U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

HFTO Hydrogen Production Overview

David Peterson, HFTO – Hydrogen Production Program Manager

2024 Annual Merit Review and Peer Evaluation Meeting

May 7, 2024 – Arlington, VA

The Hydrogen and Fuel Cell Technologies Office (HFTO)

Mission

Research, development, and demonstration (RD&D) of hydrogen and fuel cell technologies to advance:

- Clean Energy and Emissions Reduction Across Sectors
- Job Creation and a Sustainable and Equitable Energy Future

HFTO Subprograms

Hydrogen Technologies	Fuel Cell Technologies	Systems Development & Integration
Hydrogen Production Hydrogen Infrastructure	Materials & Components Systems	Transportation Chemical & Industrial Processes Energy Storage & Power Generation

Systems Analysis

Safety, Codes & Standards

Crosscutting / Enabling: manufacturing, supply chain, workforce, regional clean H_2 networks

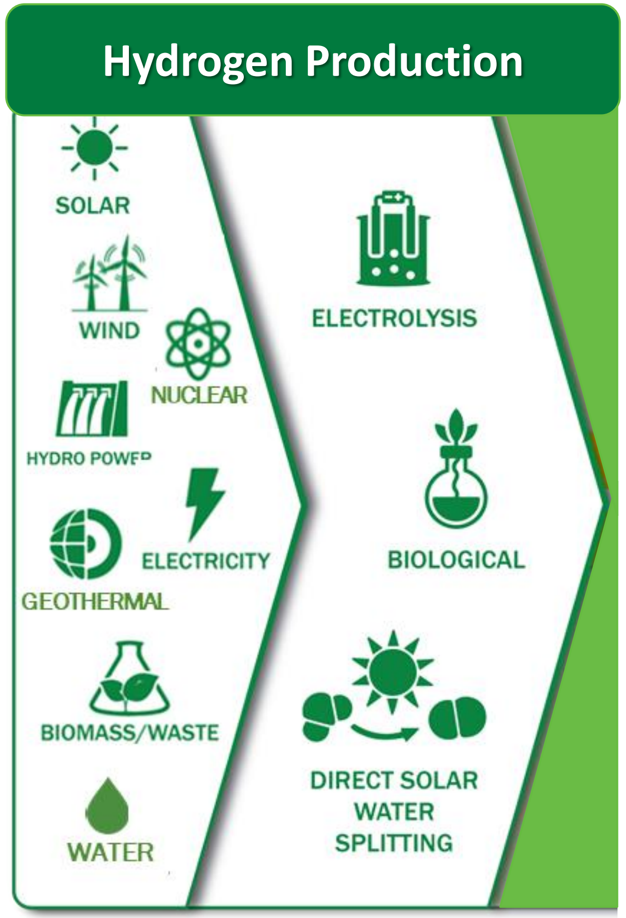
Enabling

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

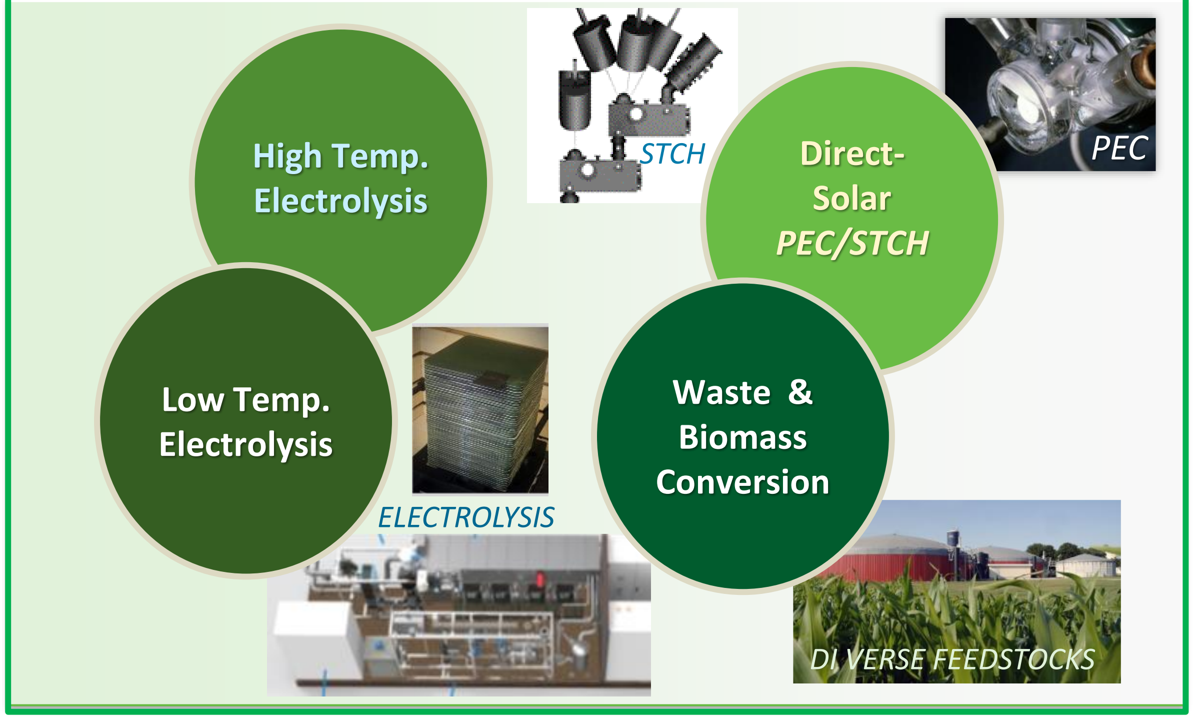
H2@Scale U.S. Department of Energy

Hydrogen Production Subprogram Overview

H_2 Production subprogram directly supports the National Clean Hydrogen Strategy and Strategic Priority #2



Near- to Mid-Term	Longer-Term
▪ *Water splitting through low- and high-temperature electrolysis leveraging clean & renewable energy resources*	▪ *Microbial-based conversion of bio- and waste-stream feedstocks* ▪ *Solar thermochemical (STCH and photoelectrochemical (PEC) water splitting*



Focus on hydrogen production pathways that utilize renewable/clean resources

Hydrogen Energy Earthshot Technology Assessments

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

The first Energy Earthshot — Hydrogen Shot—seeks to reduce the cost of clean hydrogen by 80% to $1 per 1 kg in 1 decade ("1 1 1").

Purpose

- Track technology status and RD&D improvements, including identifying key challenges and opportunities for cost reduction and technology advancement
- Identify scenarios with potential to meet H2 Shot goal

Three Technology Assessments

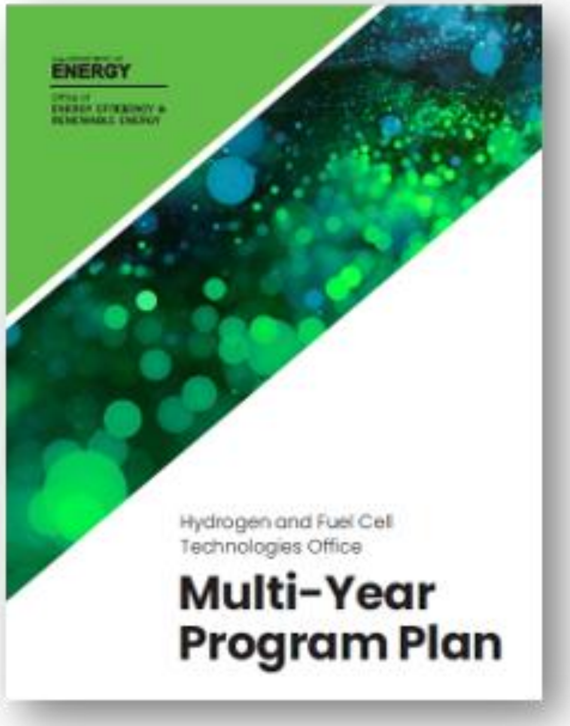
- Thermal Conversion Pathways (FECM-led): Published
- Water Electrolysis – Under final review
- Advanced Pathways (with Office of Science): Output from Technical Experts Meeting

Technology	Commercial or Advanced	Feedstock(s)	Potential By-Products	Carbon Emissions Control[1,2]
Steam Methane Reforming	Commercial	Natural Gas	n/a	Pre-/post-combustion CO_2 removal
Autothermal Reforming	Commercial	Natural Gas	Argon	Pre-combustion CO_2 removal
Partial Oxidation	Commercial	Natural Gas	Argon	Pre-combustion CO_2 removal
Plasma Pyrolysis	Commercial	Natural Gas	Carbon Black	Sequestration in solid carbon product
Gasification	Commercial	Coal and/or Biomass	Argon, Slag, and/or Sulfur	Pre-combustion CO_2 removal
Chemical Looping	Advanced	Natural Gas	Argon	CO_2 separated via chemical looping process
Dry Reforming of Methane	Advanced	Natural Gas	Argon	Pre-/post-combustion CO_2 removal
In Situ Reforming	Advanced	Natural Gas	Argon	CO_2 trapped in situ

Technology	Commercial Status	Advantages
Liquid Alkaline	Commercial	• Low-cost materials • Proven long lifetime • Established supply chain & manufacturing processes
Proton Exchange Membrane	Commercial	• High current density at high efficiency • Differential pressure operation • Dynamic operation capability
Oxide-Ion Conducting Solid Oxide	Early Commercial	• High electrical efficiency • Thermal energy integration
Alkaline Exchange Membrane	Pilot	• Low-cost materials • Dynamic operation capability
Proton-Conducting Solid Oxide	Laboratory	• High electrical efficiency • Thermal energy integration • Lower cost materials and operating temperature than O-SOEC

Advanced Pathway	Opportunities and Challenges
Photo-electrochemical (PEC)	Solar photoelectrochemical hydrogen production is a low-temperature process that bypasses the need for electricity and instead directly uses sunlight to split water into hydrogen and oxygen. It is based on semiconductor photoelectrodes and/or photocatalysts that offer theoretical potentials for solar-to-hydrogen (STH) efficiency as high as 30% under optimized circumstances. PEC hydrogen production has been demonstrated extensively at the laboratory scale, leveraging diverse semiconductor materials systems and catalysts, with early scale-up efforts underway.
Solar Thermochemical (STCH)	Direct solar thermochemical hydrogen production is another promising technology with the potential to achieve high theoretical solar-to-hydrogen conversion efficiencies. STCH processes can be divided into two broad categories: (1) direct cycles, which use concentrated solar thermal energy (at temperatures typically >1000°C) to drive a two-step metal oxide reduction/oxidation reaction to split water; and (2) hybrid cycles, which use lower temperature thermochemical reduction (<800°C, more compatible with inputs from concentrated solar or nuclear power) coupled with a secondary electrochemical step. Various STCH cycles have been demonstrated at the laboratory scale, with limited small-scale reactor demonstrations.
Biological Conversion	These processes take advantage of the ability of microorganisms to consume and digest bio- and waste-streams while releasing hydrogen. In direct hydrogen fermentation, the microbes produce the hydrogen themselves. Microbial electrolysis cells (MECs) are devices that harness the energy and protons produced by microbes breaking down organic matter combined with an additional small electric current to produce hydrogen. Both fermentation and MECs as well as hybrid systems have been demonstrated at the laboratory scale, with scale-up efforts underway.
Hybrid Approaches	In addition to the advanced pathway technologies covered in the above categories, there are unique opportunities to explore hybrid approaches coupling electrochemical, photochemical, thermochemical, and/or biological processes to enhance the efficiency and durability of affordable clean hydrogen production from diverse domestic resources

Updated HFTO Multi-Year Program Plan (MYPP)



- Sets forth HFTO's mission, goals, and strategic approach for each subprogram
- Identifies challenges, provides market-driven targets, and lays out plans with key RD&D priorities and milestones for meeting those targets and overcoming challenges

Hydrogen Production Strategic Priorities	Near-term 2025	Mid-term 2030	Longer-Term
• **Affordable, efficient and durable electrolyzers** for **GW-scale** operations			
• **Innovative approaches to clean H_2 production**, beyond electrolysis			

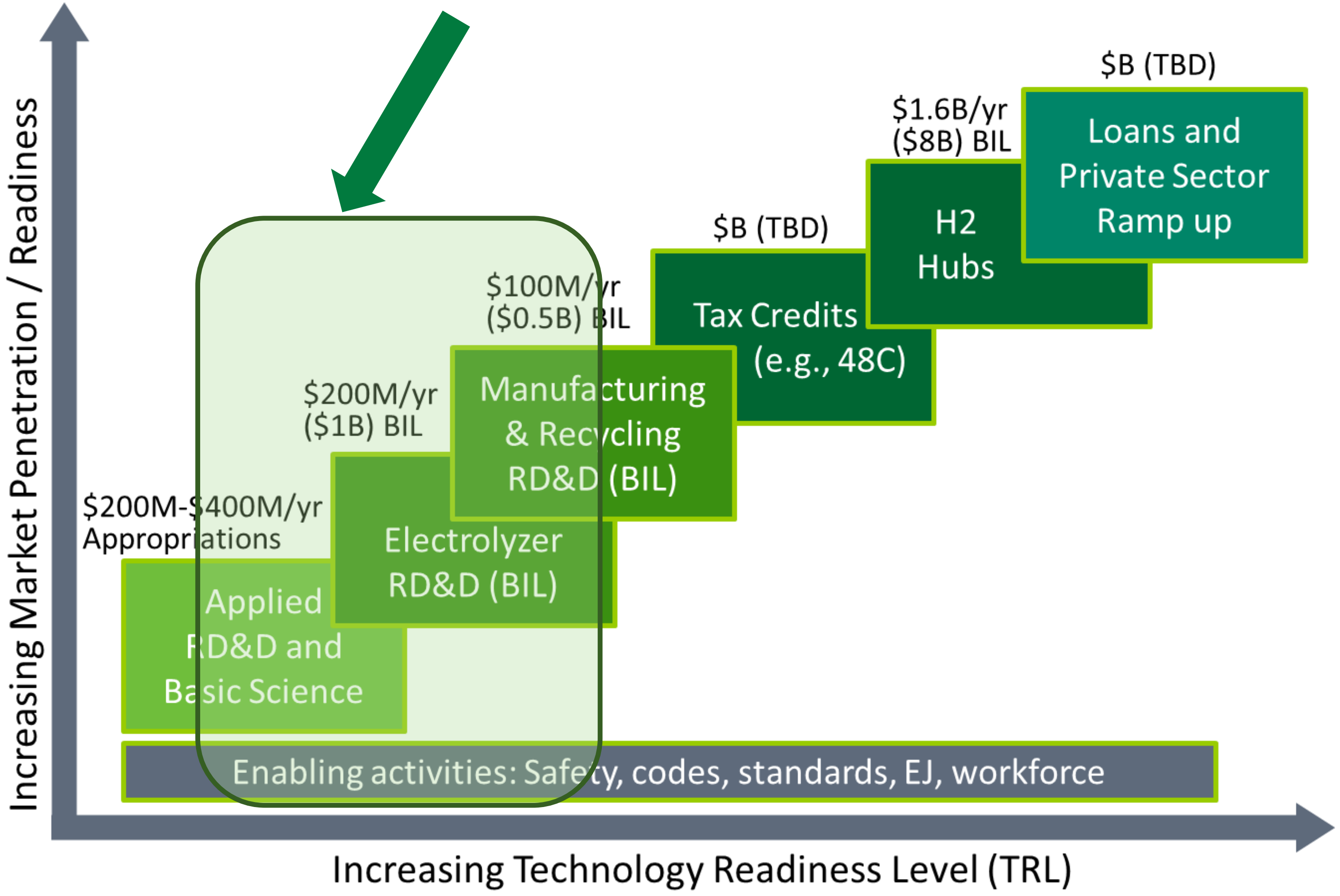
Guided by 2 hydrogen production cost targets

Clean H_2 Electrolysis Program Cost Target	2026	\$2/kg H_2
Hydrogen Energy Earthshot Cost Target	2031	\$1/kg H_2

www.energy.gov/eere/fuelcells/mypp

Hydrogen Production's Role in DOE H_2 Program RDD&D Portfolio across TRLs

HFTO Hydrogen Production Subprogram



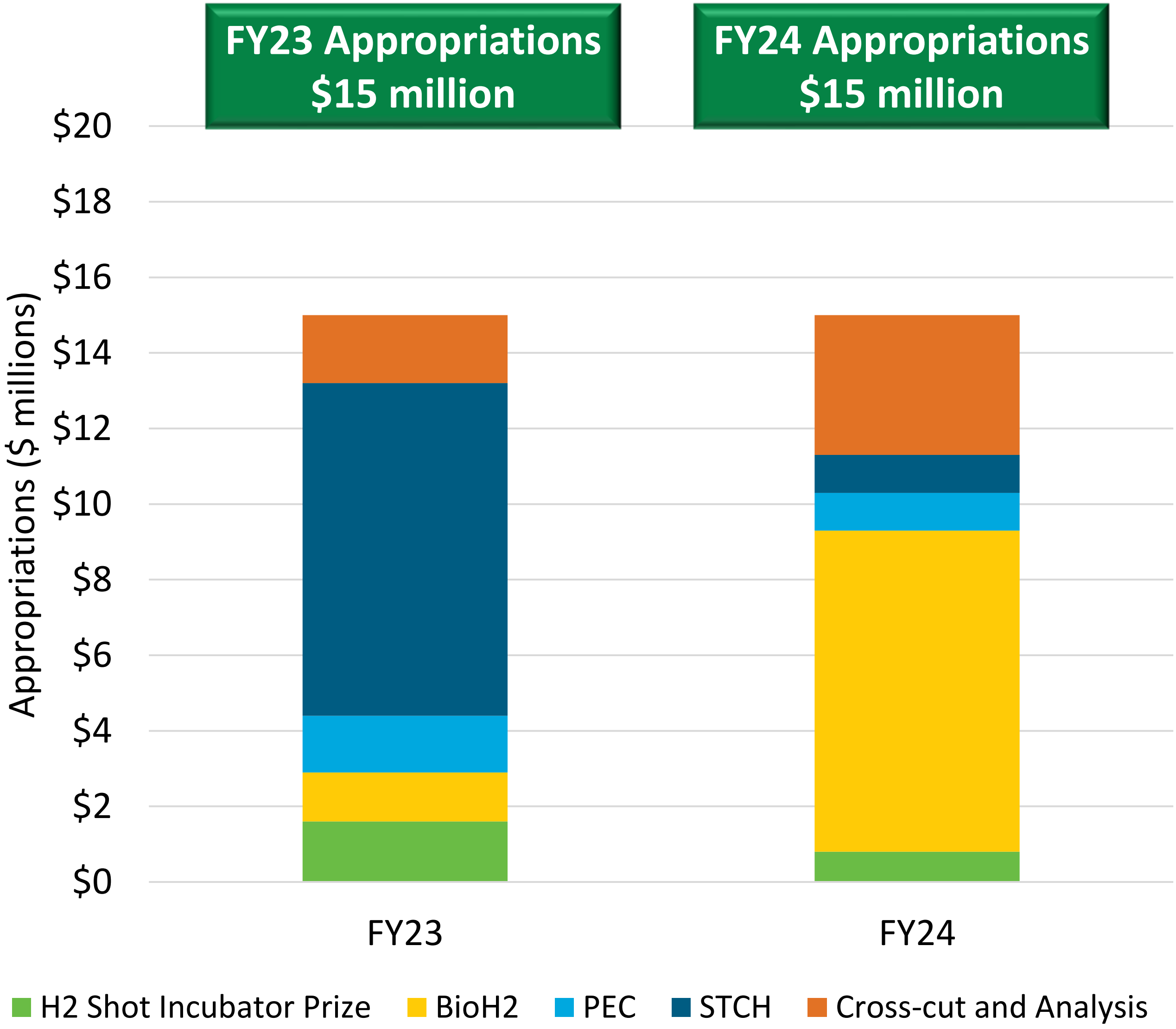
Clean Hydrogen Electrolysis Program (Sec. 816)

- **$1B**: $200M/yr (FY 2022-2026)
- **Goal:** Reduce electrolytic H_2 production cost to $2/kg clean H2 by 2026
- RDD&D program for commercialization purposes to improve efficiency, increase durability, and reduce cost of electrolyzers.

Clean Hydrogen Manufacturing & Recycling Program (Sec. 815)

- **$0.5B**: $100M/yr (FY 2022-2026)
- **Goal:** Enable manufacturing and recycling of clean H_2 technologies.
- Broad language to support domestic manufacturing and supply chains
- RD&D approaches for recycling/reuse

Hydrogen Production Core Budget*



Program Direction

H2 Production

- Bio-based hydrogen production, including biological and carbon negative pathways
  - FECM Carbon Negative Shots Pilots FOA
- Direct Water Splitting
  - PEC and STCH
- H2 Shot Incubator Prize
- All electrolysis work is being supported under the BIL Sect. 816 Clean Hydrogen Electrolysis Program as well as Sect. 815 Clean Hydrogen Manufacturing and Recycling Program

FY25 Request
$15 million

Clean H_2 Electrolysis (BIL)
$200 million/yr over 5 yr

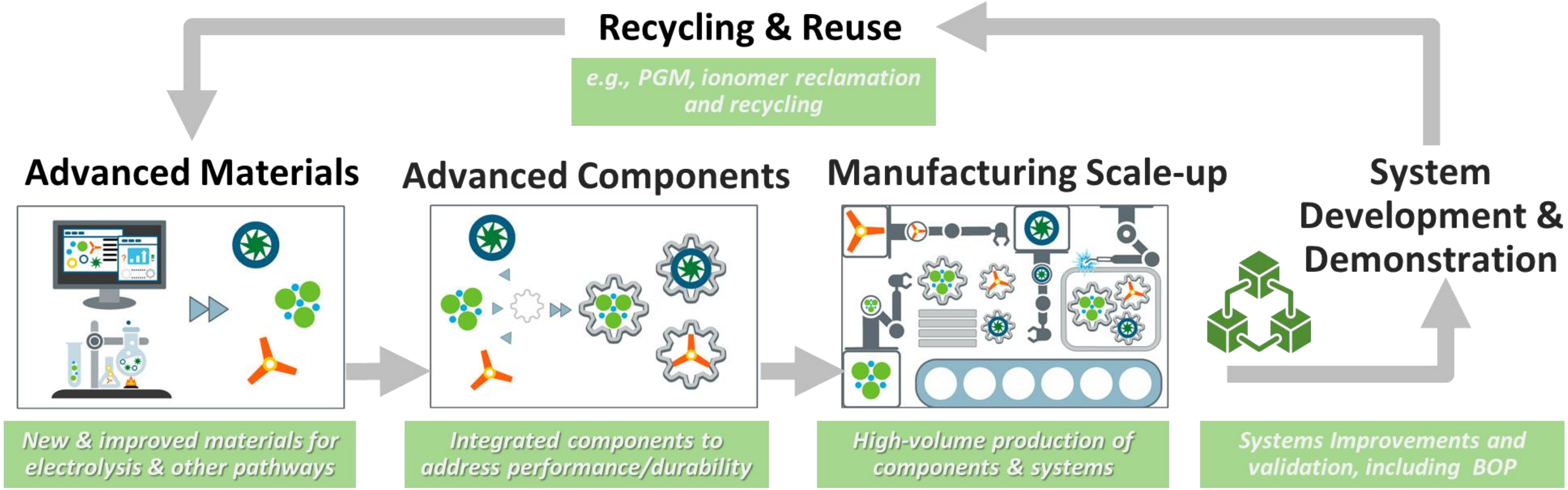
**Core budget complements BIL funding*

Hydrogen Production RD&D Execution Strategy/Approach

Target-Driven RDD&D Approach
Technoeconomic analyses to guide priorities, track progress, & set targets

Stakeholder Engagement: *Provides feedback to inform strategy; Includes Workshops, RFIs, Consortia Stakeholder Advisory Boards*

Multi-Staged Approach to Technology Progression



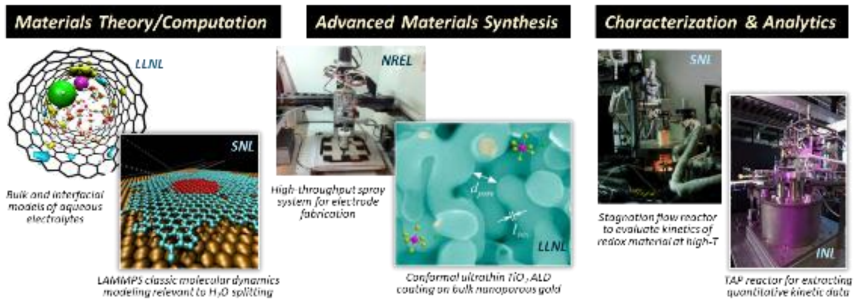
Consortia Model for Enhanced Collaboration: *Leverage world-class national lab expertise & facilities with an influx of new ideas and industry/university partners*

H_2 Production: Consortia-Supported RD&D

HydroGEN
Advanced Water Splitting Materials

Advanced materials development for:

- Photoelectrochemical (PEC)
- Solar thermochemical (STCH)
- High-temperature electrolysis (HTE)
- Low-temperature electrolysis (LTE)



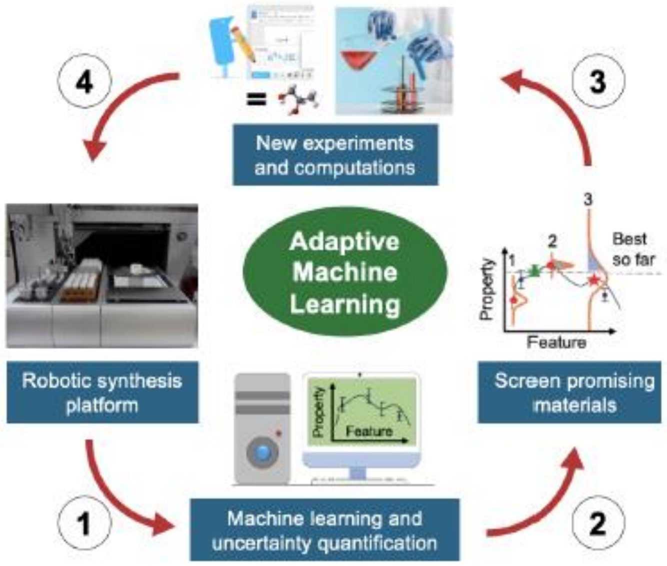
New website:

www.energy.gov/eere/h2awsm

Presentation: P148 (Tuesday, 11:00am)
Posters: P148A-E (Tuesday)

ElectroCat
Electrocatalysis Consortium

PGM-free catalyst development for LTE



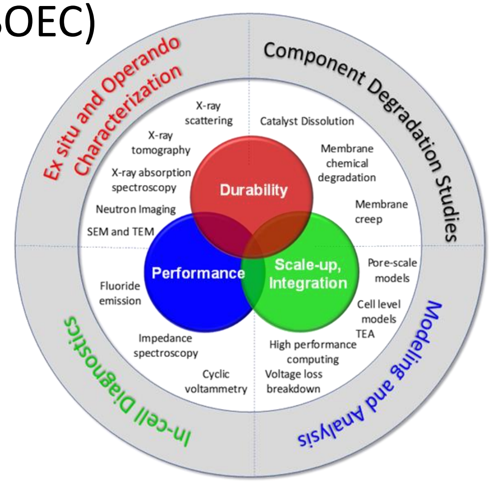
http://www.electrocat.org

Presentation: FC160 (Tues., 9:30 am in FC Session)

H2NEW
U.S. DEPARTMENT OF ENERGY

Component integration, accelerated stress test development for:

- Proton exchange membrane (PEM)
- Liquid alkaline (LA)
- Oxide ion-conducting solid oxide (O-SOEC)



https://h2new.energy.gov/

Presentation: P196 (Tuesday, 1:45pm)
Posters: P196A-H (Tuesday)

Roll-to-Roll (R2R) Consortium

ROLL TO ROLL CONSORTIUM
U.S. DEPARTMENT OF ENERGY
Hydrogen and Fuel Cell Technologies Office

Advancing efficient, high-throughput, and high-quality manufacturing processes

National Lab Team

Argonne National Laboratory
NREL Transforming ENERGY
Berkeley Lab Bringing Science Solutions to the World
Oak Ridge National Laboratory
Sandia National Laboratories

Industry Advisory Board

Association for Roll-to-Roll Converters
gm
pH Matter llc
Chemours™
IONOMR Innovations
Pajarito Powder
De Nora
nel
plug™

BIL-MNF001, Wed 3:45 in FC Session

Task Areas

- Materials Scale-Up Science
- MEA Fabrication
- Quality Control
- Process Modeling and AI / ML
- Characterization for Mfg Environment
- Technoeconomic Analysis

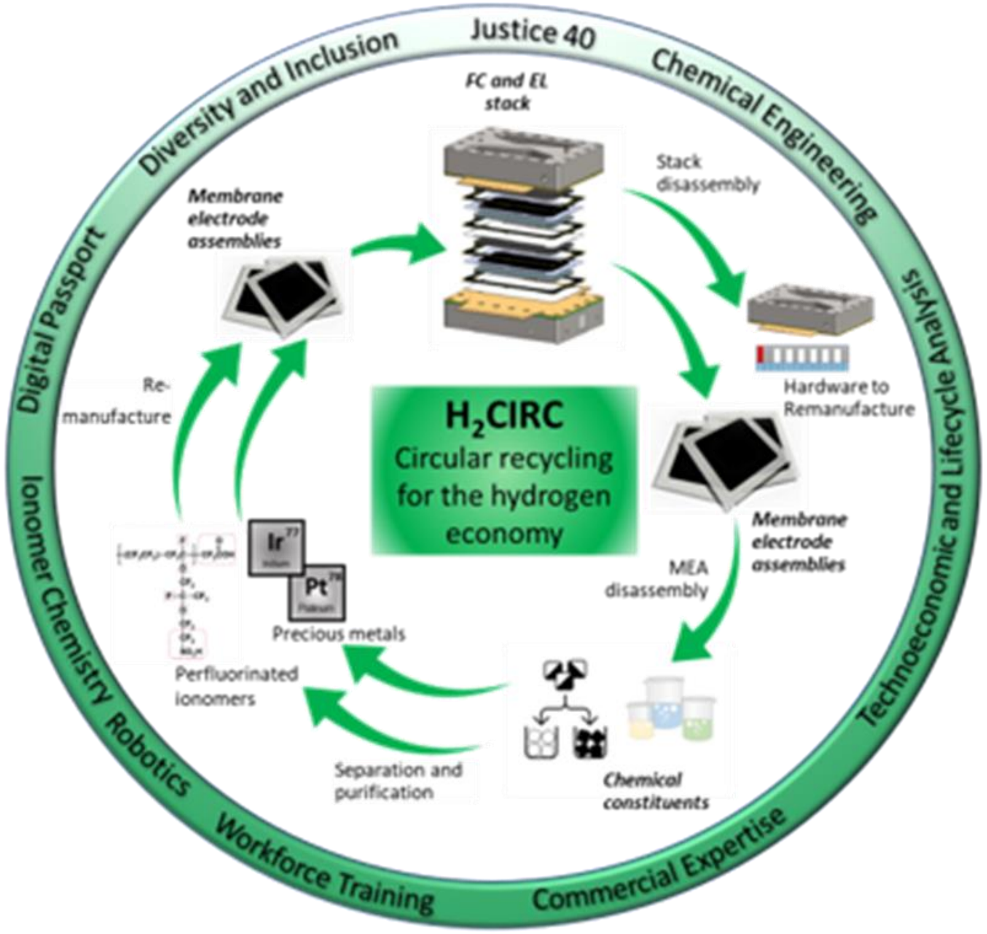
CRADA Request for Proposals

- Collaborative projects with Industry and Labs
- Concept Papers Due **June 3**

http://www.nrel.gov/hydrogen/r2r-crada-call.html

Circular Recycling for the Hydrogen Economy Consortium (H_2CIRC)

Developing a robust domestic recovery and recycling capability for electrolyzers and fuel cells



Goal: Demonstrate pilot-scale validation activities over the entire recycling process along with analysis, digital passport, and community benefits/energy equity.

Impact: Establish approach for recycling electrolyzers and fuel cells, long-term supply chain security, and environmental sustainability.

Primary Project Tasks

- Automated Stack Disassembly
- MEA Disassembly and Recycle*
- Analysis
- Digital Material Passport
- Community Benefits

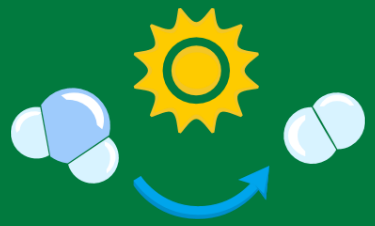
* Includes PGM reclamation and ionomer recycling

Key Participants

AIChE (Lead)	Delaware State U.
Chemours	U. of Delaware
Plug Power	Worchester Poly
Cummins	University of Houston
Heraeus	ORNL
Johnson Matthey	NREL
Nel Hydrogen	LBNL
General Motors	Strategic Analysis Inc.

Develop cost-effective, sustainable processes to recover and reuse >70% of ionomer and ≥95% of PGMs

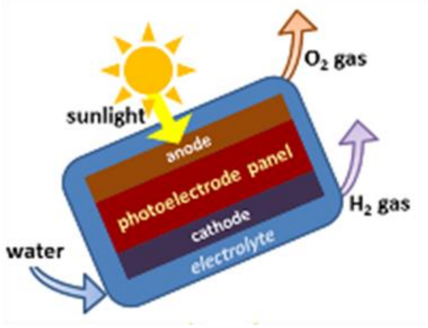
Hydrogen Production
Advanced Pathways



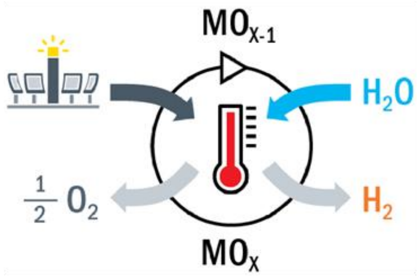
Hydrogen Shot Advanced Pathways Technical Experts Meeting

Gathered ~40 experts to discuss knowledge gaps and address applied science/engineering needs to accelerate progress

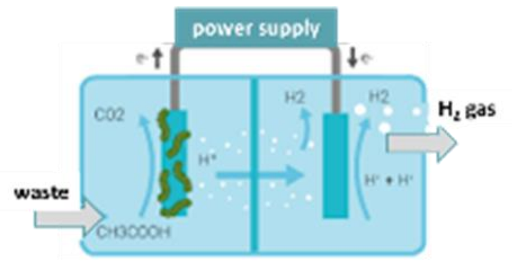
Photoelectrochemical



(Solar) Thermochemical



Biological



Conversion Processes

- Electrochemical
- Thermochemical
- Photochemical
- Biological/Microbial
- Hybrid Approaches

- **Identify systems with potential to meet H_2 Shot goals**
- **Formulate technical, economic, and social value proposition**
- **Advance rigorous technoeconomic & life-cycle analysis**

Aligned with Basic Energy Sciences

Outcomes: Publish technology assessment focused on status, challenges, and opportunities for implementing these advanced pathways; & Contribute to HFTO strategy for Advanced Pathways

Hydrogen Shot Incubator Prize

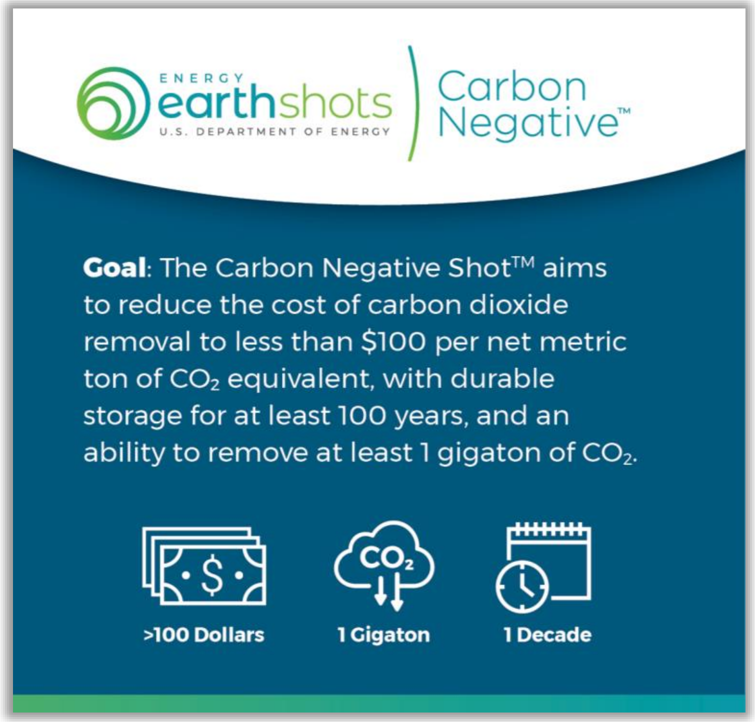
Prize winners from the Prove! Phase are working on their innovative technologies in preparation for a final presentation on their progress

- Incentivize **innovative off-roadmap technologies** with the potential to achieve the Hydrogen Shot
- Break down barriers for inventors and researchers and accelerate progress by complementing traditional FOA process
- Provide access to the national labs through vouchers

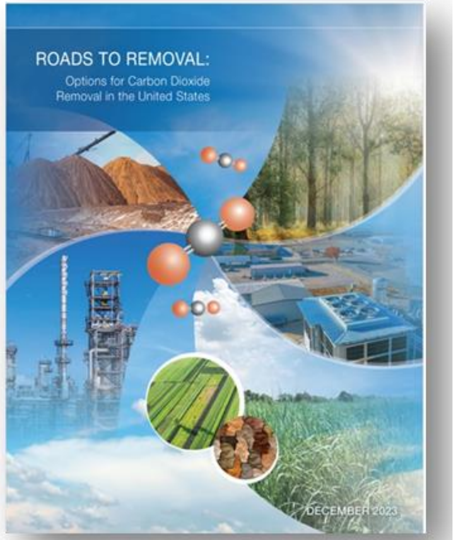
PAX Scientific Richmond, CA	Development of water purification system to enable use of high-salinity or non-potable water for electrolysis
NX Fuels Ann Arbor, MI	Development of solar-hydrogen device using low-cost, industry ready materials.
Electro-Active Technologies Knoxville, TN	Integration of solar technologies, algae, and microbial electrolysis for hydrogen production from waste.
Green Fortress Engineering Indianapolis, IN	Development of low-cost, efficient hydrogen separation membrane for an indirectly heated pyrolytic gasifier

For more information on the winners visit: www.herox.com/HydrogenShotPrize

Collaboration with FECM on Carbon Negative Shot Pilots FOA



- **HFTO, in partnership with FECM, will support one project (up to $7M) under AOI 1 – Small Biomass Carbon Removal and Storage (BiCRS) Pilots**
  - Applications under review with selections expected in late summer
- **Design, build, and test an integrated BiCRS pilot project with hydrogen co-production**



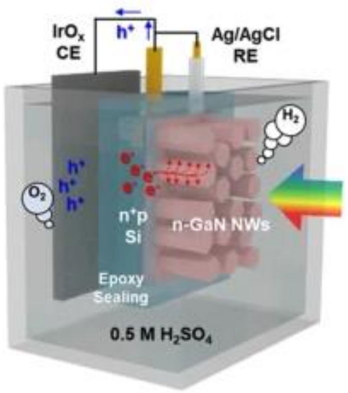
A Key Finding from the **Roads to Removal Study:**
One of the most cost-effective and promising strategies for large scale carbon removal is to produce hydrogen from biomass and store the carbon

HydroGEN Accomplishments (Node Support and Core Lab Efforts)

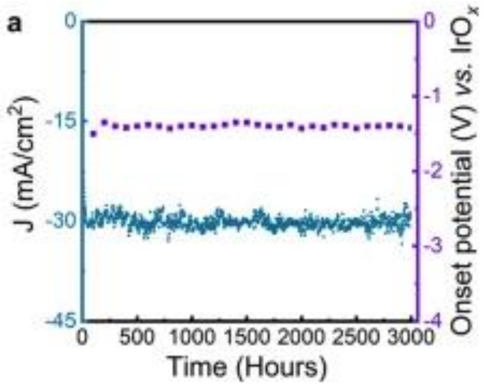
HydroGEN
Advanced Water Splitting Materials

PEC

LBNL and NREL worked with **University of Michigan** (Zetian Mi, P209) to identify stability of N-terminated GaN photoabsorbers resulting in 3,000 hr operation of two-electrode configurations with no performance degradation.



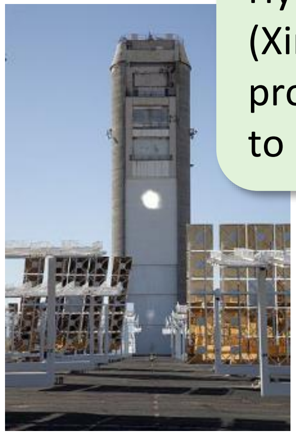
Nat. Commun. **2023**, *14*, 2047.



Demonstrated bias-free water splitting with a III-V photocathode at over 5% STH efficiency for more than 200 hours at **neutral pH** (**NREL/LBNL**)

On-sun fixture will test FOA project novel materials

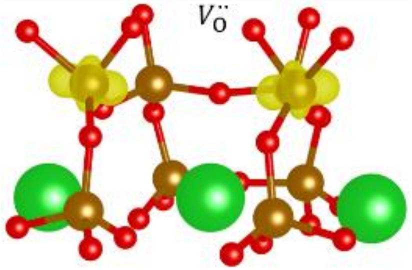
STCH



HydroGEN node experts are working with **Saint Gobain** (Xin Qian, P217) to predict water splitting rates of promising materials using ab initio calculations **(LLNL)** and to develop a viable STCH reactor for on-sun testing **(SNL)**.

High throughput materials discovery demonstrated a water splitting material predicted from theory-guided design using a newly developed and trained Machine Learning algorithm significantly increasing material screening speed. (**SNL/LLNL**)

$BaFe_2O_4$ – predicted water splitter
(*Al → increased hi-T stability*)



Benchmarking and Protocol Development for Advanced Water Splitting Technologies

5th Annual Benchmarking Meeting
Held September 20-22, 2023 at ASU

Pacific Northwest NATIONAL LABORATORY · nel · ASU Arizona State University · Caltech

6th Benchmarking Meeting
ASU California Center in Los Angeles
June 10-12, 2024
REGISTRATION OPEN

P170, Mon 3:45

Goal: ***Develop best practices in materials characterization and benchmarking: Critical to accelerate materials discovery, development, validation, and adoption***

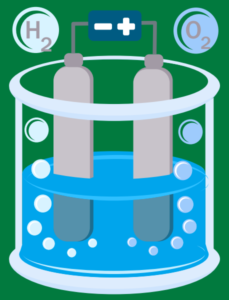
- Completed **59 test protocols** across the four H_2 production technologies involving more than 100 authors
- Published a first set of 20 protocols in an open access journal receiving over 10,000 downloads
  - 8 LTE, 4 HTE, 5 PEC, 3 STCH

Prioritizing protocols for validation testing and improvement, with first validations underway

The next level of Advanced Water Splitting Technologies Protocols are being written.

Hydrogen Production

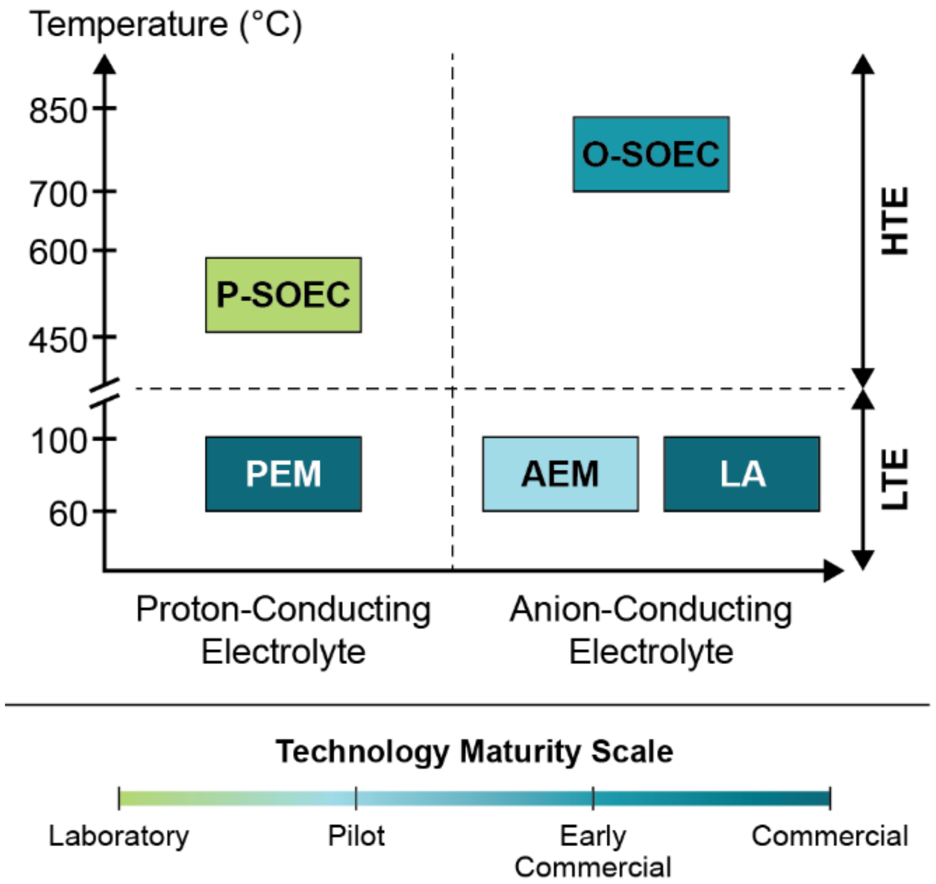
Electrolysis



Support of Diverse Electrolyzer Types

- Multiple electrolyzer types, classified by operating temperature and electrolyte type, have potential to meet cost and technical targets
- Each technology has advantages and drawbacks with unique benefits and pathways to achieve H_2 production cost goals
- Electrolyzers are at different TRLs and supported accordingly

Technology	Commercial Status	Advantages
Liquid Alkaline	Commercial	• Low-cost materials • Proven long lifetime • Established supply chain & manufacturing processes
Proton Exchange Membrane	Commercial	• High current density at high efficiency • Differential pressure operation • Dynamic operation capability
Oxide-Ion Conducting Solid Oxide	Early Commercial	• High electrical efficiency • Thermal energy integration
Alkaline Exchange Membrane	Pilot	• Low-cost materials • Dynamic operation capability
Proton-Conducting Solid Oxide	Laboratory	• High electrical efficiency • Thermal energy integration • Lower cost materials and operating temperature than O-SOEC



New BIL FOA awards and lab call projects are supporting this approach

BIL Lab Call – Advanced Materials, Components, and Interfaces for Electrolyzers

Tech.	Lead Laboratory / *Lead PI*	Project Title
PEM	Sandia National Laboratory *Cy Fujimoto*	Advanced Hydrocarbon Based Proton Exchange Membrane Water Electrolyzers
	Los Alamos National Laboratory *Jacob Spendelow*	Ultralow Iridium Catalysts with Controlled Morphology and Speciation
	Argonne National Laboratory *Ahmed Farghaly*	Accelerated Discovery of Metallic Pyrochlores OER Catalysts for PEM Water Electrolyzers: High-Throughput Computational and Experimental Approach
LA	National Renewable Energy Laboratory *Abhishek Roy*	Thin highly selective polymer membrane-separators for advanced LAW
	Oak Ridge National Lab *Jun Yang*	Hierarchically Structured Advanced Electrodes for Alkaline Water Electrolyzers
AEM	Lawrence Livermore National Laboratory *Johanna Schwartz*	Studying-Polymers-On a-Chip (SPOC): Increased alkaline stability in anion exchange membranes
	Lawrence Berkeley National Laboratory *Xiong Peng*	Hierarchical electrode design for highly efficient and stable anion exchange membrane water electrolyzers
O-SOEC	Pacific Northwest National Laboratory *Olga Marina*	Stable High-Performing Oxygen Electrode for SOEC Operating at Lower Temperatures
	SLAC National Accelerator Laboratory *Nicholas Strange*	Developing High-Entropy Materials as Superior Alternative Electrodes for Long-lasting Oxide-Conducting Solid Oxide Electrolysis Cells (O-SOECs)
P-SOEC	Idaho National Laboratory *Dong Ding*	High Performance and Robust Proton Conducting Solid Oxide Electrolysis Cells Enabled by New Materials, Interfaces and Fabrication Methods
	Lawrence Livermore National Laboratory *Joel Varley*	Directed Search for Stable and Conductive Electrolytes for Next-Generation Proton Solid Oxide Electrolysis Cells

ELY-BIL002-012, Tues. evening poster session

BIL 816 Lab Call - H2LinkSc Pilot Projects

- **HFTO lab projects coordinate with DOE Office of *Science Energy Earthshot Research Centers* (EERCs), *Energy Frontier Research Centers* (EFRCs), and other activities to bridge across basic and applied science**
- **Collaborative activities could include:**
  - *Science & technology symposia*
  - *Sample exchanges and data sharing*
  - *Hosting students across institutions*

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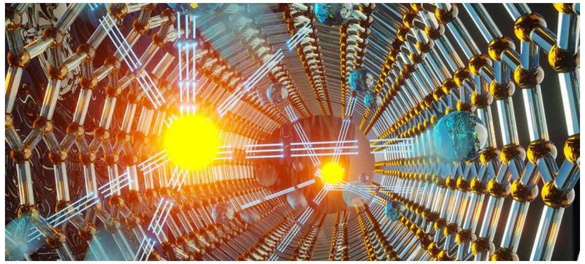
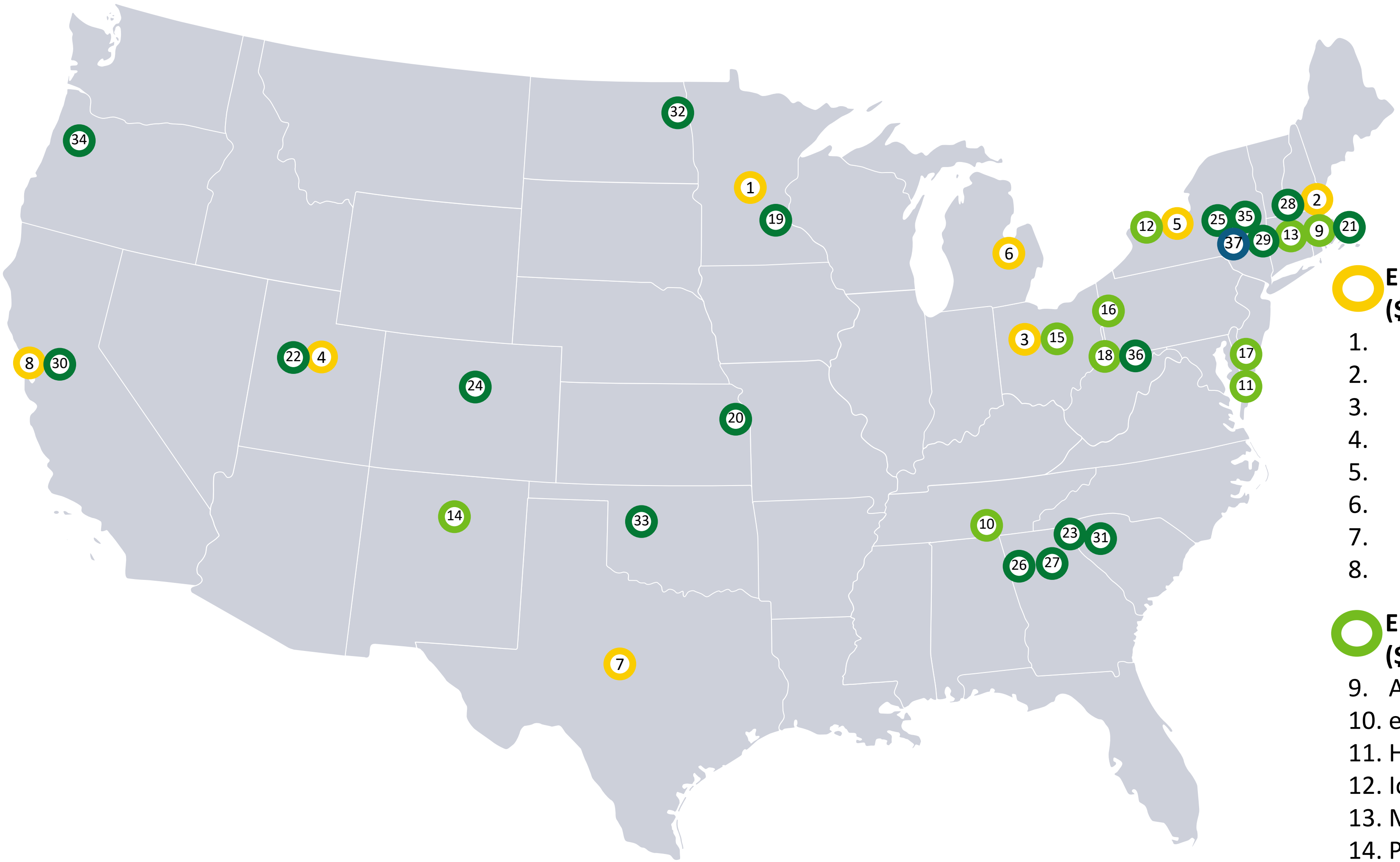


Four H2LinkSc Pilot Projects focus on electrolysis: aligned with Priority Research Opportunities identified by DOE-BES*

Electrolyzer Type	AMR Poster	Lead Organization	PI	H2LinkSc Bridging Opportunities
AEM	**ELY-BIL005**	Lawrence Livermore National Laboratory	**Dr. Johanna Schwartz**	*Ionomer-based Water Electrolysis* EERC; *Center for Alkaline-Based Energy Solution* EFRC; and the *Center for Enhanced Nanofluidic Transport* EFRC
O-SOEC	**ELY-BIL011**	Pacific Northwest National Laboratory	**Dr. Olga Marina**	Existing BES-supported projects at PNNL with expertise in materials design and modeling.
P-SOEC	**ELY-BIL009**	Idaho National Laboratory	**Dr. Dong Ding**	Both projects could "link" to the *Hydrogen for Energy and Information Sciences* EFRC focused on computation materials screening and modeling surface properties critical for stable operation of P-SOECs
P-SOEC	**ELY-BIL010**	Lawrence Livermore National Laboratory	**Dr. Joel Varley**	

*Foundational Science for Carbon-Neutral Hydrogen Technologies | Department of Energy

BIL 816 Clean Hydrogen Electrolysis Program FOA Award Selections



Electrolyzer Manufacturing ($315M DOE/$875M Total)

1. Cummins
2. Electric Hydrogen
3. NexTech Materials
4. OxEon Energy
5. Plug Power
6. Nel Hydrogen
7. thyssenkrupp nucera
8. Verdagy

Electrolyzer Supply Chain ($81M DOE/$103M Total)

9. ACS Industries
10. eSpin Technologies
11. HighT-Tech
12. Ionomr Innovations
13. Mott Corporation
14. Pajarito Power
15. Power to Hydrogen
16. PPG Industries
17. The Chemours Company
18. West Virginia University

Electrolyzer Materials/Components ($72M DOE/$83M Total)

19. 3M Company
20. Avium
21. Boston University
22. Chemtronergy
23. Clemson University
24. Colorado School of Mines
25. Ecolectro
26. Georgia Tech
27. Georgia Tech
28. Nel Hydrogen
29. Plug Power
30. Stanford University
31. Tetramer Technologies
32. University of North Dakota
33. University of Oklahoma
34. University of Oregon
35. W. L. Gore & Associates
36. West Virginia University

Recycling Consortium (815 funded) ($50M DOE/$64M Total)

37. American Institute of Chemical Engineers

Source: HFTO https://www.energy.gov/eere/fuelcells/bipartisan-infrastructure-law-clean-hydrogen-electrolysis-manufacturing-and-0

BIL 816 FOA Funding Impacts

36 Projects

RD&D and manufacturing for domestic supply chain

Enables \$2/kg H_2 by 2026

RD&D for domestic manufacturing and support for H2 Hubs

Electrolysis **10 GW/yr** Supports production of 1.3M metric tons of H_2/year

\$1.1B

Total Project Costs

Including **~\$470M** in federal cost share and **~\$590M** in cost share

900+

Direct jobs created

Plus, thousands of indirect jobs across the U.S.

23 States

Benefiting 24 disadvantaged communities across the U.S. with initiatives in workforce development, energy equity, and DEIA

Analysis Efforts Identify Cost Reduction Strategies and Pathways to Achieve Cost Targets

Key Cost Drivers for Clean Hydrogen Production

Manufacturing Throughput
- Automation
- Increased line speed
- Quality assurance/ quality control

Electrolyzer Properties
- System lifetime
- System performance and efficiency
- Material, component, and equipment costs

Energy System Integration
- Integration with clean energy sources
- Electricity price
- Capacity factor
- Installation costs

Today: \$5-\$7/kg clean H_2 scenarios*

*across multiple renewable energy scenarios

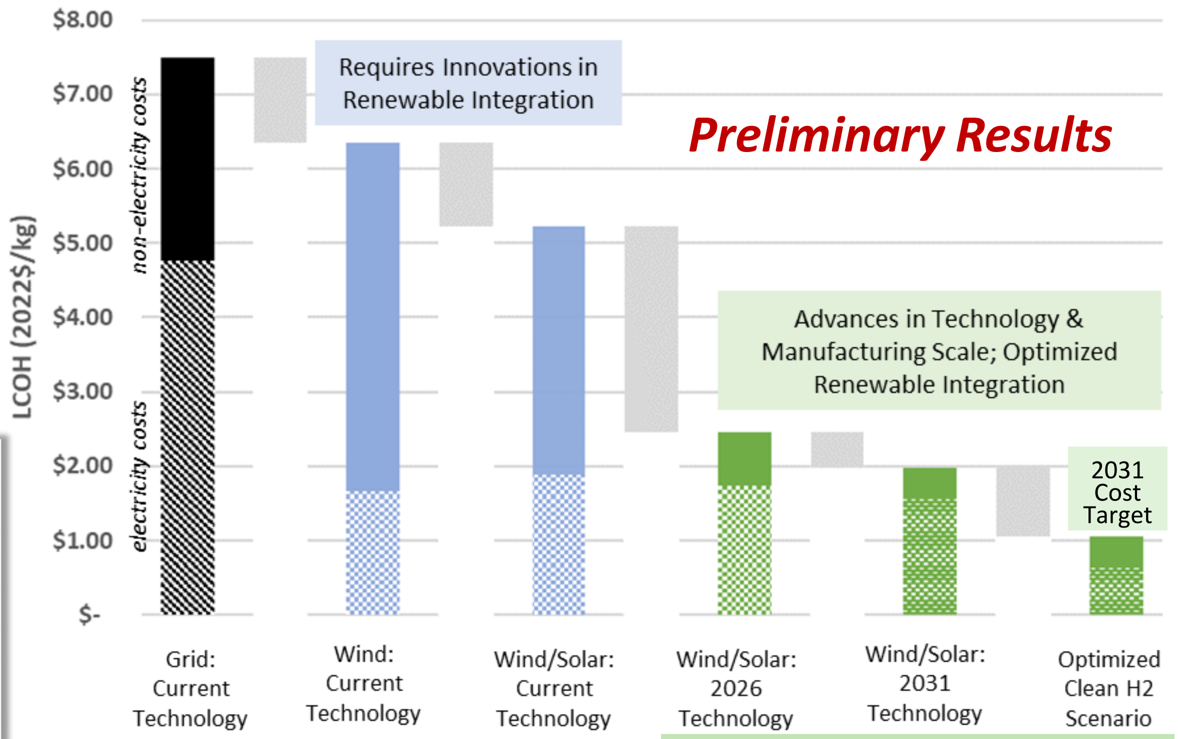
2026 BIL target: \$2/kg clean H_2

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

PEM Electrolyzer Technical Targets

CHARACTERISTIC	UNITS	2022 STATUS[c]	2026 TARGETS	ULTIMATE TARGETS
Stack				
Total Platinum Group Metal Content (both electrodes combined)[d]	mg/cm^2	3.0	0.5	0.125
	g/kW	0.8	0.1	0.03
Performance		2.0 A/cm2 @ 1.9 V/cell	3.0 A/cm2 @ 1.8 V/cell	3.0 A/cm2 @ 1.6 V/cell
Electrical Efficiency[e]	kWh/kg H_2 (% LHV)	51 (65%)	48 (69%)	43 (77%)
Average Degradation Rate[f]	mV/kh (%/1,000 h)	4.8 (0.25)	2.3 (0.13)	2.0 (0.13)
Lifetime[g]	Operation h	40,000	80,000	80,000
Capital Cost[h]	\$/kW	450	100	50
System				
Energy Efficiency	kWh/kg H_2 (% LHV)	55 (61%)	51 (65%)	46 (72%)
Uninstalled Capital Cost[h]	\$/kW	1,000	250	150
H_2 Production Cost[i]	\$/kg H_2	>3	2.00	1.00

PEM Electrolysis: Example Pathway to H2 Shot LCOH



Consistent with PEM electrolyzer stack and system targets

To meet hydrogen production cost targets, need combination of high-volume manufacturing; technology advancements; and close integration of electrolyzers with low-cost, clean electricity sources

Analysis Efforts Identify Cost Reduction Strategies and Pathways to Achieve Cost Targets

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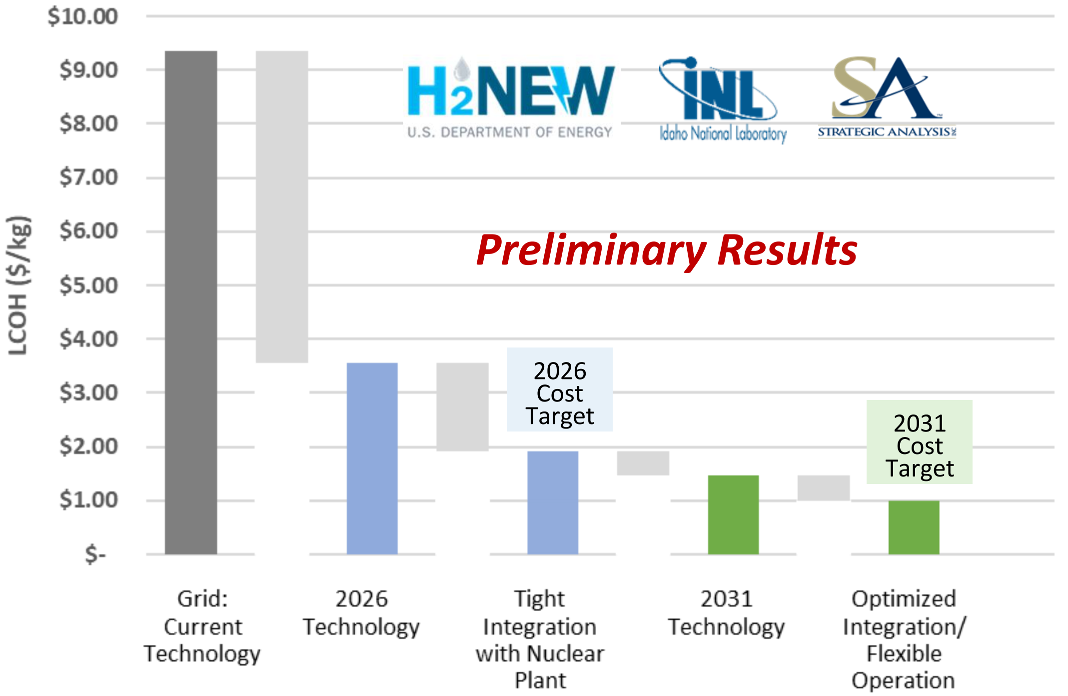
High-T Electrolyzer Technical Targets

CHARACTERISTIC	UNITS	2022 STATUS[C]	2026 TARGETS	ULTIMATE TARGETS
Stack				
Performance	A/cm^2 @ 1.28 V/cell	0.6	1.2	2.0
Electrical Efficiency [d]	kWh/kg H_2 (% LHV)	34 (98%)	34 (98%)	34 (98%)
Average Degradation Rate [e]	mV/kH (%/1,000 h)	6.4 (0.50)	3.2 (0.25)	1.6 (0.12)
Lifetime [f]	Operation h	20,000	40,000	80,000
Capital Cost [g]	\$/kW	300	125	50
System				
Electrical Efficiency	kWh/kg H_2 (% LHV)	38 (88%)	36 (93%)	35 (95%)
Energy Efficiency [h]	kWh/kg H_2 (% LHV)	47 (71%)	44 (76%)	42 (79%)
Uninstalled Capital Cost [g]	\$/kW	2,500	500	200
H_2 Production Cost [i]	\$/kg H_2	>4	2.00	1.00

High-T Electrolysis: Example Pathway to H2 Shot LCOH



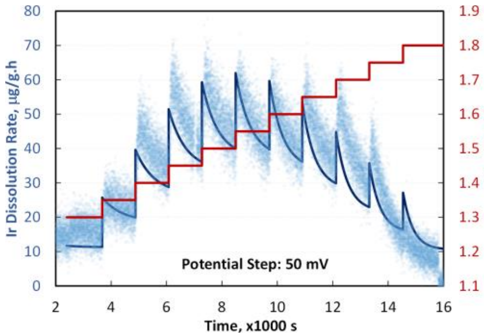
Consistent with HTE stack and system status and 2026 targets

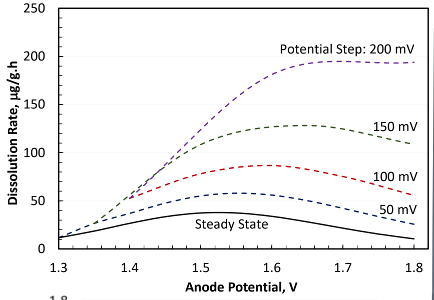
Consistent w/ stack & system ultimate targets

To meet hydrogen production cost targets, need combination of high-volume manufacturing; technology advancements; and close integration of electrolyzers with low-cost, clean electricity sources

H2NEW Accomplishments

Ir dissolution, x-ray studies, and modeling





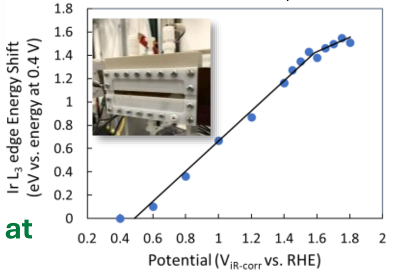
2-Species Dissolution Model

$IrO_2 + H_2O = IrO_2OH + H^+ + e^-$ (formation 1)

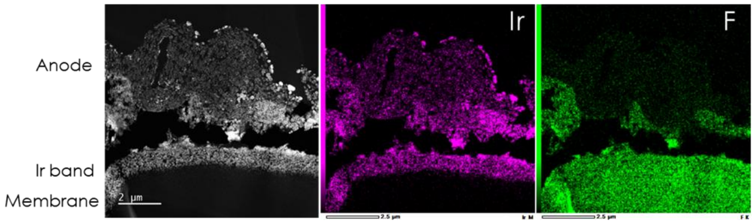
$IrO_2 + 2H_2O = IrO_4^{2-} + 4H^+ + 2e^-$ (diss. 1)

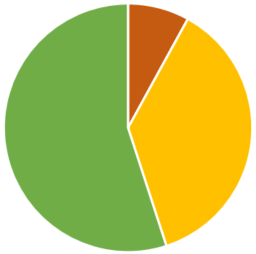
$IrO_2OH + H_2O = IrO_4^{2-} + 3H^+ + e^-$ (diss. 2)

Modeled aqueous dissolution rate at 1.55-1.6 V: 35 µg $g_{cat}^{-1}\ h^{-1}$



Advanced cell characterization





Anode: 0.22 ± 0.04 mg_{Ir}/cm^2

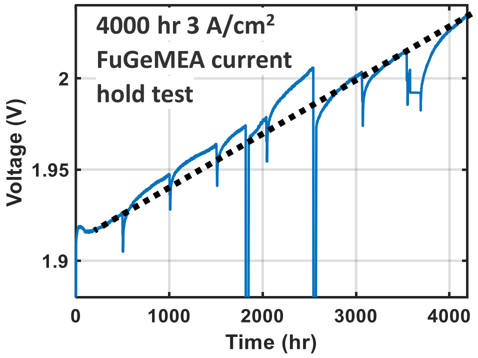
Cathode: ~0.03 mg_{Ir}/cm^2

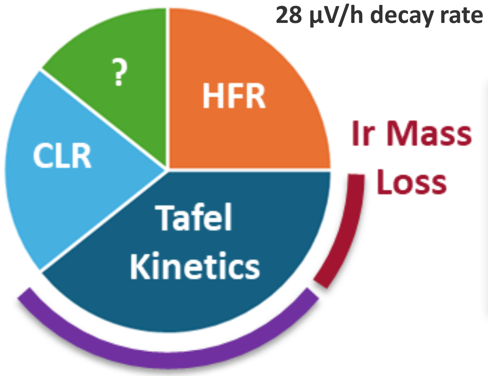
Membrane Ir band:

0.14 ± 0.04 mg_{Ir}/cm^2

45% of Ir lost from anode over 4,000 h

Single cell long duration testing and loss mechanism quantification





HFR-Ohmic: ~ 7 µV / hr (~2.5 µΩ cm^2/hr)

Catalyst kinetics:

~ 11 $\mu V_{HFR\text{-}free}$ / hr at 0.1 A/cm^2

Catalyst layer resistance: ~6 $\mu V_{HFR\text{-}free}$.

Unaccounted for: ~4 $\mu V_{HFR\text{-}free}$.

Ir mass loss rate 110 µg $g_{cat}^{-1}\ h^{-1}$

Advanced Fundamental Understanding of Iridium Dissolution Mechanisms and Impact on Cell Degradation

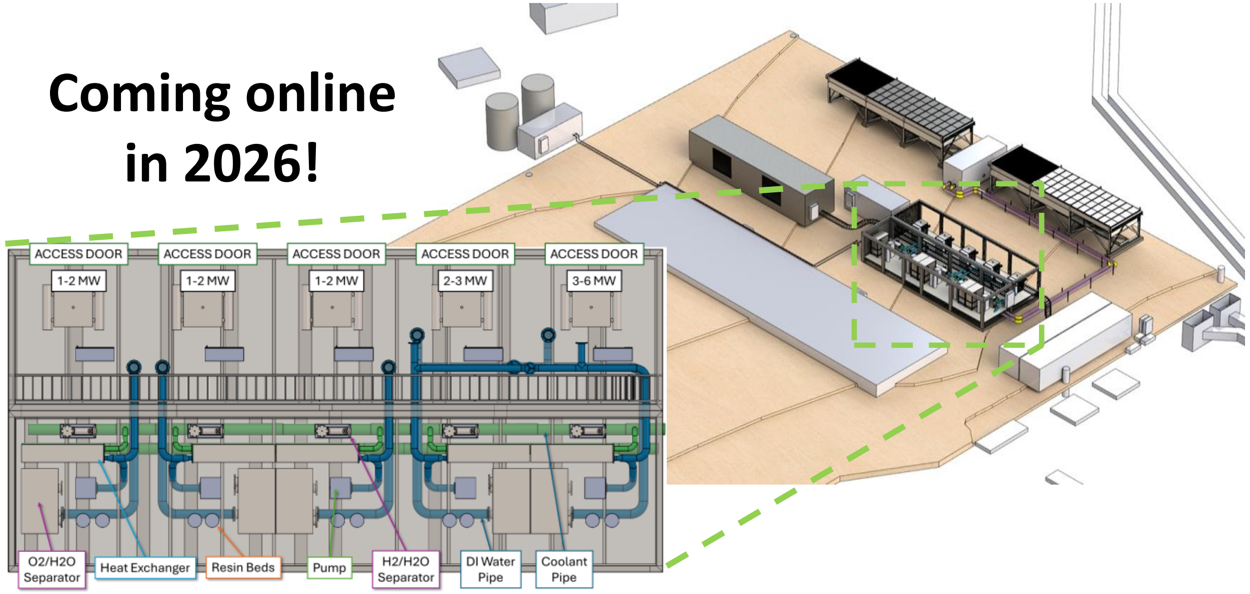
- Developed a comprehensive research approach involving in-cell studies, electrochemical half cells, modeling, and advanced characterization
- IrOx catalyst is least stable between 1.5 and 1.55 V (v RHE) at steady state operation
- In situ X-ray data shows appearance of higher oxidation state IrOx species at 1.6 V corresponding to suppression of dissolution
- Step change in potential results in increased Ir dissolution compared to more gradual change (e.g., ramping) or steady state operation
- Catalyst kinetics is responsible for ~40% of the degradation rate and ~45% of Ir is lost from anode over 4,000 hr with most of it ending up as a band at the membrane surface
- Data has implications for operating strategies and mitigation approaches.

Expansion to Multi-MW Electrolyzer Stack and System Test Capabilities

Low-Temperature Electrolyzers – NREL *(ELY-BIL001)*

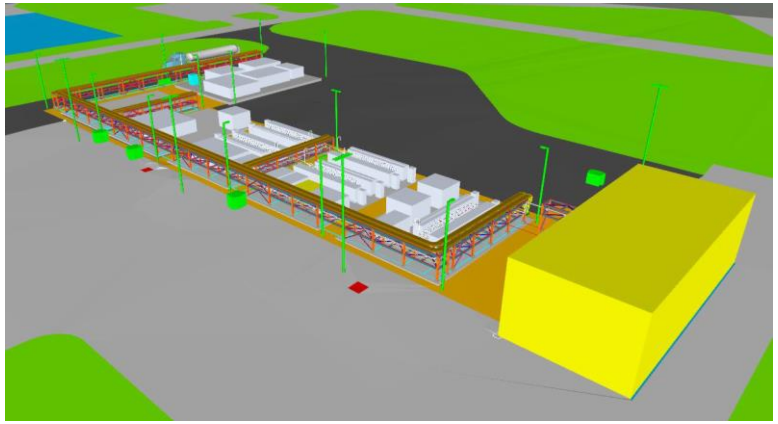
- Expansion of NREL's Flatirons Campus ARIES capability to support industry
- Full system testing **up to 10 MW_{AC}**
- Parallel stack testing **up to 6 MW_{DC}** in aggregate for PEM and/or alkaline stacks
- Grid integration with renewable energy production and other ARIES assets

Coming online in 2026!



High-Temperature Electrolyzers – INL *(SDI006)*

- High Temp Test Facility (HTTF) is cornerstone of INL's Energy Technology Proving Ground
- Full, simultaneous HTE systems testing **up to 10 MW_{AC}** in aggregate
- Simulated nuclear integration and future physical integration with microreactors
- Multiple H_2 end use test possibilities including fueling for INL coach fleet and bio-CO2 capture



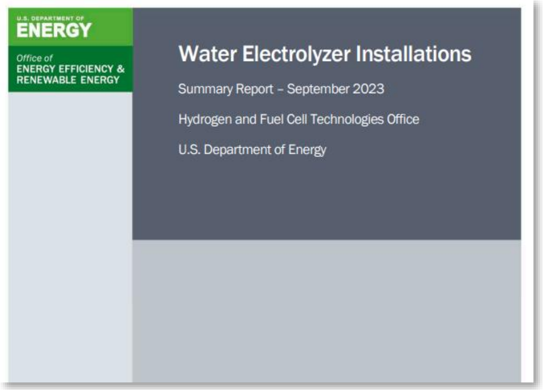
Coming online in 2025!

Recent Stakeholder Engagement

Electrolyzer Installation Webinar

- 450 virtual attendees in September 2023
- Expert speakers from project developers, utilities, OEMs, and national laboratories
- Challenges, cost drivers, and lessons learned for large-scale electrolyzer installations identified

Summary report of key findings available online!


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

Water Electrolyzer Installations

Summary Report – September 2023

Hydrogen and Fuel Cell Technologies Office

U.S. Department of Energy

https://www.energy.gov/eere/fuelcells/electrolyzer-installation-webinar

Electrolyzer Data Collection Effort

- Performance, reliability, operating, and installation cost data from ***deployed electrolyzers***
- Data will be securely stored, aggregated, and anonymized
- Data will help refine assumptions & track progress towards \$2/kg H_2 goal

SDI015, SDO017; Wed. evening poster session

Contact:

LTE: Sam Sprik, NREL, sam.sprik@nrel.gov

HTE: Micah Casteel, INL, micah.casteel@inl.gov

Milestones, Collaborations, Team

H_2 Production Program Highlights and Milestones Summary

FY2023	FY2024	FY2025
BIL Sections 815 & 816 FOA released	BIL 815 & 816 FOA projects selected, and work commences	Progress towards meeting \$2/kg H_2 target tracked including use of electrolyzer real-world data collection
Electrolyzer Installation Costs Webinar	Updated H_2 Production Cost Record Posted	Recycling and Recovery Consortium launched
BIL Section 816 Lab Call released and selections made	BIL Lab Call projects commenced	R2R CRADA projects selected and initiated
5th Annual AWS benchmarking meeting	Technical Experts Meeting on "Advanced Pathways" held	Hydrogen Shot Technology Assessment on Advanced Pathways published
Award and kick off direct solar water splitting HydroGEN FOA awards	Hydrogen Shot Incubator Prize "Prove!" Phase winners announced	Hydrogen Shot Incubator Prize Pitch Day hosted
Expand H2NEW, HydroGEN, and ElectroCat Consortia	Roll-to-Roll Consortia launched and CRADA call released	Carbon Negative Shot BiCRS pilot project awarded
Electrolyzer stack and system technical targets released	Hydrogen Shot Electrolysis Technology Assessment published	FY25 FOAs released – Topics TBD
Kick-off multi-MW electrolyzer validation/ test facilities effort	HFTO Multi-Year Program Plan published	Commission/start operation of HTE validation center

Collaboration Network

Fostering technical excellence, economic growth and environmental justice

Efforts Support Over:
12 national laboratories
25 universities
35 companies

DOE H_2 Program Collaborations		
Collaboration across H_2 through Joint Strategy Teams (JST)		
AMMTO	MESC	BETO
SETO	OCED	ARPA-E
SC	FECM	NE
DOE Cross-Cutting Initiatives		
Critical Materials	AI/ML	Clean Energy Manufacturing
Industrial Decarbonization	Carbon Negative	Long Duration Energy Storage

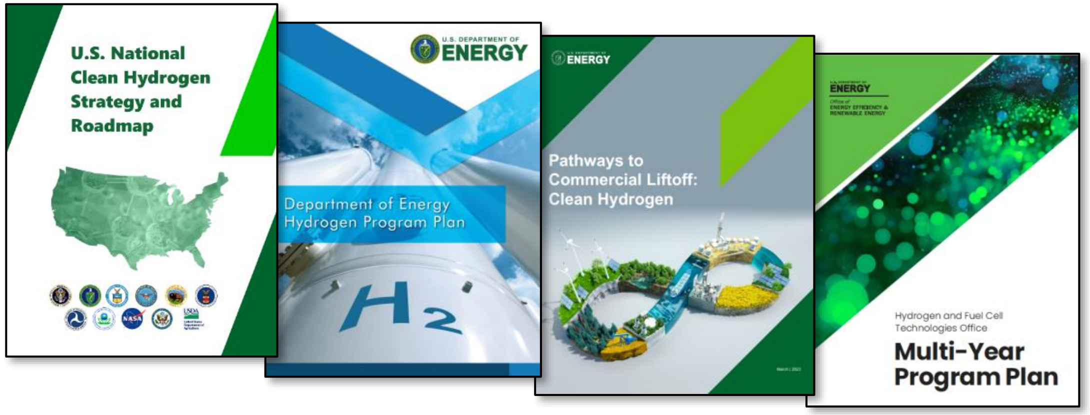
Hydrogen Interagency Task Force

Industry Engagements
Workshops
Requests for Information
AWS Benchmarking and Protocol Development
H2NEW
HydroGEN
ElectroCat

International Collaborations
IPHE, IEA TCPs, Mission Innovation, and other multi-lateral agreements

Resources and Opportunities for Engagement

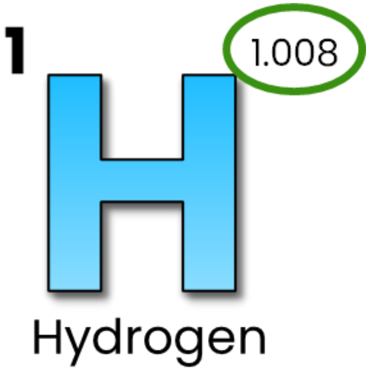
Key Publications



www.hydrogen.energy.gov

Hydrogen and Fuel Cells Day October 8

- Held on hydrogen's very own atomic weight-day



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Hydrogen Shot Fellowship

The U.S. Department of Energy (DOE) is looking for talented, bright, early career professionals to partner with DOE Hydrogen Program Managers working to achieve the Hydrogen Energy Earthshot goal of $1 per 1 kilogram in 1 decade ("1 1 1").

Are you graduating soon or just starting your career in hydrogen?

Do you want to help make clean hydrogen affordable for all?

The Hydrogen Shot Fellowship might be the opportunity you're looking for!

Apply today at: www.zintellect.com Keyword: Hydrogen Shot

The Hydrogen Production Team

Acting Program Manager

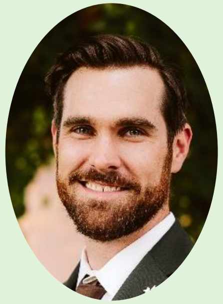
David Peterson

Technology Managers

McKenzie Hubert

Anne Marie Esposito

Elias Pomeroy



James Vickers

Kat Rinaldi

Will Gibbons (Fuel Cells)

Support Contractors

Leah Mcgovern

David Aguerrebere

Corey Schaffer

Technical Project Officer

Kim Cierpik-Gold

Fellows

Open Position

Open Position

Thank You

Dr. David Peterson
Acting Hydrogen Production Program Manager
Hydrogen and Fuel Cell Technologies Office
David.peterson@ee.doe.gov
U.S. Department of Energy

www.energy.gov/fuelcells
www.hydrogen.energy.gov

Session Preview

Hydrogen Production Presentation Schedule – May 7th and 8th

May 7th

9:00 AM	Hydrogen Production Technologies Subprogram Overview
9:30 AM	Megawatt-Scale Low Temperature Electrolyzer Research Capability
10:00 AM	High Temperature Electrolyzer Megawatt-Scale Test Facility
10:30 AM	Break
11:00 AM 11:30 AM 12:00 PM	HydroGEN Overview: A Consortium on Advanced Water Splitting Materials
12:30 PM	Lunch (provided)
1:45 PM 2:15 PM 2:45 PM	H2NEW Consortium: Hydrogen from Next-Generation of Electrolyzers of Water
3:15 PM	Break
3:45 PM	Hydrogen Production Cost and Performance Analysis / SA
4:15 PM	Benchmarking Advanced Water Splitting Technologies: Best Practices in Materials Characterization / PNNL
4:45 PM	Low-Cost Manufacturing of High Temperature Electrolysis Stacks / Nexceris
5:15 PM	BioHydrogen (BioH2) Consortium to Advance Fermentative Hydrogen Production

May 8th

9:00 AM	Scalable halide perovskite photoelectrochemical cell modules with 20% solar-to-hydrogen efficiency and 1000 hours of diurnal durability / Rice	PEC
9:30 AM	All-Perovskite Tandem Photoelectrodes for Low-Cost Solar Hydrogen Fuel Production from Water Splitting / Toledo	PEC
10:00 AM	Gallium Nitride (GaN) Protected Tandem Photoelectrodes for High Efficiency, Low Cost, and Stable Solar Water Splitting / Michigan	PEC
10:30 AM	Break	PEC
11:00 AM	>200 cm2 Type-3 PEC Water Splitting Prototype Using Bandgap-Tunable Perovskite Tandem and Molecular-Scale Designer Coatings / Yale	PEC
11:30 AM	Demonstration of a Robust, Compact Photoelectrochemical (PEC) Hydrogen Generator / Calthech	PEC
12:00 PM	Semi-Monolithic Devices for Photoelectrochemical Hydrogen Production / Hawaii	PEC
12:30 PM	Lunch (provided)	
1:45 PM	Non-intermittent, Solar-thermal Processing to Split Water Continuously via a Near-isothermal, Pressure-Swing Redox Cycle / CU Boulder	(S)TCH
2:15 PM	Accelerated Discovery and Development of Perovskites for Solar Thermochemical Chemical Hydrogen Production / CU Boulder	(S)TCH
2:45 PM	Ca-Ce-Ti-Mn-O-Based Perovskites for Two-Step Solar Thermochemical Hydrogen Production Cycles / Washington Univ.	(S)TCH
3:15 PM	Break	(S)TCH
3:45 PM	Inverse Design of Perovskite Materials for Solar Thermochemical Water Splitting / ASU	(S)TCH
4:15 PM	Scalable Solar Fuels Production in A Reactor Train System by Thermochemical Redox Cycling of Novel Nonstoichiometric Perovskites / St. Gobain	(S)TCH
4:45 PM	Metal-Organic Framework-Based Heterostructure Electrocatalysts with Tailored Electron Density Distribution for Cost-Effective and Durable Fuel Cells and Electrolyzers / U Texas, El Paso	Catalysts
5:15 PM	Single-Walled Carbon Nanotubes with Confined Chalcogens as the Catalysts and Electrodes for Oxygen Reduction Reaction in Fuel Cells / U. Cal Riverside	Catalysts

Hydrogen Production Poster Session – May 7th, 5:30-7:00pm

P148A	HydroGEN: Low Temperature Electrolysis	Shaun Alia, NREL
P148B	HydroGEN: High Temperature Electrolysis	Dong Ding, INL
P148C	HydroGEN: Photoelectrochemical (PEC) Water Splitting	Joel Ager, LBNL
P148D	HydroGEN: Solar Thermochemical Hydrogen (STCH) Water Splitting	Sean Bishop, SNL
P148E	HydroGEN: Cross-Cut Modeling	Tadashi Ogitsu, LLNL
P154	Thin-Film, Metal-Supported High-Performance and Durable Proton-Solid Oxide Electrolyzer Cell	Tianli Zhu, Raytheon Technologies Research Center
P176	Development of Durable Materials for Cost Effective Advanced Water Splitting Utilizing All Ceramic Solid Oxide Electrolyzer Stack Technology	Brian Oistad, Saint-Gobain
P183	Extremely Durable Concrete Using Methane Decarbonization Nanofiber Co-Products with Hydrogen	Alan Weimer, University of Colorado, Boulder
P184	Scalable and Highly Efficient Microbial Electrochemical Reactor for Hydrogen Generation from Lignocellulosic Biomass and Waste	Hong Liu, Oregon State University
P196a	H2NEW LTE: Durability and AST Development	Rangachary Mukundan, LBNL
P196b	H2NEW LTE: Benchmarking and Performance	Deborah Myers, ANL
P196c	H2NEW LTE: Manufacturing, Scale-Up, and Integration	Scott Mauger, NREL
P196d	H2NEW LTE: System and Techno-Economic Analysis -- Hydrogen from Next-Generation Electrolyzers	Alex Badgett, NREL
P196e	H2NEW HTE: Durability and AST Development	Olga Marina, PNNL
P196f	H2NEW HTE: Cell Characterization	David Ginley, NREL
P196g	H2NEW HTE: Multiscale Degradation Modeling	Brandon Wood, LLNL
P196h	H2NEW LTE: Liquid Alkaline Water Electrolysis	Meital Shviro, NREL

P197	Advanced Manufacturing Processes for Gigawatt-Scale Proton Exchange Membrane Water Electrolyzers	Andrew Steinbach, 3M
P198	Enabling Low Cost PEM Electrolysis at Scale Through Optimization of Transport Components and Electrode Interfaces	Chris Capuano, Nel Hydrogen
P199	Integrated Membrane Anode Assembly & Scale-Up	Adam Paxson, Plug Power
P202	Novel Microbial Electrolysis Cell Design for Efficient Hydrogen Generation from Wastewaters	Ruggero Rossi, Pennsylvania State University
P203	Novel Microbial Electrolysis System for Conversion of Biowastes into Low-Cost Renewable Hydrogen	Noah Meeks, Southern Company Services, Inc.
ELY-BIL002	Ultralow Iridium Catalysts with Controlled Morphology and Speciation	Jacob Spendelow, LANL
ELY-BIL003	Accelerated Discovery of Metallic Pyrochlores OER Catalysts for PEM Water Electrolyzers: High-Throughput Computational and Experimental Approach	Ahmed Farghaly, ANL
ELY-BIL004	Hierarchical Electrode Design for Highly Efficient and Stable Anion Exchange Membrane Water Electrolyzers	Xiong Peng, LBNL
ELY-BIL005	Studying-Polymers-On a-Chip (SPOC): Increased Alkaline Stability in Anion Exchange Membranes	Johanna Schwartz, LLNL
ELY-BIL006	Hierarchically Structured Advanced Electrodes for Alkaline Water Electrolyzers	Jun Yang, ORNL
ELY-BIL007	Thin, Highly Selective Polymer Membrane Separators for Advanced Liquid Alkaline Water Electrolysis	Abhishek Roy, NREL
ELY-BIL008	Advanced Hydrocarbon Based Proton Exchange Membrane Water Electrolyzers	Cy Fujimoto, SNL
ELY-BIL009	High Performance and Robust Proton Conducting Solid Oxide Electrolysis Cells Enabled by New Materials, Interfaces and Fabrication Methods	Dong Ding, INL
ELY-BIL010	Directed Search for Stable and Conductive Electrolytes for Next-Generation Proton Conducting Solid Oxide Electrolysis Cells	Joel Varley, LLNL
ELY-BIL011	Stable High-Performing Oxygen Electrode for SOEC Operating at Lower Temperatures	Olga Marina, PNNL
ELY-BIL012	Developing High-Entropy Materials as Superior Alternative Electrodes for Long-lasting Oxide-Conducting Solid Oxide Electrolysis Cells (O-SOECs)	Nicholas Strange, SLAC

Session Logistics

General Information

- This meeting is a review, not a conference
  - **Questions will be taken first from reviewers**, and then from other audience members as time allows
- The schedule will be strictly followed so that reviewers can move between sessions
- Presentations are 20 minutes followed by 10 minutes Q&A

Thank You, Reviewers!

Your input on our Program and subprograms helps guide our decisions.

Thank you for your thoughtful, objective, and timely feedback!

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- **Increase access to domestic, clean transportation fuels.**
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