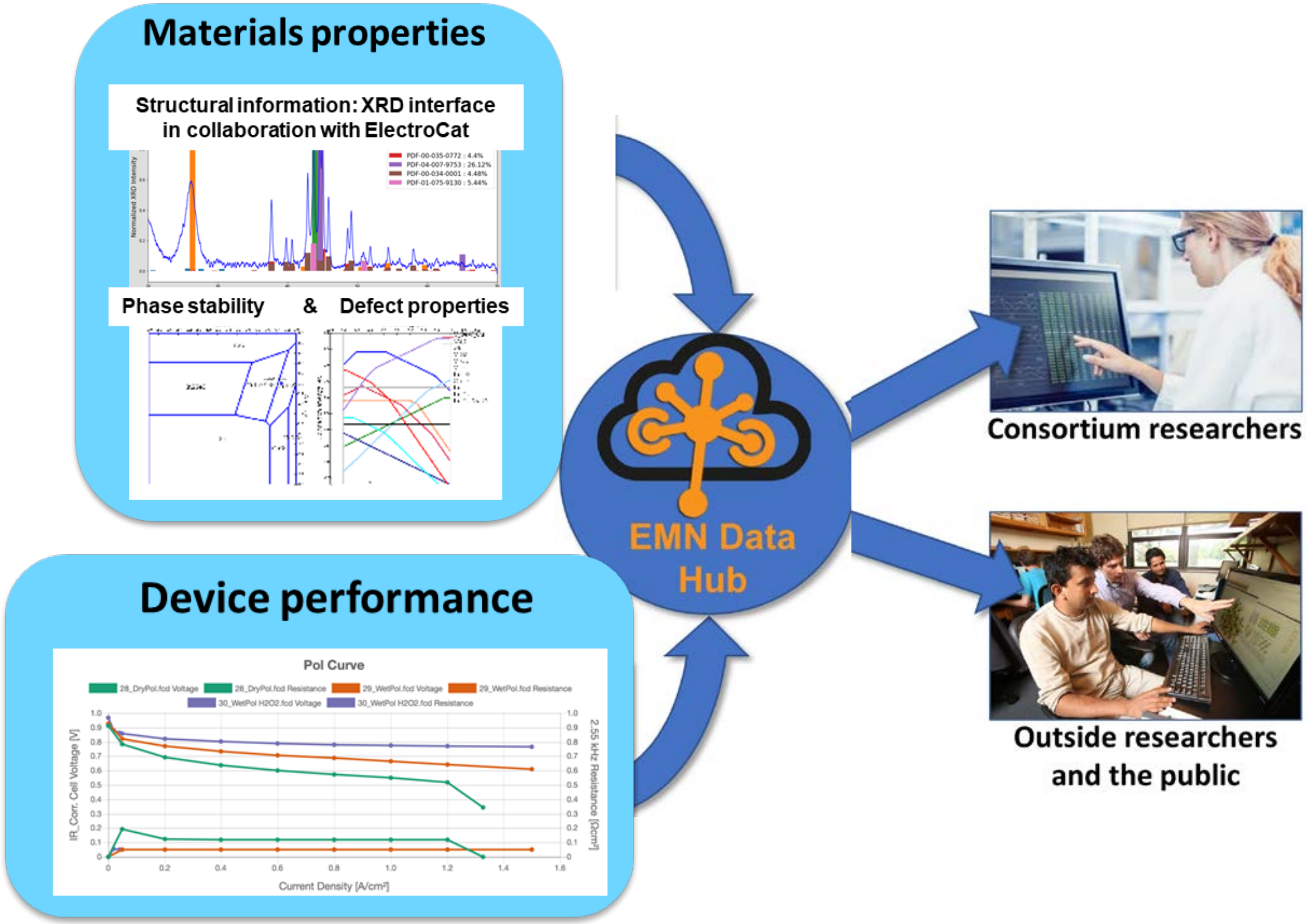
Make	Move	Store	Use
H2NEW Hydrogen from Next-generation Electrolyzers of Water U.S. DEPARTMENT OF ENERGY	H-Mat Hydrogen Materials Compatibility Consortium	HyMARC Hydrogen Materials Advanced Research Consortium	MILLION MILE FUEL CELL TRUCK U.S. DEPARTMENT OF ENERGY
HydroGEN Advanced Water Splitting Materials	HyMARC Hydrogen Materials Advanced Research Consortium		ElectroCat Electrocatalysis Consortium
	HyBlend U.S. DEPARTMENT OF ENERGY		

Crosscutting:

- Analysis
- Manufacturing
- Codes & Standards

www.h2new.energy.gov
www.awsm.org
www.h-mat.org
www.hymarc.org
www.millionmilefuelcelltruck.org
www.electrocat.org

Energy Material Network Data Hubs: Software Platforms for Advancing Collaborative Energy Materials Research



HydroGEN Advanced Water Splitting Materials · DuraMAT Durable Module Materials Consortium · ChemCatBio Chemical Catalysis for Bioenergy · HyMARC · ElectroCat Electrocatalysis Consortium · H-Mat Hydrogen Materials Compatibility Consortium · LightMAT Lightweight Materials Consortium

Simple data interface developed

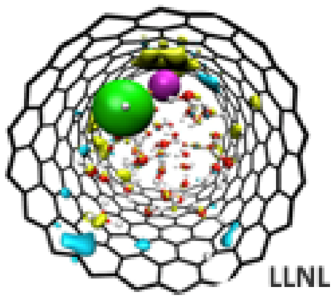
- Have proven capable of effectively leveraging geographically dispersed equipment resources and scientific expertise
- Enabled consortium in making significant advancements in their research and disseminate them the community.

White, Munch, Wunder, Guba, Van Allsburg, Dinh, *et al.* *International Journal of Advanced Computer Science and Applications*, *12(6), 2021*. http://dx.doi.org/10.14569/IJACSA.2021.0120677

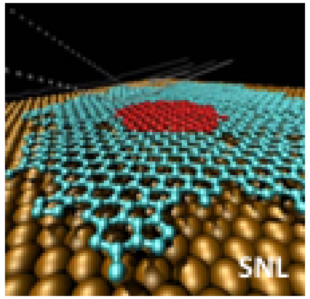
https://www.energy.gov/eere/energy-materials-network/energy-materials-network

HydroGEN Advanced Water Splitting Consortium

Materials Theory/Computation

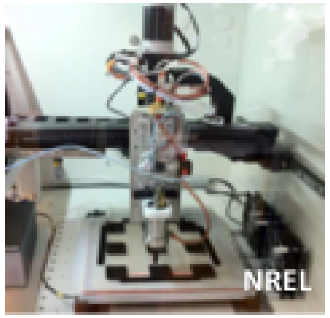


Bulk & interfacial models of aqueous electrolytes

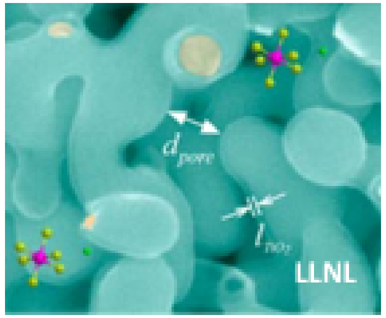


LAMMPS classic molecular dynamics modeling relevant to H_2O splitting

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

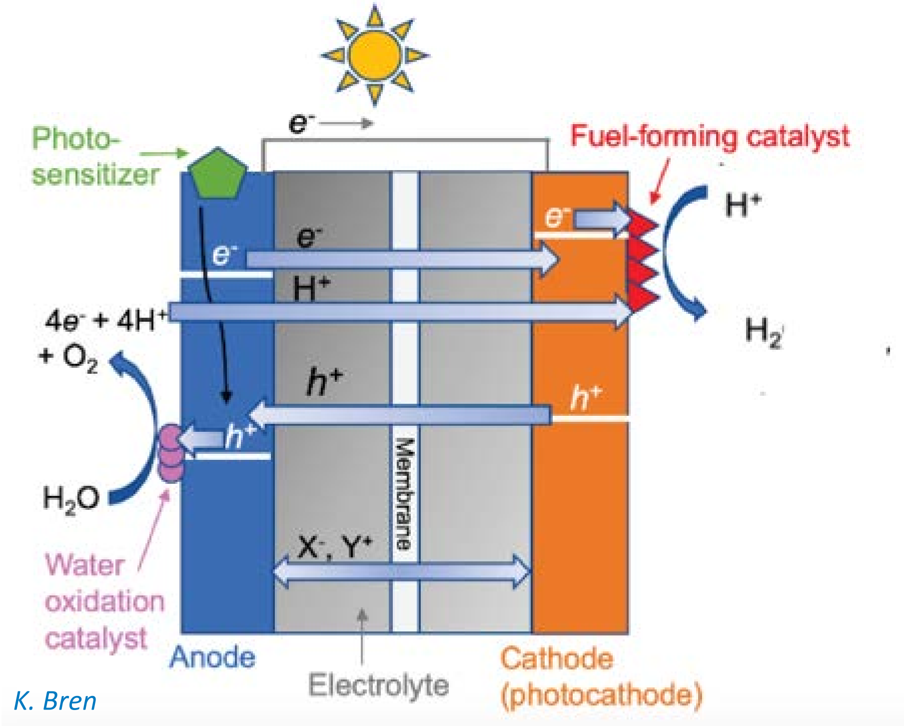
Key Accomplishments

- Achieved 70% PEM electrolyzer cell efficiency while improving durability & reducing cost
- Scaled up baseline cell by 8X with 9% STH efficiency & 100 h stability integrated PV-PEC system
- Discovered new STCH compounds with H_2 production capacities > state of the art at lower temperatures
- Demonstrated a metal-supported o-SOEC cell with dramatically improved stability

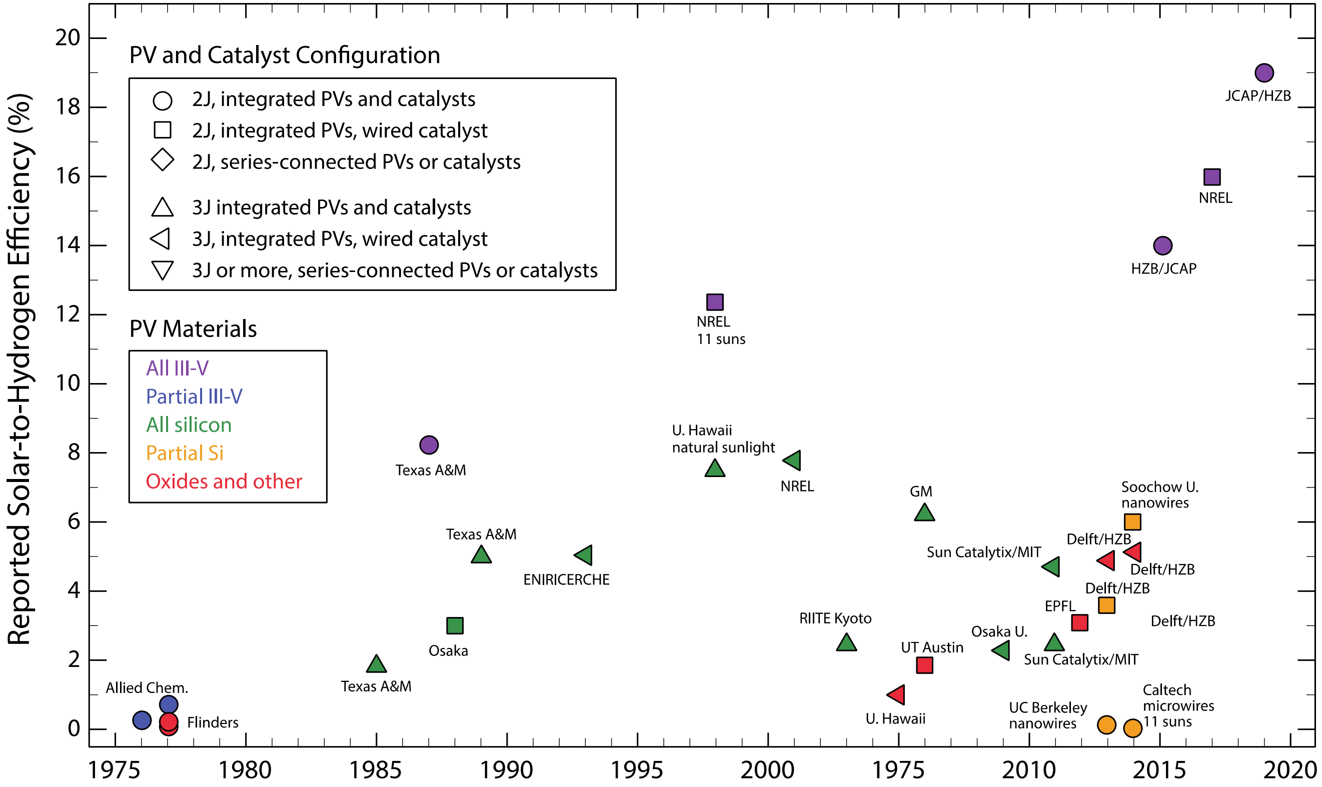
NREL NATIONAL RENEWABLE ENERGY LABORATORY · BERKELEY LAB · INL Idaho National Laboratory · Sandia National Laboratories · Lawrence Livermore National Laboratory

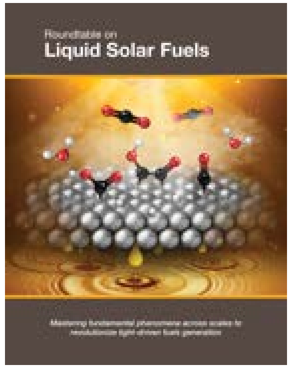
Solar Fuels (Direct sunlight to chemical energy)
Approaches to Solar Hydrogen (Photoelectrochemistry): $H_2O \rightarrow H_2 + \frac{1}{2}O_2$

Adapted from: Ager et al. EES 8, 2811 (2015)



K. Bren





JCAP JOINT CENTER FOR ARTIFICIAL PHOTOSYNTHESIS www.solarfuelshub.org

HydroGEN Advanced Water Splitting Materials

https://science.osti.gov/bes/Community-Resources/Reports

http://mission-innovation.net/wp-content/uploads/2021/03/Converting-Sunlight-into-Solar-Fuels-and-Chemicals-MI-Challenge-5-roadmap-Feb-2021-final.pdf

Huyen Dinh, NREL

https://h2awsm.org

Hydrogen Utilization: Renewable Methane Production from H_2 and CO_2

- Utilize excess electricity production for the electrolysis of water to H_2 and O_2
- Optimized strain of methanogenic archaea to perform methanation under industrial conditions
- 98% Carbon conversion of CO_2 to CH_4
- Post-processing for pipeline quality natural gas

Significance and Impact

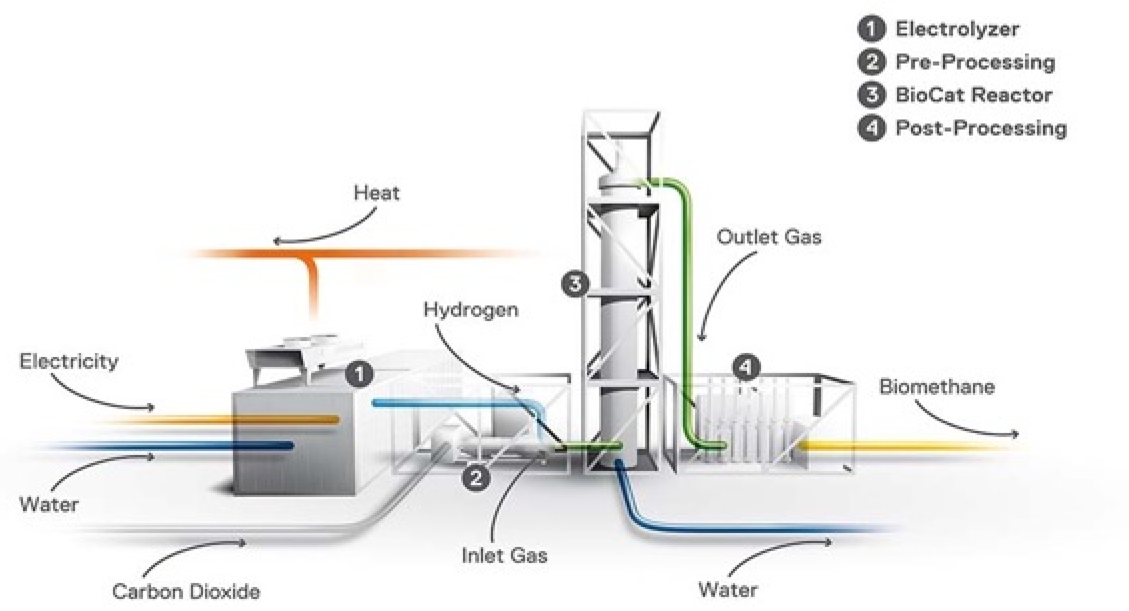
- Potential long term storage strategy via conversion of electricity & CO2 to CH4
- High efficiency CO2 capture and conversion strategy
- Demonstrated route to renewable methane

SoCalGas A Sempra Energy utility

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Electrochaea

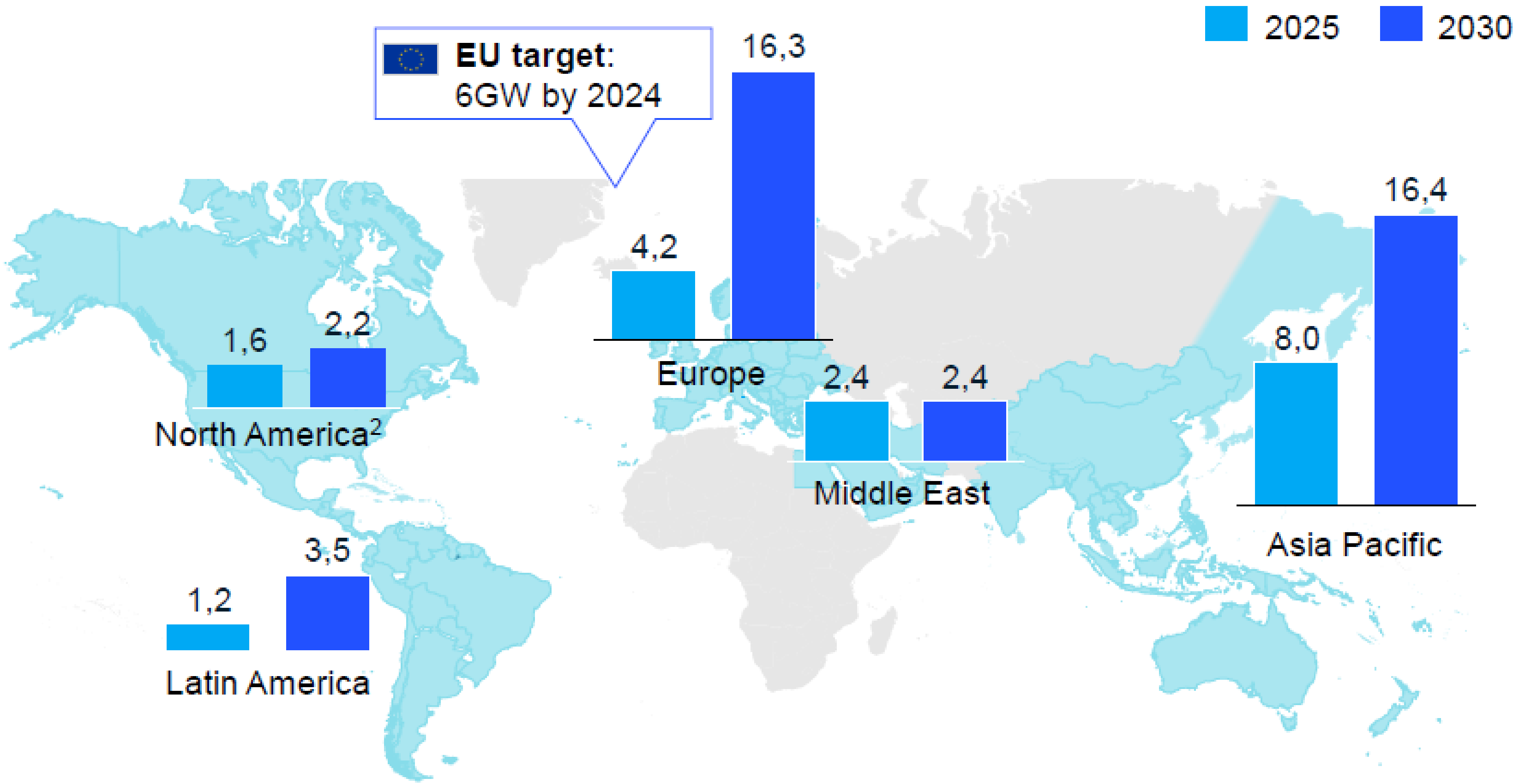
K. Harrison, N. Dowe ,…



$$4H_2 + CO_2 \xrightarrow{\text{Biocatalyst}} CH_4 + 2H_2O$$

Key Regions and Market Growth - Examples

Examples of Global electrolyzer project announcements, GW (not exhaustive)



Top 10 largest announced projects to be set up by 2030, GW

Rank	Country	Company	GW
1	Australia	HRA	5.00
2	China	BEIH	5.00
3	Australia	H2U	3.00[3]
4	Saudi Arabia	ACWA POWER	2.00[4]
5	Chile	ENGIE, Enaex	1.60[5]
6	Chile	HIF, SIEMENS, enel	1.60
7	Portugal	edp	1.00
8	Denmark	Shell, Everfuel	1.00
9	Germany	Ørsted	0.67
10	Australia	origin	0.5

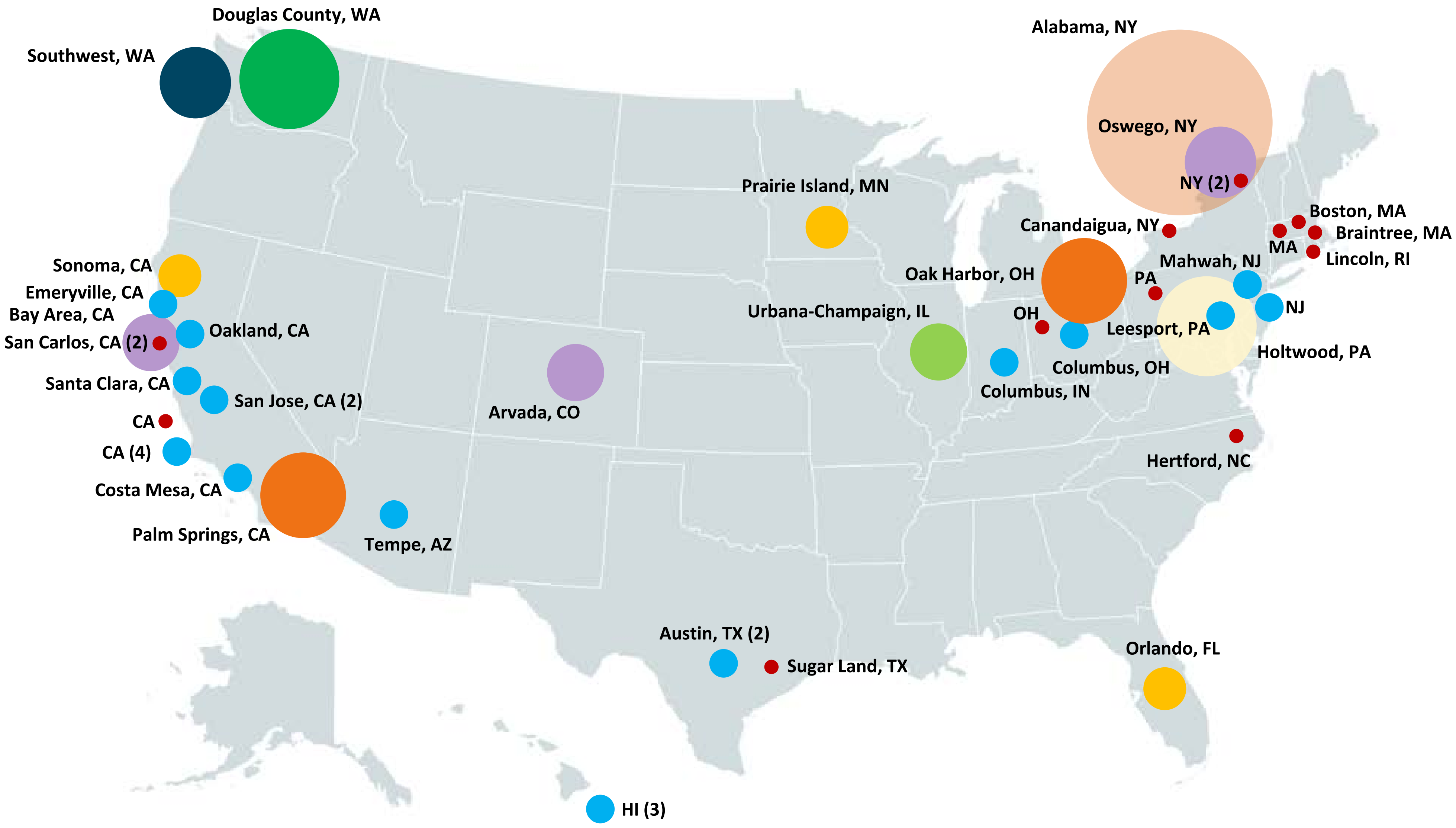
1. Includes early stage capacity deployment of projects with full commission after 2030; 2. Nel and Nikola announced a project with 1 GW electrolyzer capacity; project timeline TBD (not included in projects to the right)
3. Electrolyzer will be built in stages, scaling up over time to reach up to 3 GW capacity and with first production in 2025; 4. Scheduled to be on stream in 2025. Deployment timeline not announced.
5. A pilot plant will become operational by 2024, the potential upscaling to 1.6 GW will start in 2026

(From Sunita Satyapal, DOE EERE-HFTO)

McKinsey & Company

U.S. Hydrogen Electrolyzer Locations and Capacity

U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY



Electrolyzer Power Capacity

- 120 KW
- 180 KW
- 500 KW
- 1000 KW
- 1250 KW
- 1500 KW
- 2000 KW
- 5000 KW
- 30000 KW
- 120000 KW

PEM: polymer electrolyte membrane
Current and under construction installations over 120 kW as of June 2021

Source: Arjona et al., DOE Hydrogen Program Record, June 2021

To report a planned or installed PEM electrolyzer with a capacity of 0.5 MW or greater in your state, please contact fuelcells@ee.doe.gov

Technology R&D in a System

Grid and Renewables Coupling

Electrolyzers as dispatchable loads in power systems, dynamic operations and integration with renewable production

Hydrogen Production

Full stack scale electrolyzer and BOP performance, system optimization when coupled to grid/renewables and end uses

Distribution and Storage

System scale distribution and storage challenges, vehicle and ground storage performance and modeling

End Use Applications

Transportation applications, industrial applications, natural gas blending, renewable synthetic molecules

Safety and Sensors

Development and evaluation of safety and sensor systems, component failure characterization

Enabler: Center for Hydrogen Safety

Global Center for Hydrogen Safety established to share best practices, training resources and information

High Priority: Lessons learned and best practices on safety

Encourage membership (industry, govt, universities, labs) to join CHS

CENTER FOR Hydrogen SAFETY 水素安全センター

Connecting a Global Community

www.aiche.org/CHS

IPHE

Hydrogen Council

AIChE

Pacific Northwest NATIONAL LABORATORY

hySafe

Over 60 partners: government, industry, universities and more

Access to >110 countries, 60,000 members

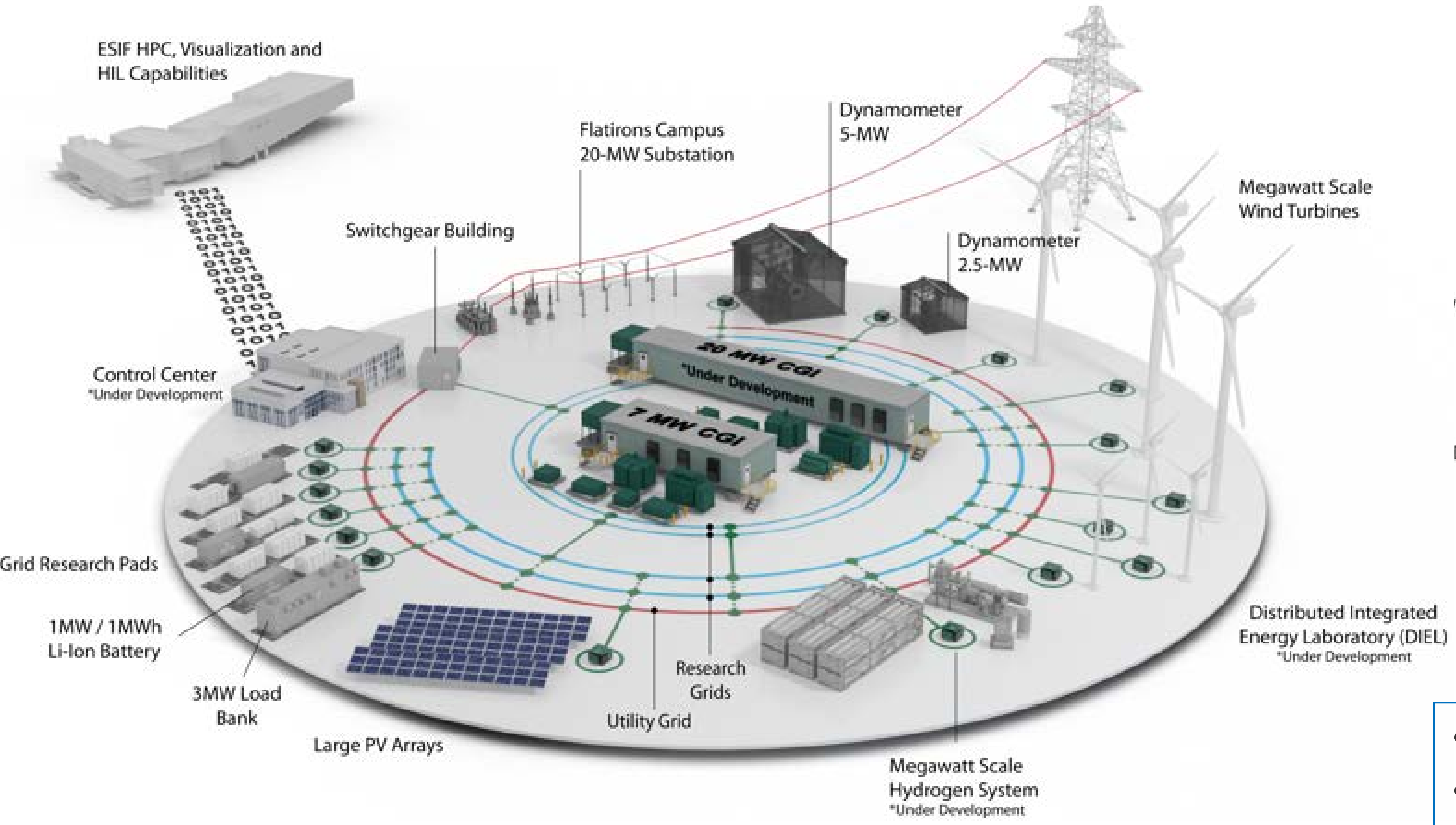
CENTER FOR Hydrogen SAFETY

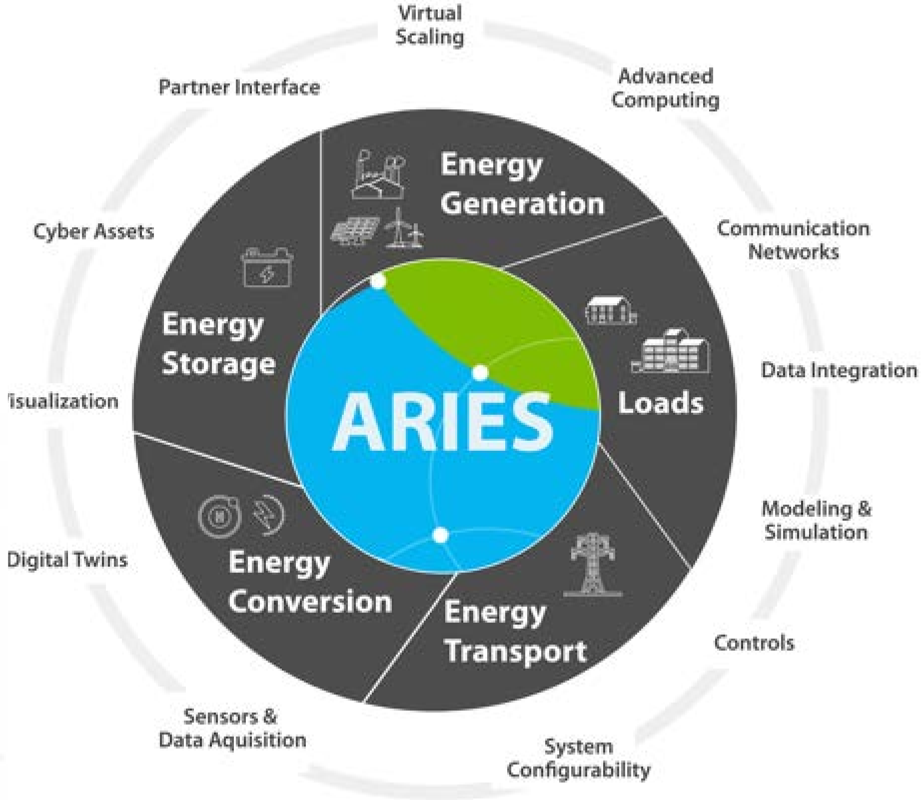
Connecting a Global Community

HYDROGEN Safety Panel

HYDROGEN Emergency Response Training Resources

Advanced Research on Integrated Energy Systems (ARIES)

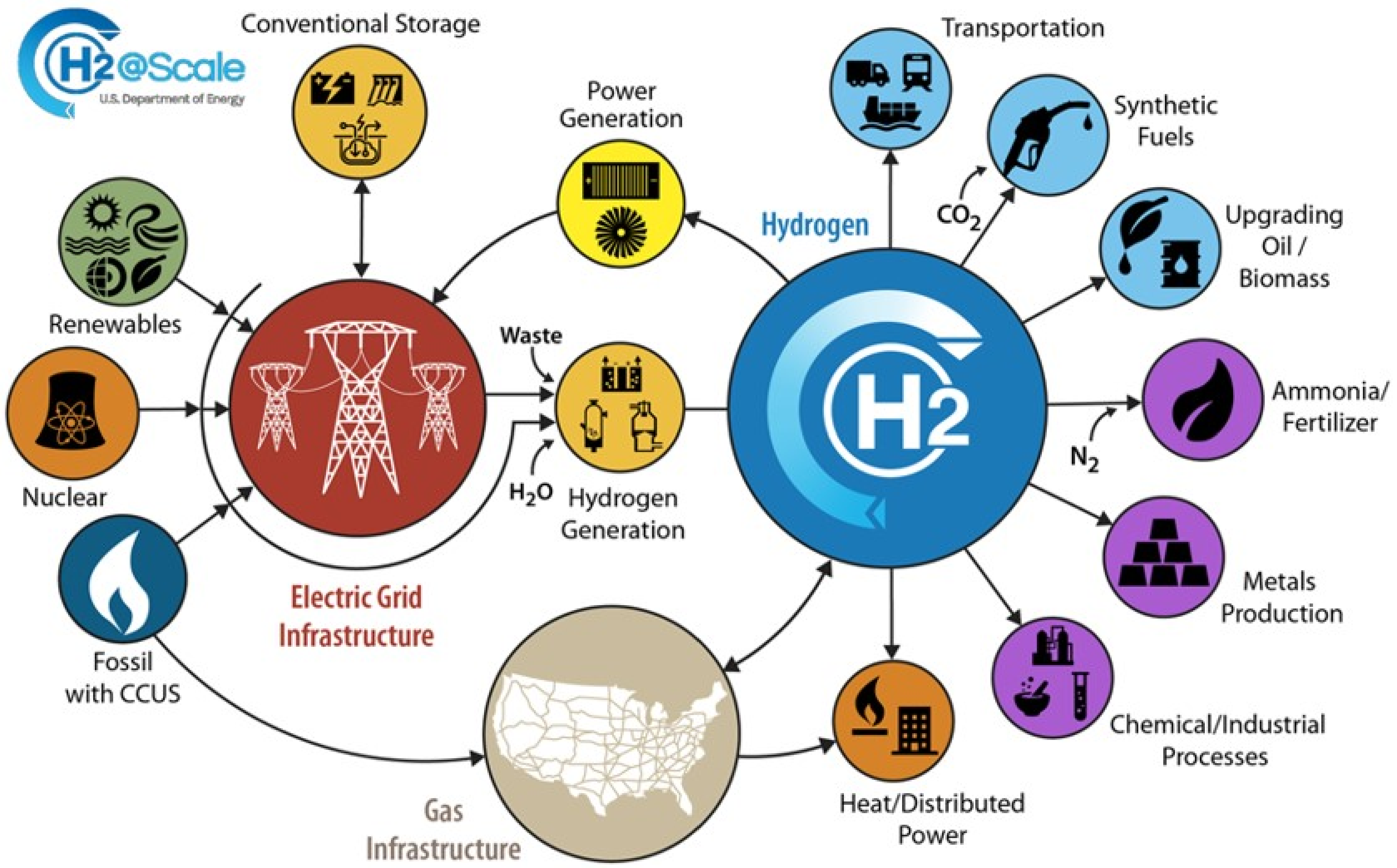




- Device/technology development
- Hardware in-the-loop testing
- Integrating multiple diverse technologies
- Controlling many interconnected devices
- Interoperability, performance, reliability, …
- Multi-scale analysis and modeling
- Collaborations and partnership

Jen Kurtz *et al.*
https://www.nrel.gov/aries/

Getting to Gigatons and Terawatts: Challenges and Opportunities



Hydrogen can play a major role in all energy sectors: grid, transportation, industry, buildings, agriculture

- Interconversion of electrical and chemical energy
- Grid integration
- Pathway to electrify energy sectors—cross-sector coupling
- Fuel, feedstocks, chemicals/materials

Hydrogen Earthshot (1 1 1)

Opportunity for parallel development and deployment

- Accelerate innovation for MAKE, MOVE, STORE, USE

International Collaboration

https://www.energy.gov/eere/fuelcells/h2scale