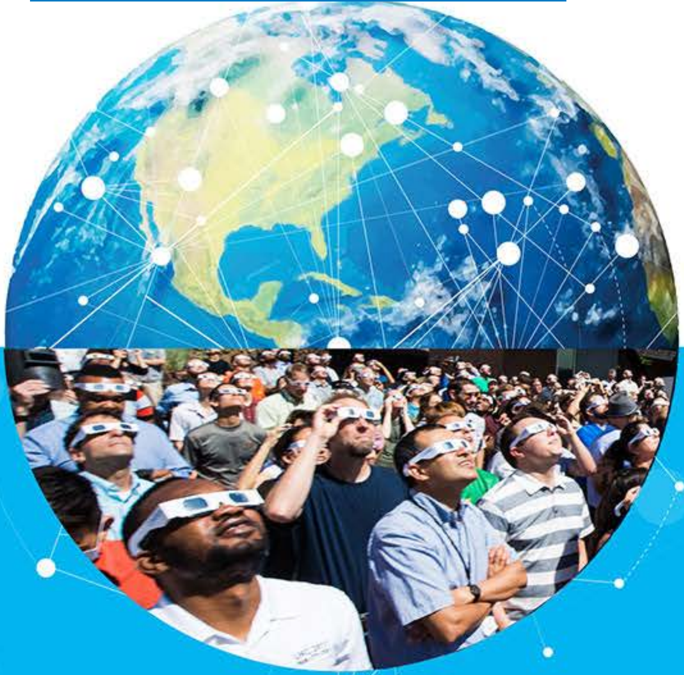
NREL Transforming ENERGY



Clean Hydrogen Production R&D at NREL

Huyen N. Dinh (She/Her/Hers)
FECM RECS Workshop, NREL
July 18, 2023

Photo by Dennis Schroeder, NREL 46840

What is the hydrogen energy earthshot goal?

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Hydrogen Energy Earthshot

“Hydrogen Shot”

“1 1 1”
$1 for 1 kg clean hydrogen in 1 decade

Launched June 7, 2021
Summit Aug 31-Sept 1, 2021

S. Satyapal, et al., “Overview of DOE RFI Supporting Hydrogen Bipartisan Infrastructure Law Provisions, Environmental Justice, and Workforce Priorities, Feb. 24, 2022

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

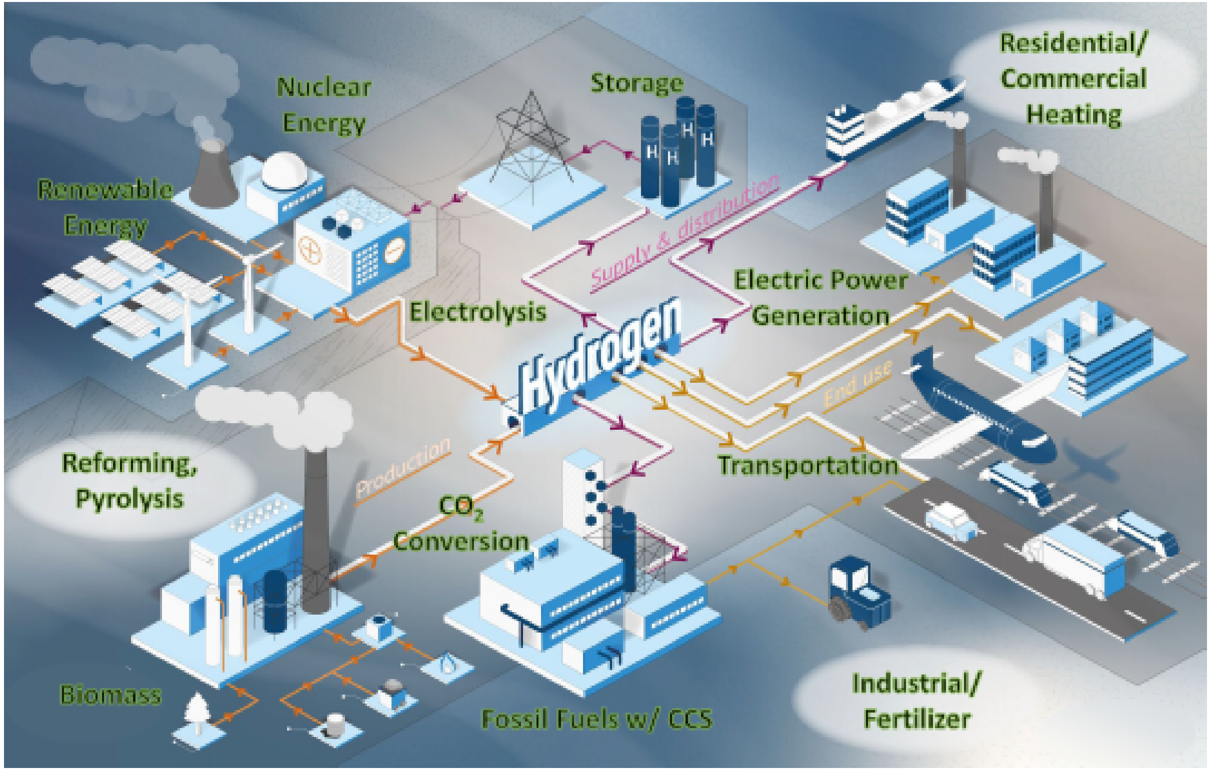
Bipartisan Infrastructure Law – Hydrogen Highlights

- **Covers $9.5B** for clean hydrogen:
  - $8B for at least 6-10 regional clean H_2 hubs
  - $1B for electrolysis RD&D
  - $0.5B for clean H_2 technology manufacturing and recycling R&D
- Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $2 per kilogram by 2026
- Requires developing a National Hydrogen Strategy and Roadmap

President Biden Signs the Bipartisan Infrastructure Bill into law on November 15, 2021. Photo Credit: Kenny Holston/Getty Images

S. Satyapal, et al., "Overview of DOE RFI Supporting Hydrogen Bipartisan Infrastructure Law Provisions, Environmental Justice, and Workforce Priorities, Feb. 24, 2022

Hubs Enable Multiple Feedstocks and End Uses



H_2 Ecosystem: Potential for different clean H_2 production methods, end uses, and necessary infrastructure all in close proximity

Additional Key Items beyond H_2 Technology:

- Environmental Justice
- Community Engagement
- Job Creation
- Workforce Development
- Labor Standards
- Diversity, Equity, Inclusion
- Commercial Sustainability
- U.S. Manufacturing

S. Satyapal, et al., "Overview of DOE RFI Supporting Hydrogen Bipartisan Infrastructure Law Provisions, Environmental Justice, and Workforce Priorities, Feb. 24, 2022

What is the highest clean hydrogen production tax credit (45V) under the Inflation Reduction Act (IRA)?

Clean Hydrogen Production Tax Credit (45V) up to $3/kg

Carbon Intensity (kg CO_2 per kg H_2)*	Max Tax Credit ($/kg H_2)
4–2.5	$0.60
2.5–1.5	$0.75
1.5–0.45	$1.00
0.45–0	$3.00

Definition of Clean H_2 is < 0.45 kg CO_2eq/kg H_2

2023 Hydrogen Program Overview, Sunita Satyapal, Hydrogen and Fuel Cell Technologies Office (HFTO) Director and DOE Hydrogen Program Coordinator: Presentation slides: Hydrogen Program Overview; https://www.hydrogen.energy.gov/annual-review/annual_review23_proceedings.html

3 Key Strategies of the DOE Clean H_2 Strategy & Roadmap

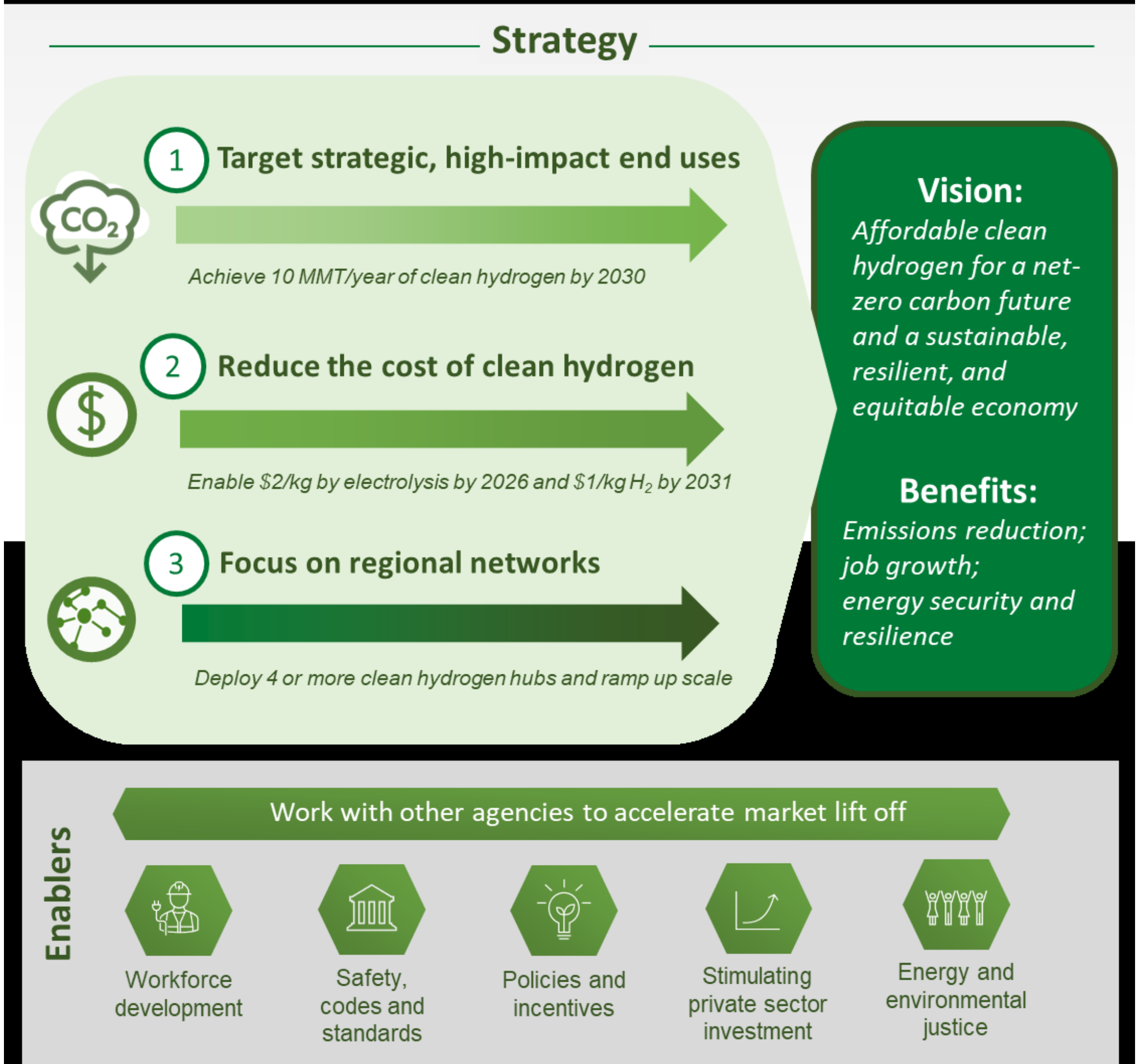
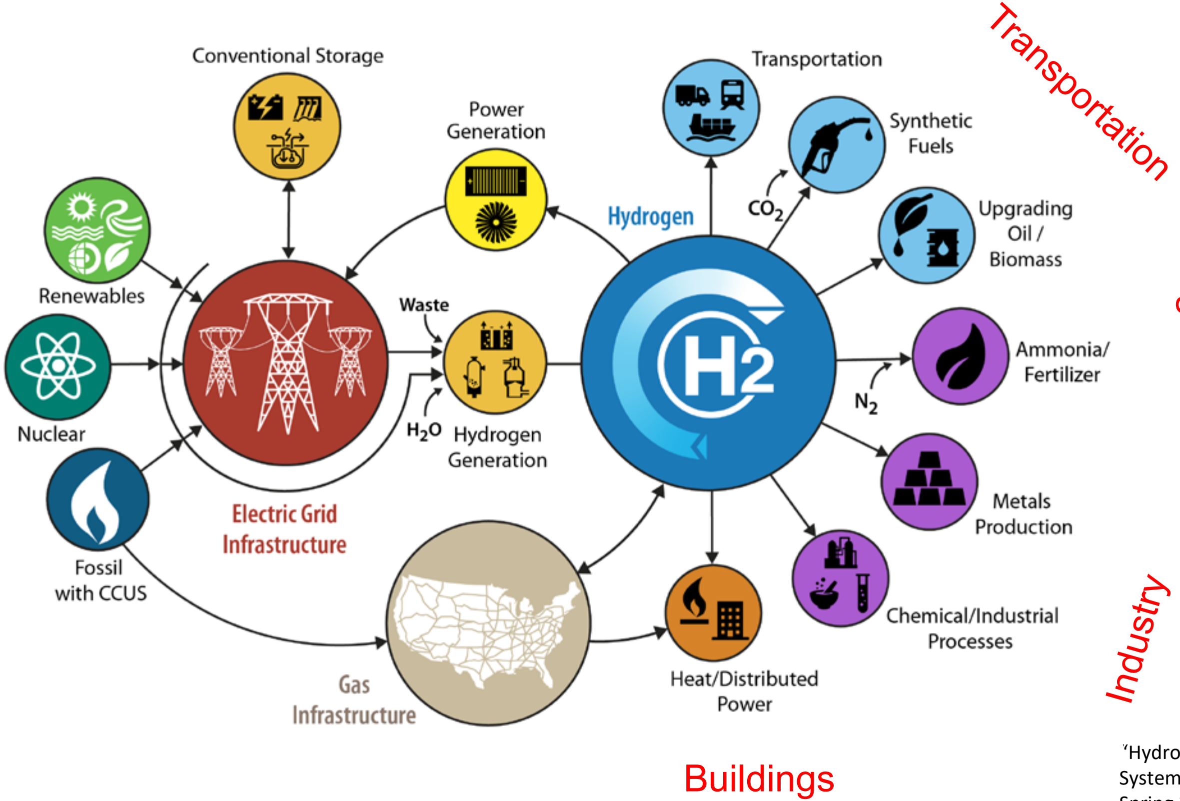


Figure 16 The national strategies for clean hydrogen and the Department of Energy's Hydrogen Program mission and context

U.S. D.O.E National Clean Hydrogen Strategy and Roadmap Draft (September 2022)

H2@Scale: Enabling Affordable, Reliable, Clean and Secure energy



Transportation and Beyond

Large-scale, low-cost hydrogen from diverse domestic resources enables an economically competitive and environmentally beneficial future energy system across sectors

Hydrogen can address specific applications that are hard to decarbonize

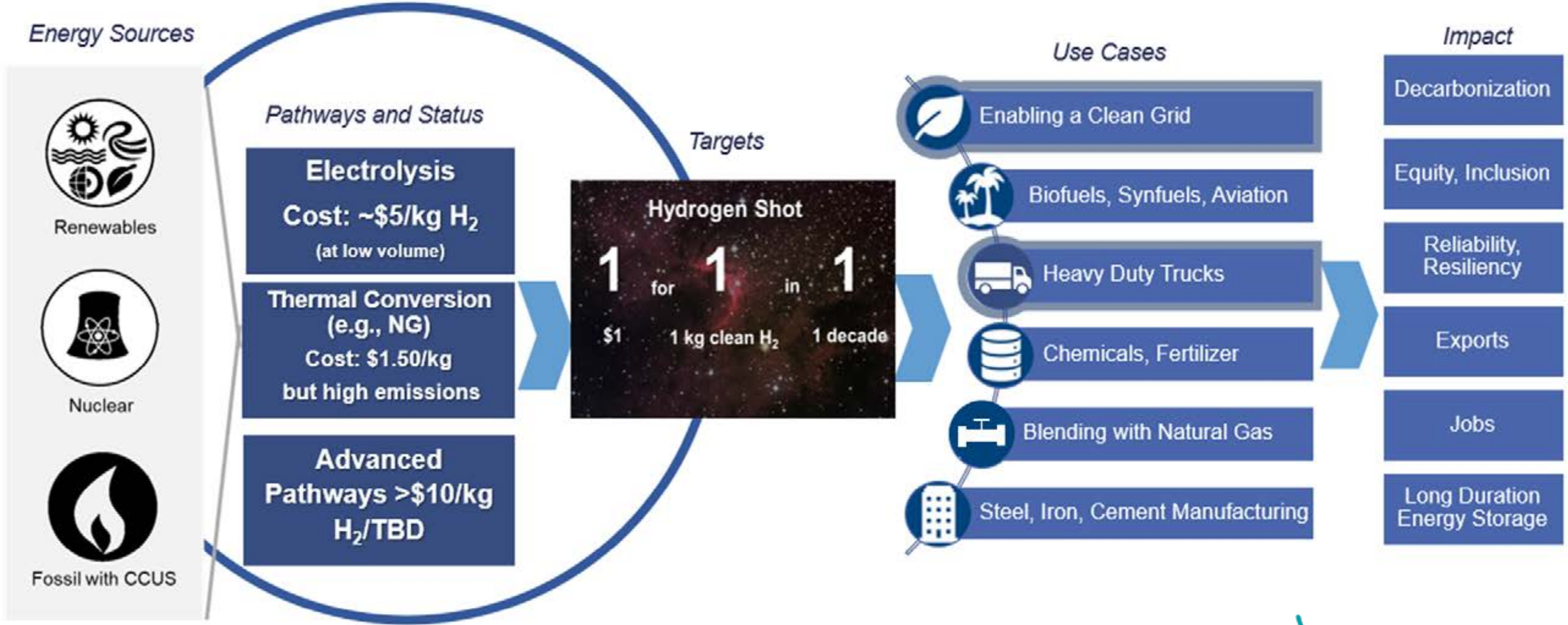
Today: 10 MMT H_2 in the US

Economic potential: 2x to 4x more

“Hydrogen at Scale (H_2@Scale): Key to a Clean, Economic, and Sustainable Energy System,” Bryan Pivovar, Neha Rustagi, Sunita Satyapal, *Electrochem. Soc. Interface* Spring 2018 27(1): 47-52; doi:10.1149/2.F04181if.

Source: DOE Hydrogen and Fuel Cell Technologies Office, https://energy.gov/eere/fuelcells/h2-scale

Leveraging Diverse Domestic Clean H_2 Options



ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Potential of Clean H_2 Demand in Key Sectors

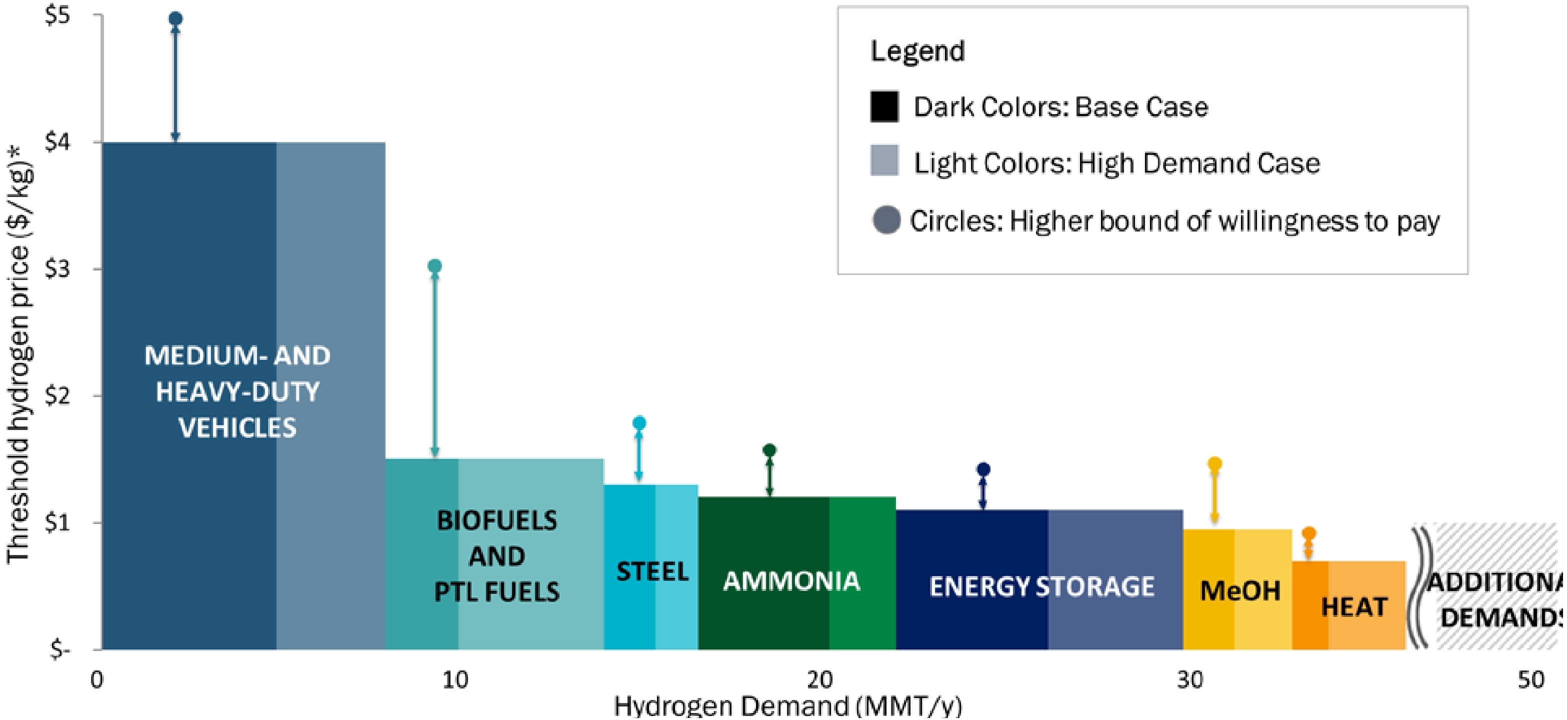
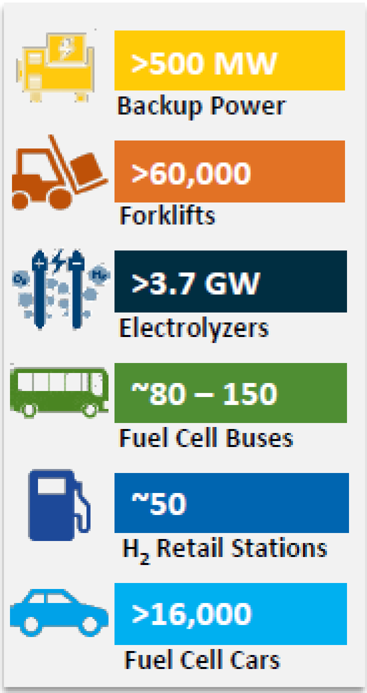


Figure 11: Scenarios showing estimates of potential clean hydrogen demand in key sectors of transportation, industry, and the grid, assuming hydrogen is available at the corresponding threshold cost.

U.S. D.O.E National Clean Hydrogen Strategy and Roadmap Draft (September 2022)

How many hydrogen fuel cell cars have been deployed in U.S?

Examples of Deployments



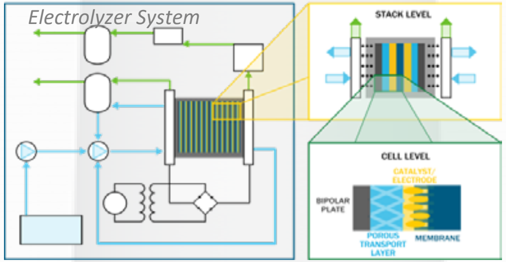
2023 Hydrogen Program Overview Presentation, Sunita Satyapal, Hydrogen and Fuel Cell Technologies Office (HFTO) Director and DOE Hydrogen Program Coordinator: https://www.hydrogen.energy.gov/annual-review/annual_review23_proceedings.html

All Pathways Contribute to the Mission

ELECTROLYSIS

Critical path to sustainable clean H_2 production at scale

Reduce costs to achieve scale



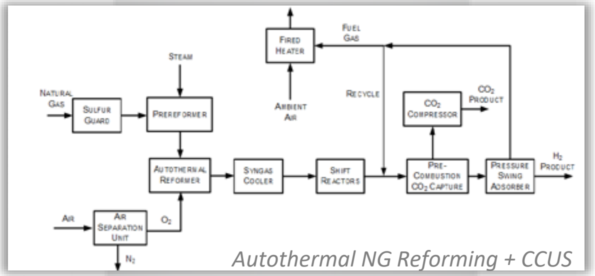
- Reduce capital cost of integrated electrolyzer systems (stacks and balance of plan) at GW scales to <$150/kW
- Optimize integration of electrolyzer systems with renewable and nuclear power to leverage on-site electricity costs <$200/MWh

Expand Production Capacity

THERMAL CONVERSION

Decarbonization through industrial retrofits

Add CCUS to reduce emissions



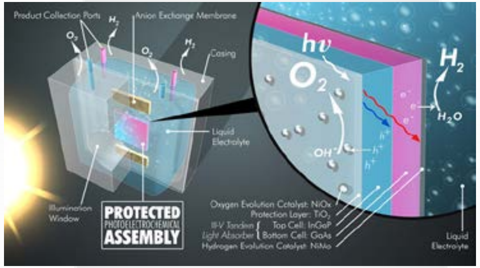
- Improve performance and cost of integrated systems for natural gas reforming with CCUS achieving emissions targets
- Develop diverse options such as gasification of waste feedstocks & pyrolysis of natural gas

Adapt Current Production

ADVANCED PATHWAYS

Innovative approaches offering cross-cutting benefits

Achieve high-impact breakthroughs



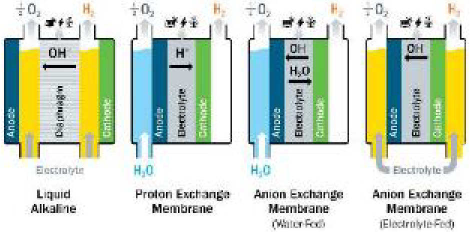
- Develop advanced H_2O-splitting systems with solar-to-H_2 conversion efficiencies >30%
- Develop robust microbial processes and systems to produce affordable clean H_2 from diverse bio- and waste-feedstocks

Explore Promising Alternatives

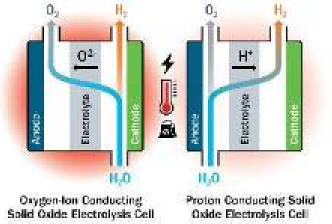
R&D on Advanced Production Technologies

Challenge: Wind and solar took ~40 years to be cost competitive… we need to do that for green hydrogen production in the next 5-10 years

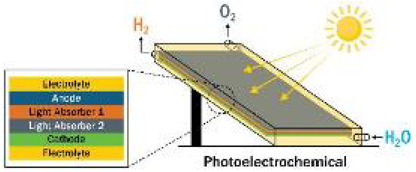
- **Near-term:** focus on electrolysis (water splitting with electricity and nuclear)
  - Accelerate **research on advanced water-splitting** technologies – take advantage of today's renewable and nuclear power
  - Achieve $100/kW electrolyzer stack goal in just 5 years through **H2NEW** consortium
  - Include research on both **LTE (PEM, liquid alkaline), and HTE (solid oxide) electrolyzer** technologies
  - **Research urgency:** Need order of magnitude increase in effort on electrolysis to accelerate development to meet near-term cost goals *(NOTE: new $1B BIL activity now enables this)*
- **Longer-term:** Use solar energy or heat to more directly to split water
  - Photoelectrochemical (PEC) and solar thermochemical (STCH) H_2 production
  - Incubate and support promising technology development through **HydroGEN** consortium



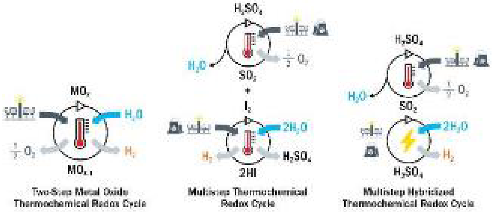
LTE



HTE



PEC



STCH

S. Alia, D. Ding, A. McDaniel, F. M. Toma, H.N. Dinh, "**How to Make Clean Hydrogen AWSM: *The Advanced Water Splitting Materials Consortium*" *ECS Interface, 30(4) Winter 2021.***

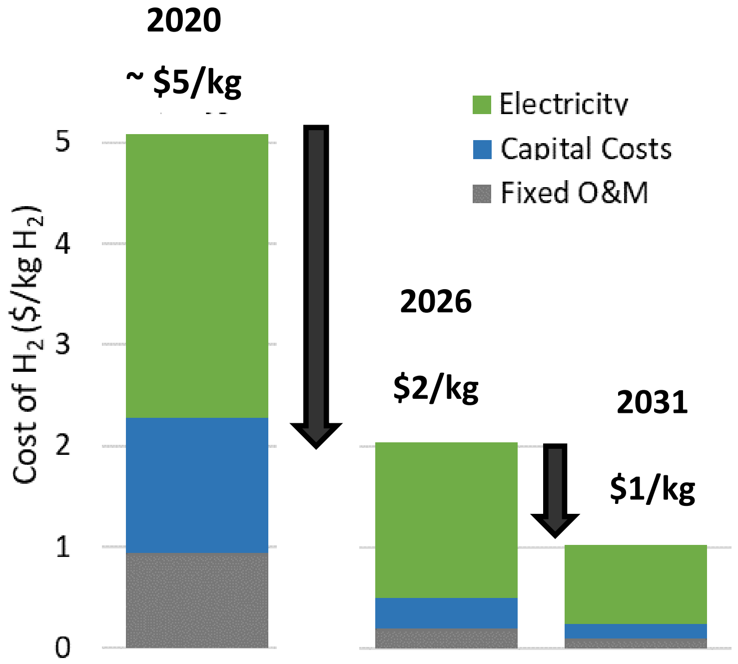
Hydrogen Shot: "1 1 1"

$1 for 1 kg in 1 decade for clean hydrogen

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

Launched June 7, 2021
Summit Aug 31-Sept 1, 2021

Example: Cost Reduction of Clean H_2 from Electrolysis



Electrolysis: One of several pathways to reach goals

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

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)

(Adapted from multiple briefing slides from Sunita Satyapal, DOE's HFTO)

H2NEW : H2 from Next-generation Electrolyzers of Water

H2NEW
U.S. DEPARTMENT OF ENERGY

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

- Launching in Q1 FY21
- Both low- and high-temperature electrolyzers
- $50M over 5 years

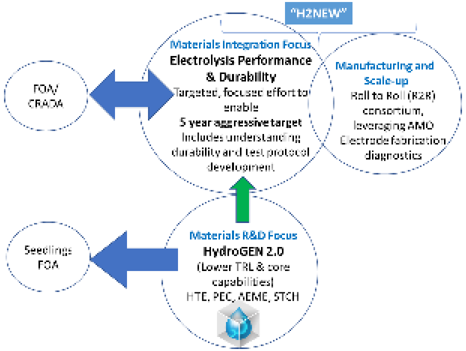
National Lab Consortium Team

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

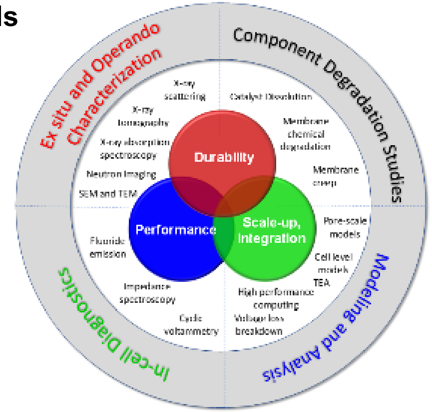
Clear, well-defined stack metrics to guide efforts.

Electrolyzer Stack Goals by 2026		
	LTE PEM	HTE
Capital Cost	\$100/kW	\$125/kW
Performance	3 A/cm² @ 1.8 V	1.2 A/cm² @ 1.28 V
Lifetime	80,000 hr	40,000 hr

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



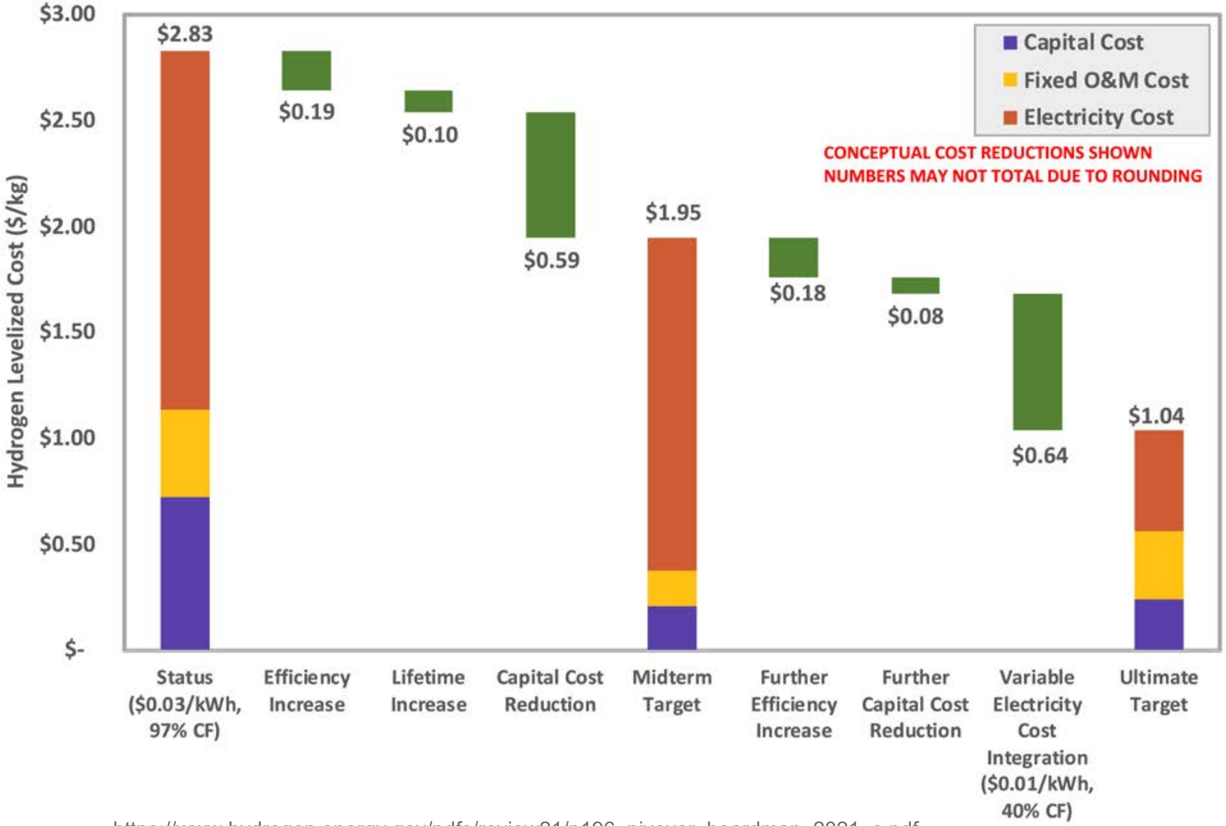
Utilize combination of world-class experimental, analytical, and modeling tools



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.

Potential Impact: Hydrogen Levelized Cost (HLC)



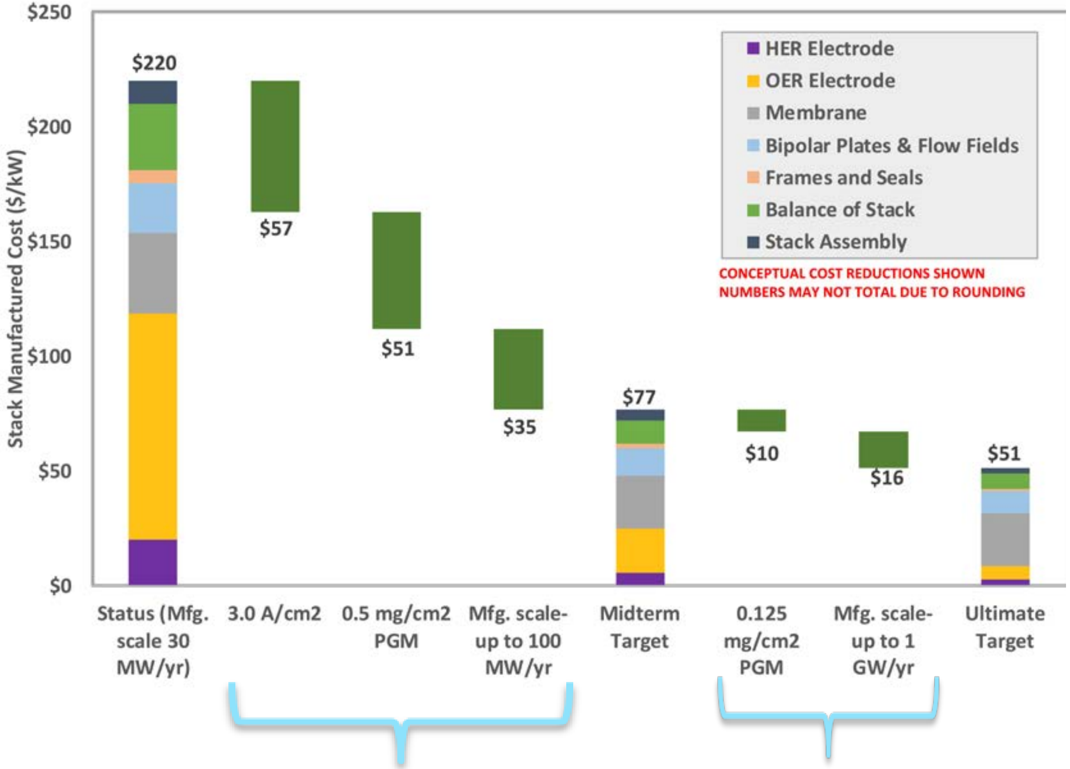
https://www.hydrogen.energy.gov/pdfs/review21/p196_pivovar_boardman_2021_o.pdf

Select pathway to $2/kg and $1/kg identified.

Much of HLC gains possible through greatly decreasing capital costs and enabling lower cost of electricity through variable operation.

These advances can’t come with compromised durability or efficiency, so all three areas are linked.

Potential Impact: Stack Costs (PEM)



Stack Targets	Status	2026	Ultimate
Cell (A/cm^2)	2.0	3.0	3.0
Cell voltage (V)	1.9	1.8	1.6
Lifetime (khr)	40	80	80
Degradation (mV/khr)	4.8	2.3	2.0
Capital Cost ($/kW)	450	100	50
PGM loading (mg/cm^2)	3	0.5	0.125

https://www.energy.gov/eere/fuelcells/technical-targets-proton-exchange-membrane-electrolysis

These 3 areas

1. Increased efficiency/current density
2. Decreased PGM loading
3. Scale-up

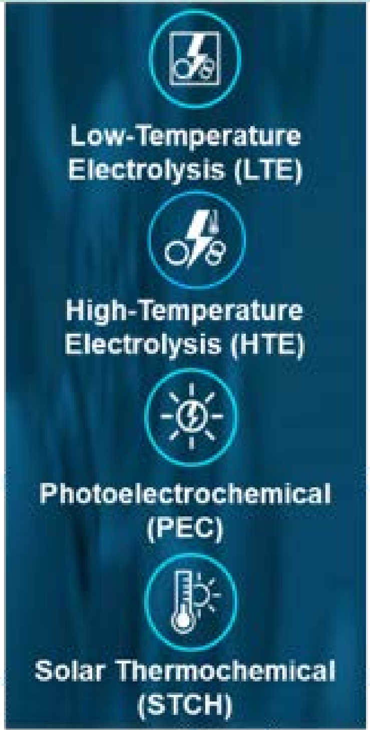
Are the strongest levers for addressing stack costs and primary focus of H2NEW.

HydroGEN Consortium

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

Goal: Accelerating R&D of innovative advance water splitting (AWS) materials and technologies for clean, sustainable and low-cost hydrogen production.

Water



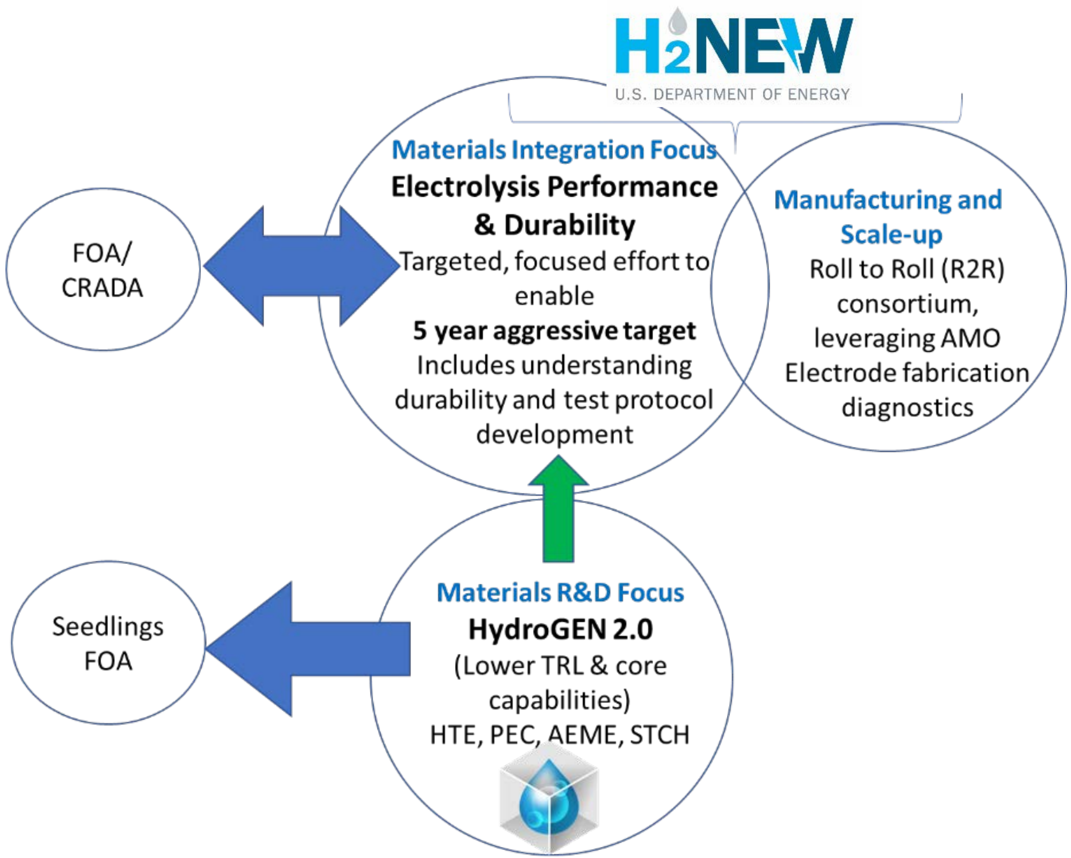
National Lab Consortium Team

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

H_2 Production Target: $1/kg

HydroGEN is advancing Hydrogen Shot goals by fostering cross-cutting innovation using theory-guided applied materials R&D to accelerate the time-to-market and advance all emerging water-splitting pathways to enable clean, low cost, and sustainable low-cost hydrogen production

HydroGEN Materials R&D Feeds to H2NEW Materials Integration



H2NEW — Hydrogen from Next-generation Electrolyzers of Water
U.S. DEPARTMENT OF ENERGY

- Polymer electrolyte membrane (PEM) electrolysis
- Oxygen-conducting solid oxide electrolysis (SOEC)
- Liquid alkaline electrolysis

HydroGEN 2.0 (lower TRL AWS)

- Alkaline exchange membrane (AEM) electrolysis
- Metal-supported SOEC (MS-SOEC)
- Proton-conducting SOEC (p-SOEC)
- Photoelectrochemical (PEC)
- Solar thermochemical (STCH)

A Balanced AWSM R&D Portfolio

Low Temperature Electrolysis (LTE) (8 Projects)

PEM Electrolysis

- PEME component integration
- PGM-free OER catalyst
- Reinforced membranes

AEM Electrolysis

- PGM-free OER and HER catalyst
- Novel AEM and ionomers
- Bipolar membranes
- Electrodes

High Temperature Electrolysis (HTE) (8 Projects)

O^{2-} conducting SOEC

- Degradation mechanism at high current density operation
- Nickelate-based electrode and scalable, all-ceramic stack design
- Neodymium and lanthanum nickelate

H^+ conducting SOEC

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

Photoelectrochemical (PEC) (7 Projects)

Semiconductors

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

Perovskites

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

Solar Thermochemical (STCH) (7 Projects)

STCH

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

Hybrid Thermochemical

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

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

PGM = platinum group metal
SOEC = solid oxide electrolysis cells

National Laboratory Collaboration is Critical for Success

H2NEW — Hydrogen from Next-generation Electrolyzers of Water

U.S. DEPARTMENT OF ENERGY

Hydrogen Production

- NREL — Transforming ENERGY
- INL — Idaho National Laboratory
- Argonne NATIONAL LABORATORY
- BERKELEY LAB — Bringing Science Solutions to the World
- Lawrence Livermore National Laboratory
- Los Alamos NATIONAL LABORATORY — EST. 1943
- NETL — NATIONAL ENERGY TECHNOLOGY LABORATORY
- OAK RIDGE National Laboratory
- Pacific Northwest NATIONAL LABORATORY

HydroGEN — Advanced Water Splitting Materials

Hydrogen Production

- NREL — Transforming ENERGY
- BERKELEY LAB — Bringing Science Solutions to the World
- Sandia National Laboratories
- Lawrence Livermore National Laboratory
- INL — Idaho National Laboratory

BioH2

Hydrogen Production

- NREL — Transforming ENERGY
- BERKELEY LAB — Bringing Science Solutions to the World
- Argonne NATIONAL LABORATORY
- Pacific Northwest NATIONAL LABORATORY

HyMARC — Hydrogen Materials Advanced Research Consortium

Hydrogen Storage

- Sandia National Laboratories
- NREL — Transforming ENERGY
- Pacific Northwest NATIONAL LABORATORY
- Lawrence Livermore National Laboratory
- BERKELEY LAB — Bringing Science Solutions to the World

M2FCT — MILLION MILE FUEL CELL TRUCK

U.S. DEPARTMENT OF ENERGY

Fuel Cells

- BERKELEY LAB — Bringing Science Solutions to the World
- Los Alamos NATIONAL LABORATORY — EST. 1943
- Argonne NATIONAL LABORATORY
- NREL — Transforming ENERGY
- OAK RIDGE National Laboratory

NREL Research Spans MAKE/MOVE/STORE/USE

Make

R&D on Advanced Production Technologies

Move

Infrastructure Research & Large Scale Demonstration and Deployment

Store

Hydrogen Storage Materials and Systems Research

Use

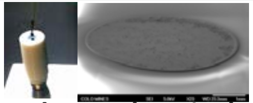
Hydrogen Penetration into Heavy-Duty Transportation Sector

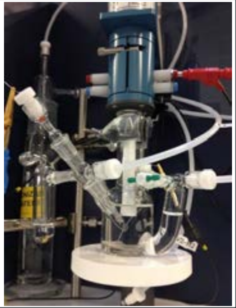
Expanding Green Hydrogen Into New End-Use Cases

NREL's HFCT Program Strategy is on Accelerating Progress & Impact

Energy justice and American jobs are considerations that underly all these efforts.

Hydrogen Core Competencies – From Powders to Power: FC & LTE

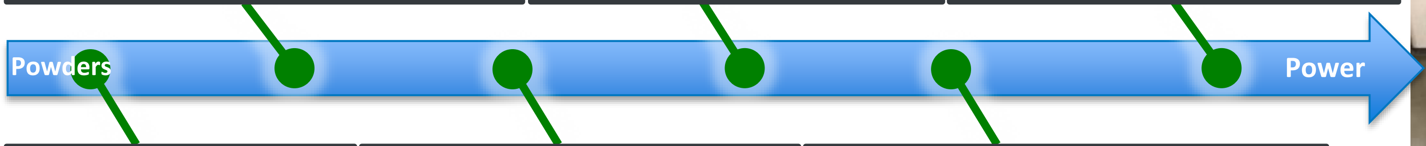




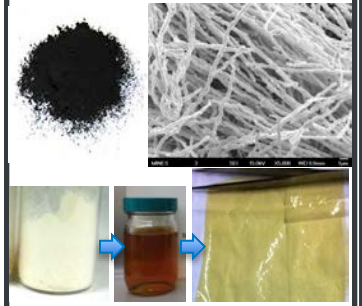
Electrochemical Characterization:
RDE & RRDE stations for Mass & Specific Activity, ECA, ORR; EQCMB, Seiras

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

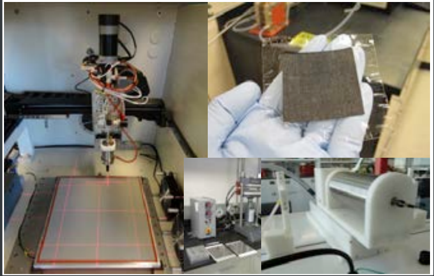
Manufacturing Lab
QC Diagnostic Development, Areal characterization, Roll-to-roll demonstration



Material Synthesis:
Catalyst & Membrane Development



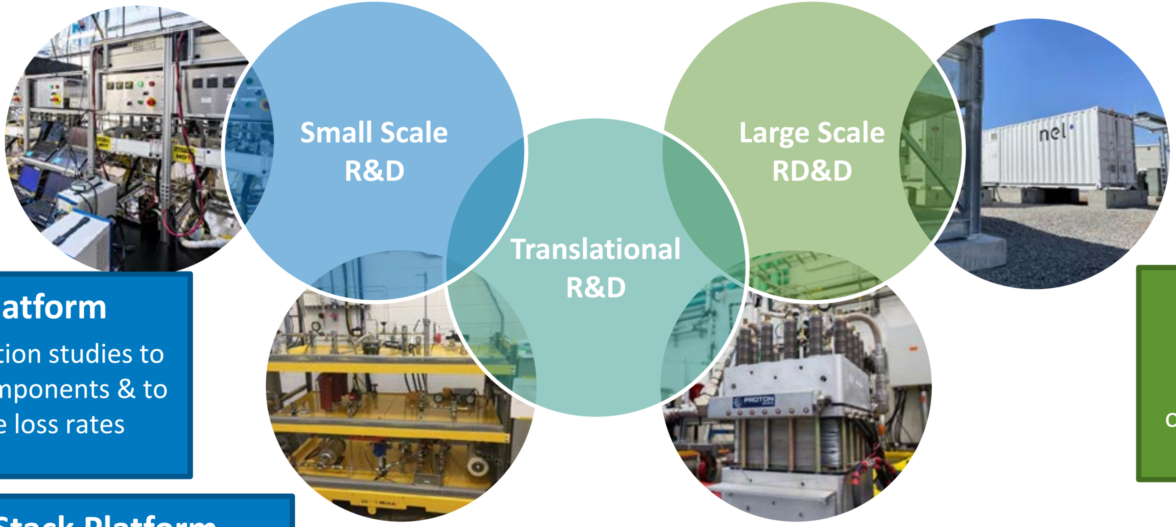
MEA integration
Coating, Spraying, Painting, Electrospinning, Lamination, Hot Press Transfer, Edge protection



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

Systems Integration in ESIF … and soon Flatirons Campus

Growing Electrolyzer Capability at NREL
From Watts to Multi-MegaWatts



Single Cell Platform

Accelerated degradation studies to optimize material components & to determine voltage loss rates

Short Stack Platform

In-situ high–speed cell voltage, stack, and balance of plant (BOP) performance monitoring for continual intermittent operation

Full System Platform

Energy systems integration, durability, control & optimization with electrolysis, storage, and end uses

Full Stack Platform

Scaling electrolysis to characterize durability, response, and controls of multiple stacks

Experimental capabilities to accelerate advances from fundamental, single cell research to integrated systems research; with industry relevant scale and operation conditions

Images: NREL

NREL Current Electrolyzer Capability Summary

Single Stack Testing

- 16 PEM
- 6 alkaline

Short Stack

- PEM stack test bed for short stacks
- Highly automated
- 5-25kW

Full Stack

- PEM stack test bed capability of up to 1 MW
- High-fidelity control and data collection
- Dynamic, integrated controls

System

- PEM system at Flatirons
- System integration with ARIES platform
- capability for 2 x 1.25 MW

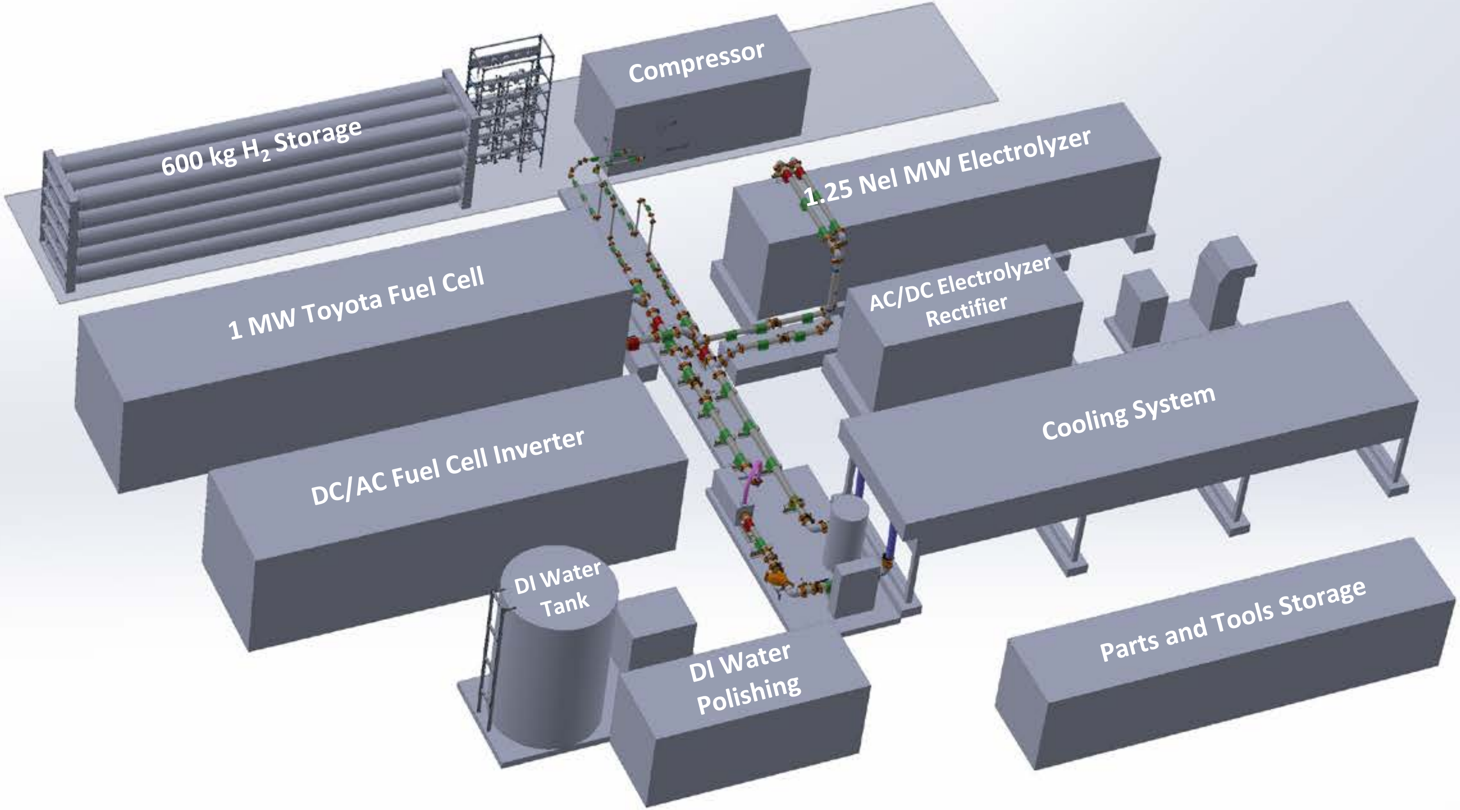
The Role of Large-Scale Validation and Demonstration

- Prior to investment, investors, utilities, and other stakeholders need to **de-risk H_2 systems** through operating in real-life industrial environments

- Large-scale deployments (~100MW) need to be **de-risked** through smaller scale validation (1-5MW) with analysis to extrapolate to larger systems

- NREL's **Flatirons Campus** has this capability

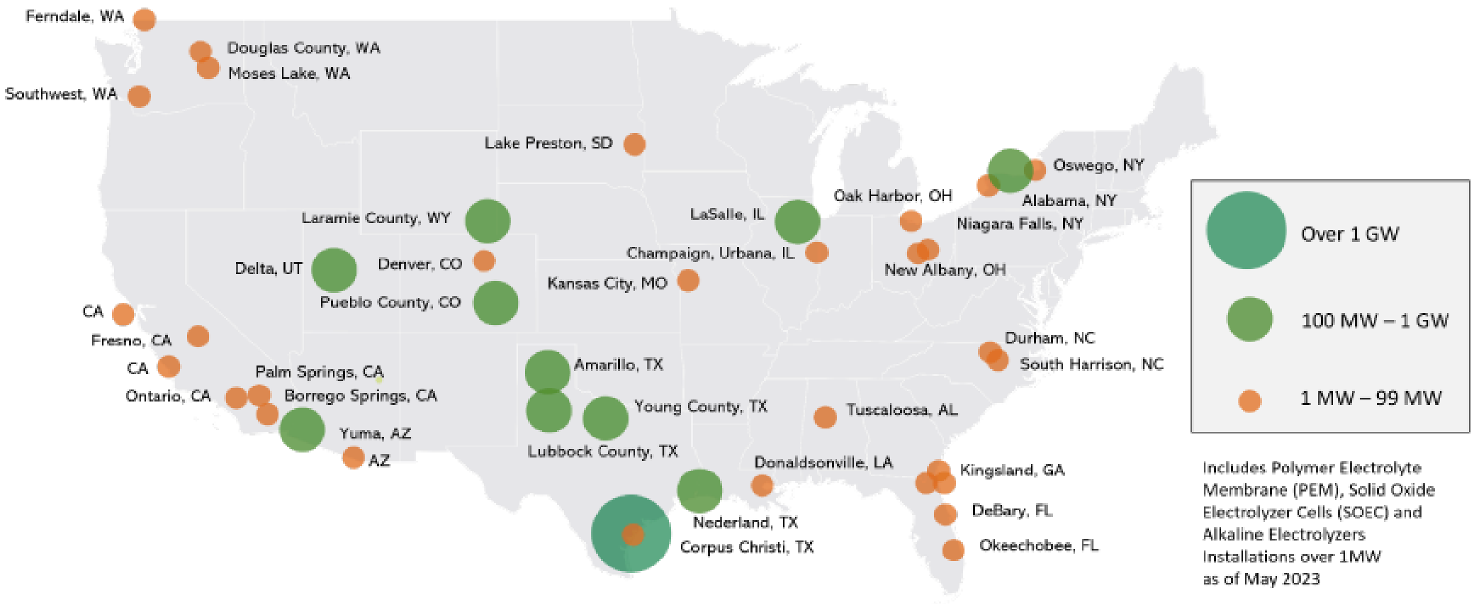
3D Layout of Flatirons Campus Hydrogen System



Recent View of Flatirons Campus H_2 System

How many planned & installed electrolyzer capacity in the U.S.?

Total 3.7 GW in Electrolyzer Capacity
5-fold increase since 2022

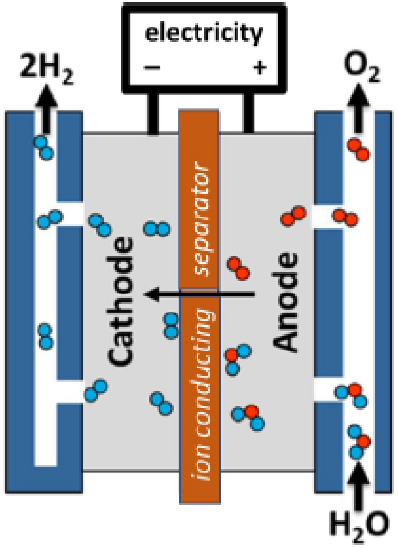


Includes Polymer Electrolyte Membrane (PEM), Solid Oxide Electrolyzer Cells (SOEC) and Alkaline Electrolyzers Installations over 1MW as of May 2023

Source: Arjona, V., DOE Program Record #23003, June 2023

2023 Hydrogen Program Overview Presentation, Sunita Satyapal, Hydrogen and Fuel Cell Technologies Office (HFTO) Director and DOE Hydrogen Program Coordinator: https://www.hydrogen.energy.gov/annual-review/annual_review23_proceedings.html

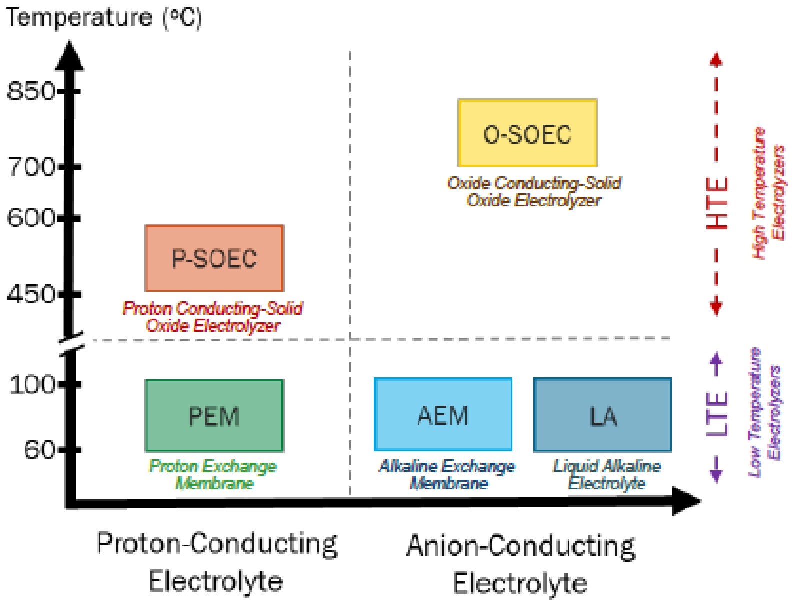
Water Electrolysis Overview



Water electrolyzer cell configuration (H^+ Conductor):

Anode: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

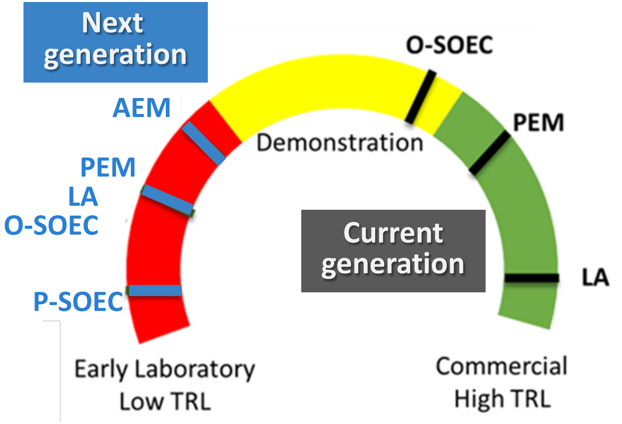
Cathode: $4H^+ + 4e^- \rightarrow 2H_2$



Electrolyzer technologies differentiated by electrolyte conducting species and temperature

Overview of Electrolyzer Technologies

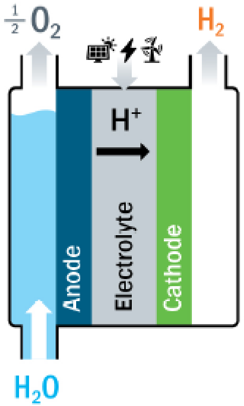
- **Current generation at high TRL** (LA, PEM, O-SOEC) ready for commercialization
- **Next generation at lower TRL** needed to achieve performance and cost targets to meet \$1/kg H_2



Technology	Advantages	Development Needs
Liquid Alkaline (LA)	Most mature, Low-cost materials, Long lifetime	Improved performance, Dynamic operation capability
Proton Exchange Membrane (PEM)	High performance, dynamic operation capable	Lower cost materials (e.g., reduced PGMs)
Oxide-ion conducting Solid Oxide (O-SOEC)	High efficiency, thermal energy integration	Improved lifetime, intermittent operation
Alkaline Exchange Membrane (AEM)	Low-cost materials, High performance and dynamic operation potential	Improved lifetime, Supporting electrolyte required?
Proton-conducting Solid Oxide (P-SOEC)	High efficiency potential, thermal integration, Lower cost materials	Improved lifetime and Faradaic efficiency

Lower-TRL Next generation (AEM, P-SOEC) have the potential to achieve performance and cost targets needed to meet \$1/kg H_2, but further development is required

Low Temperature Water Electrolysis: **PEM**



PEM water electrolysis:

$$\text{Anode (OER): } 2H_2O \rightarrow 4H^+ + O_2 + 4e^- (E^0 = 1.23V \quad (1)$$

$$\text{Cathode (HER): } 4H^+ + 4e^- \rightarrow 2H_2 (E^0 = 0V) \quad (2)$$

S. Alia, D. Ding, A. McDaniel, F.M. Toma, and H.N. Dinh, "Chalkboard 2 - How to Make Clean Hydrogen," *Electrochemical Society Interface* 30 (2022): 49. https://doi.org/10.1149/2.F13214IF

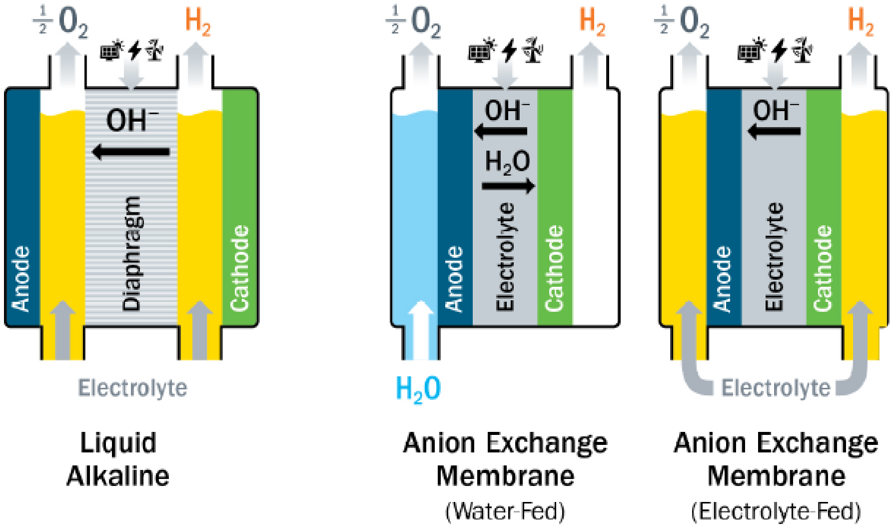
Materials Needs for PEM:

- **Thrifting/replacing of Ir**
  - Supports
  - Novel compositions/structures
  - Electrode fabrication impacts
- **Improved membranes**
  - Increased selectivity, thin membranes
  - Improved durability
  - Recombination layers
- **Novel Porous Transport Layers (PTLs)**
  - Materials
  - Morphology
  - Coatings

Low Temperature Water Electrolysis: **Alkaline**

Alkaline Needs:

- **Traditional (Conc. KOH)**
  - Intermittent operating capability
  - Operating pressure
  - Degradation mechanisms/ASTs
  - Performance/efficiency improvements
- **AEM/hybrid (low conc/KOH-free systems)**
  - Novel materials development
    - Stable polymers
    - Advanced catalysts
  - Performance dependence on electrolyte
  - Degradation mechanisms/ASTs



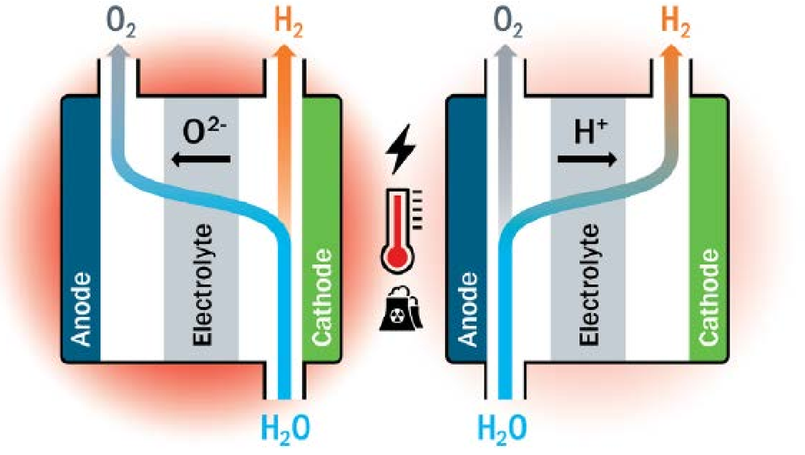
AEM or LA water electrolysis:

$$\text{Cathode: } 4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- (E = 1.23) \quad (3)$$

$$\text{Anode: } 4OH^- \rightarrow +2H_2O + O_2 + 4e^- (E^0 = 0V) \quad (4)$$

S. Alia, D. Ding, A. McDaniel, F.M. Toma, and H.N. Dinh, "Chalkboard 2 - How to Make Clean Hydrogen," *Electrochemical Society Interface* 30 (2022): 49. https://doi.org/10.1149/2.F13214IF

High Temperature Electrolysis: Solid Oxide Electrolysis Cell (SOEC)



Oxygen-Ion Conducting Solid Oxide Electrolysis Cell

Proton Conducting Solid Oxide Electrolysis Cell

o-SOEC:

$$\text{Cathode: } 2H_2O + 4e^- \rightarrow 2O^{2-} + 2H_2 \quad (5)$$

$$\text{Anode: } 2O^{2-} \rightarrow O_2 + 4e^- \quad (6)$$

p-SOEC:

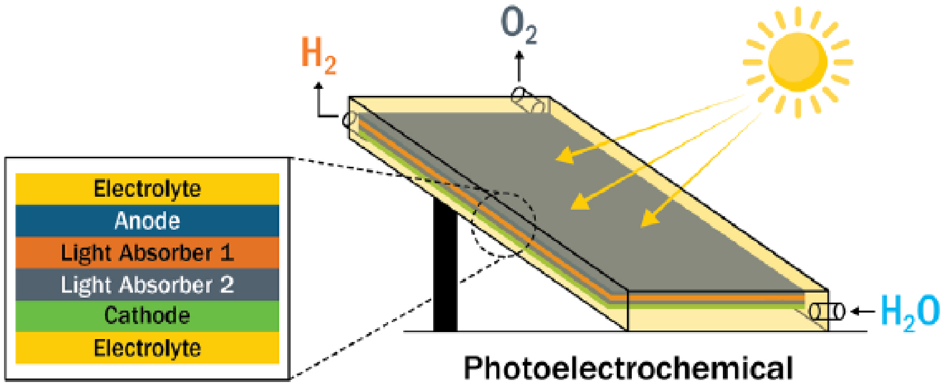
$$\text{Anode: } 2\text{H}_2O \rightarrow 4H^+ O_2 + 4e^- \quad (7)$$

$$\text{Cathode: } 4H^+ + 4e^- \rightarrow 2H_2 \quad (8)$$

- **Oxygen ion (O^{2-})conducting SOEC (*o-SOEC*)**
  - Typically operate at 700-850°C
  - Technologically advanced
  - High efficiency and high solid oxide conduction & kinetics
  - Durability issues: microstructure evolution, thermal stresses, Cr migration
- **Proton conducting SOEC (*p-SOEC*)**
  - Operate at 400-600°C
  - Lower technology readiness level (TRL)
    - Slower kinetics,
    - Electrolyte is less mature (synthesis, densification, proton conduction)

S. Alia, D. Ding, A. McDaniel, F.M. Toma, and H.N. Dinh, "Chalkboard 2 - How to Make Clean Hydrogen," *Electrochemical Society Interface* 30 (2022): 49. https://doi.org/10.1149/2.F13214IF

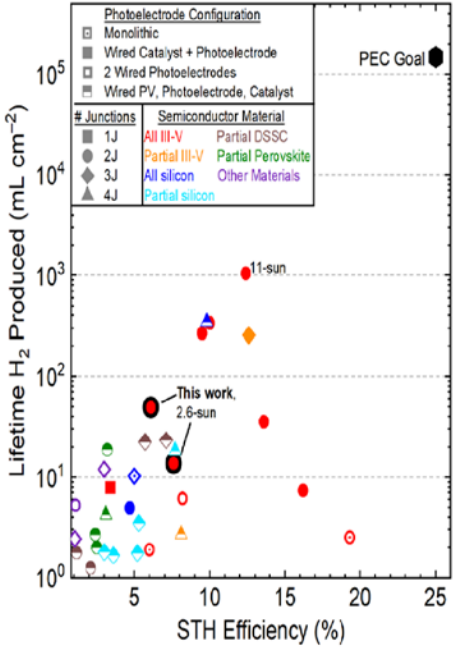
Photoelectrochemical (PEC) Water Splitting



PEC water splitting:

$$H_2O + hv \rightarrow \frac{1}{2}O_2 + H_2 \quad (9)$$

PEC research is focused on the developing stable, high-performing and integrated cells to realize the \$2/kg production of H_2



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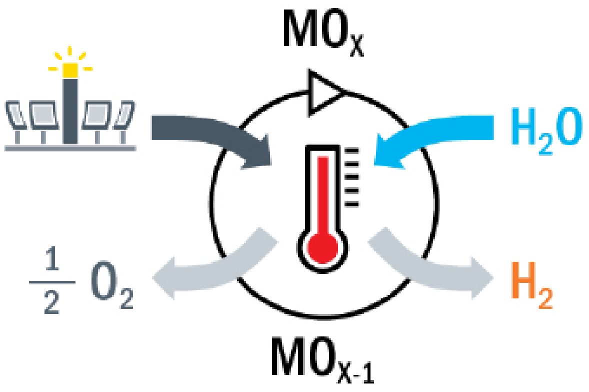
Solar Thermochemical (STCH) Water Splitting



Two-Step Metal Oxide Thermochemical Redox Cycle

STCH water splitting:

Oxygen Evolution Reaction: $MO_x + heat \rightarrow \frac{1}{2} O_2 + MO_{x-1}$ (10)

Hydrogen Evolution Reaction: $\mathrm{MO}_{x-1} + H_2O \rightarrow H_2 + MO_x$ (11)

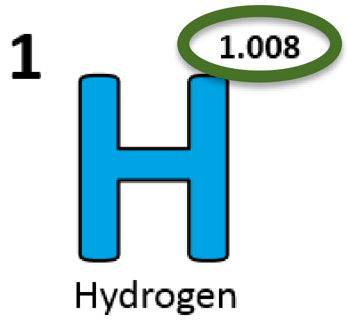
- Metal cation is redox active element in two-step cycle.
- R&D effort focused on MO_x materials discovery.

S. Alia, D. Ding, A. McDaniel, F.M. Toma, and H.N. Dinh, "Chalkboard 2 - How to Make Clean Hydrogen," *Electrochemical Society Interface* 30 (2022): 49. https://doi.org/10.1149/2.F13214IF

When is Hydrogen & Fuel Cells Day?

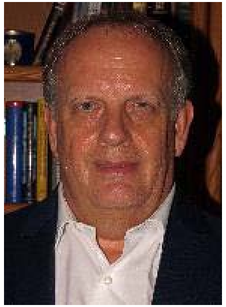
Hydrogen and Fuel Cells Day
October 8

Held on hydrogen's very own atomic weight-day



Acknowledgements

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



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Thank You

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NREL/PR-5900-87216

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

NREL Transforming ENERGY

How many Energy EarthShots are there?

7

- Energy Earthshots U.S. Department of Energy | Hydrogen
- Energy Earthshots U.S. Department of Energy | Storage™
- Energy Earthshots U.S. Department of Energy | Carbon Negative
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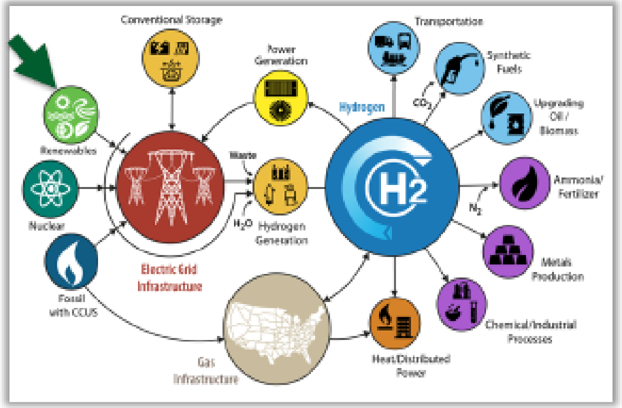
- Energy Earthshots U.S. Department of Energy | Clean Fuels & Products Shot

EERE Clean Hydrogen Mission & Portfolio

Feedstocks:
• Renewable Energy and Water
Technologies
• Electrolysis: Low- and High-Temperature • Advanced Water Splitting: Photo-electrochemical, Solar/High-T Thermochemical • Biological Approaches

Production, Storage, Delivery, Conversion, and End-Use RD&D; Emphasis on Renewable Integration



Example Activities
Hydrogen & Fuel Cell Technology RD&D
Wind Hybrid Systems
Solar Fuels Production
Bio-fuels and Products
Offshore Energy Harvesting
Geological Hydrogen
Manufacturing & Industrial Decarbonization

Today
\$4-6/kg clean H_2 scenarios*

2026
BIL target: \$2/kg clean H_2

2031
H2 Shot target: \$1/kg clean H_2

*across multiple renewable energy scenarios

Potential Future Flatirons Hydrogen Capabilities

- Heavy duty vehicle fueling
- Large-scale storage technologies
- Liquid hydrogen systems
- H_2 power systems (fuel cell systems, turbines, engines, etc.)
- Natural gas blending
- Molecule building (ammonia, green steel, etc.)
- Grid integration of H_2 technologies with renewables

Upcoming ARIES Demonstration of Materials-based H_2 Storage Technology

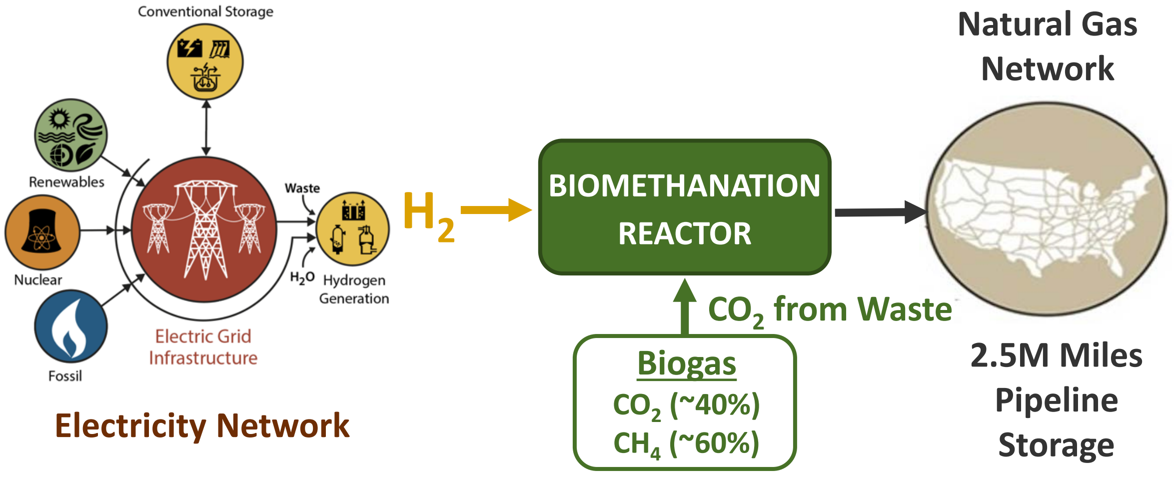
2 X 260 kg H_2 = 520 kg storage

2022-2023: ARIES demonstration at NREL of GKN Hydrogen metal hydride technology after 10 years of R&D

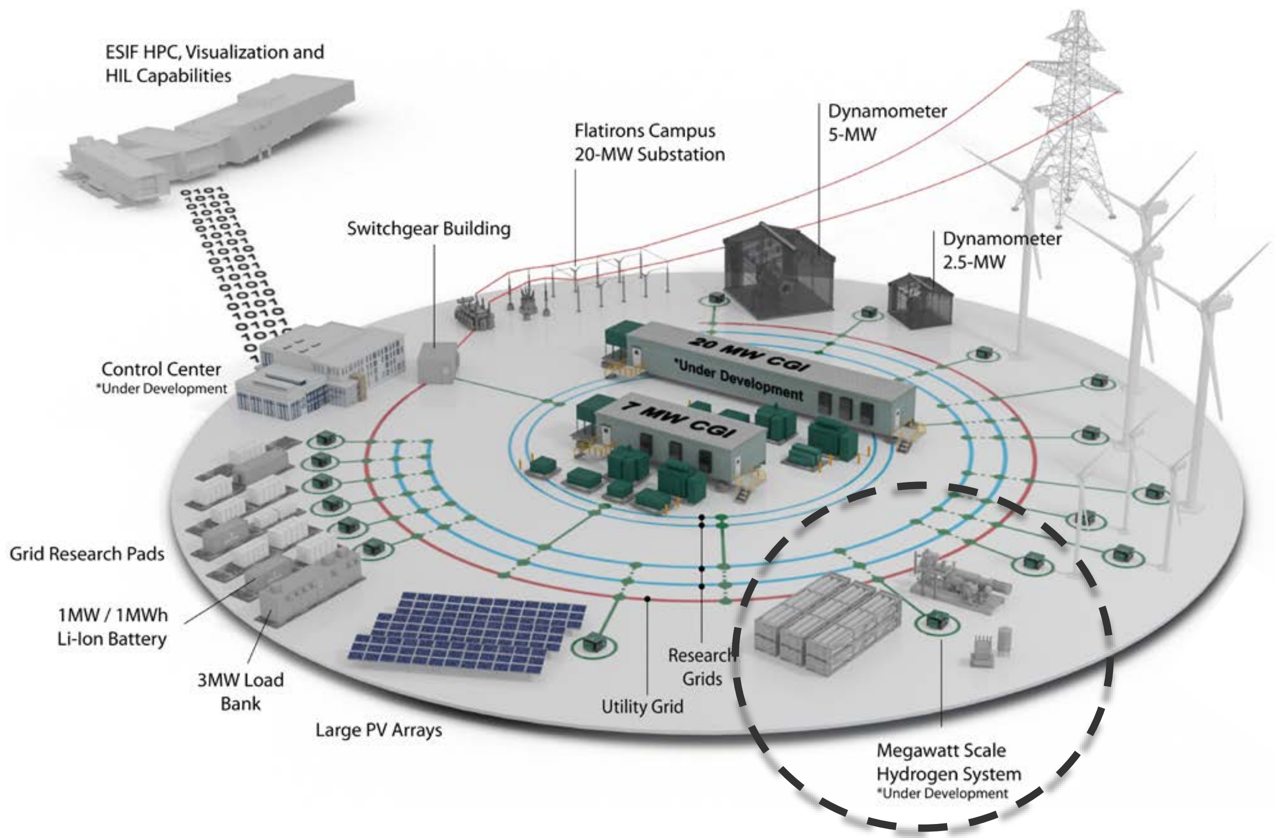
E2M: Renewable Natural Gas (RNG)

NREL, SoCalGas, Electrochaea, and the DOE are partnering on a first-of-its-kind bioreactor system in the U.S. It produces RNG from renewable H_2 and waste CO_2 from dairies, landfills, wastewater treatment plants. RNG:

- Has an energy density ~3x that of H_2
- Can be stored in quantities of 100s of terawatt hours of energy for a long time
- Is a direct drop-in replacement for fossil natural gas
- Benefits rural underserved communities
- Will start decarbonizing our country's expansive fossil natural gas grid



ARIES Hydrogen System Integration



Integrated Megawatt Scale Hydrogen System