Clean Hydrogen: energy carrier, renewables enabler, and sector coupler to accelerate the energy transition and meet climate goals

Huyen N. Dinh
Director of HydroGEN, NREL

RE3 Workshop: Clean Hydrogen and Industrial Decarbonization
Louisville, Kentucky
March 9, 2023
Hydrogen Energy Earthshot

“Hydrogen Shot”

“111”

$1 for 1 kg clean hydrogen in 1 decade

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

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

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 H₂ in the US

Economic potential: 2x to 4x more

Illustrative example, not comprehensive

https://www.energy.gov/eere/fuelcells/h2-scale
H2@Scale Opportunities: Deep Decarbonization, Economic Growth, Jobs

Global Potential by 2050

- $2.5 trillion in annual revenues and
- 30 million jobs, along with
- 10-20% global emissions reductions
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)
Figure 10: Willingness to pay, or threshold price, for clean hydrogen in several current and emerging sectors (including production, delivery, and conditioning onsite, such as additional compression, storage, cooling, and/or dispensing).

U.S. D.O.E National Clean Hydrogen Strategy and Roadmap Draft (September 2022)
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)
R&D on Advanced Production Technologies

**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 low temperature electrolysis [LTE] (PEM, liquid alkaline), and high temperature electrolysis [HTE] (solid oxide) electrolyzer technologies
- **$1B BIL** activity now enables an order of magnitude increase in effort on electrolysis to accelerate development

**Longer-term:** Use solar energy or heat to more directly split water
- Photoelectrochemical (PEC) and solar thermochemical (STCH) H₂ production
- Incubate and support promising technology development through **HydroGEN** consortium

---

Hydrogen Shot: “1 1 1”
$1 for 1 kg in 1 decade for clean hydrogen

Example: Cost Reduction of Clean H₂ from Electrolysis

- **2020**
  - ~ $5/kg

- **2025**
  - $2/kg

- **2030**
  - $1/kg

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 HTO)
Pathways to Reduce the Cost of Electrolytic H₂

Example: Cost Reduction of Clean Electrolytic H₂

- **2020**: ~ $5/kg
- **2025**: $2/kg
- **2030**: $1/kg

Key enablers for lower cost electrolytic H₂:
- Low-cost electricity, variable operation
- High electrical efficiency
- Low-cost capital expense
- Increased durability/lifetime
- Low-cost manufacturing processes
- Manufacturing at MW-scale
- Increased power density

**Electrolyzer goals for 2025**

<table>
<thead>
<tr>
<th>Goal</th>
<th>Unit</th>
<th>PEM</th>
<th>SOEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher electrical efficiency</td>
<td>% (LHV)</td>
<td>≥ 70</td>
<td>≥ 98</td>
</tr>
<tr>
<td>Lower stack costs</td>
<td>$/kW</td>
<td>≤ 100</td>
<td>≤ 100</td>
</tr>
<tr>
<td>Increased durability</td>
<td>hours</td>
<td>80,000</td>
<td>60,000</td>
</tr>
<tr>
<td>Lower system CAPEX</td>
<td>$/kW</td>
<td>≤ 250</td>
<td>≤ 300</td>
</tr>
</tbody>
</table>

PEM = polymer electrolyte membrane; SOEC = solid oxide electrolysis cell

https://www.hydrogen.energy.gov/pdfs/review21/plenary7_stetson_2021_o.pdf
A comprehensive, concerted effort focused on overcoming technical barriers to enable affordable, reliable and efficient electrolyzers to achieve <$2/kg H₂

- Launched Oct 2020
- PEM, SOEC, and liquid alkaline (new)
- FY21: $10M; FY22: $10M, FY23: $19.5-28M

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

Clear, well-defined stack metrics to guide efforts.

<table>
<thead>
<tr>
<th>Draft Electrolyzer Stack Goals by 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>LTE PEM</td>
</tr>
<tr>
<td>HTE</td>
</tr>
<tr>
<td>Capital Cost</td>
</tr>
<tr>
<td>$100/kW</td>
</tr>
<tr>
<td>$100/kW</td>
</tr>
<tr>
<td>Elect. Efficiency (LHV)</td>
</tr>
<tr>
<td>70% at 3 A/cm²</td>
</tr>
<tr>
<td>98% at 1.5 A/cm²</td>
</tr>
<tr>
<td>Lifetime</td>
</tr>
<tr>
<td>80,000 hr</td>
</tr>
<tr>
<td>60,000 hr</td>
</tr>
</tbody>
</table>

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.
Accelerating AWS Materials R&D to Enable <$2/kg H₂
- Leveraging & streamlining access to world-class capabilities & expertise
- Providing a robust, secure, searchable, & sharable Data Hub
- Developing universal standards & best practices for benchmarking & reporting
- Fostering cross-cutting innovation

HydroGEN 2.0 Focus Areas

LTE: Enable high efficiency, durable AEMWE without supporting electrolytes

HTE: Identify electronic leakage mechanisms in p-SOEC for higher cell performance at lower temperatures

STCH: Develop global understanding of material structure & composition required to achieve high yield performance

PEC: Scale-up & improved durability through corrosion mitigation & ~neutral pH operation

Innovative Consortia Model Connecting AWS Community and Enhancing R&D
- 5 Core Labs with >60 capabilities & expertise in electrolysis, PEC, & STCH
- Supported ~30 projects awarded through FOAs
- Aiding development of > 35 AWS test protocols
- Addressing R&D gaps through collaborative Lab-led research efforts

Key Technical Accomplishments
- Achieved high PGM-free (lower cost) AEME performance (< 1.75 V at 500 mA/cm²) and durability (<40 mV/kh)
- Achieved >90% Faradaic efficiency at 1 A/cm², 600°C, 70% steam for p-SOEC
- Achieved >100 hours stability with peak efficiency exceeding 20% solar to hydrogen efficiency for halide perovskite photoelectrodes (PEC)
- Developed high-throughput materials search strategy to identify STCH materials: identified ~200 promising new STCH compounds

Website: https://www.h2awsm.org/
BioH2 Consortium

**Overall Objective:** Develop a high-solids microbial fermentation technology to convert renewable lignocellulosic biomass resources into H₂ via strain engineering and integrate microbial electrolysis cell (MEC) to meet DOE H₂ production cost goal of < $2/kg-H₂
Goals of HyMARC are to:

• Discover new storage materials for both transportation and stationary hydrogen storage applications
• Double the energy density of compressed-hydrogen gas storage
• Provide foundational understanding to accelerate materials discovery
• Develop metrics for hydrogen carriers and match with applications
• Serve as a gateway to access National Lab facilities

HyMARC: Hydrogen Materials Advanced Research Consortium
Accelerating Hydrogen Storage Material Design, Development and Deployment

Advanced material & synthesis concepts
Foundational R&D
Computational models
Synthetic protocols
Advanced characterization tools
Validation of material performance
Guidance to FOA projects
Database development
TEA of long- and short- term hydrogen storage materials systems

https://www.hymarc.org/
M2FCT focuses on commercialization of fuel-cell trucks demand a greater focus on efficiency and significantly longer lifetimes, and 4 to 5x improvements in durability.
National Laboratory Collaboration is Critical for Success

Hydrogen Production

H₂NEW
U.S. DEPARTMENT OF ENERGY

Hydrogen from Next-generation Electrolyzers of Water

NREL
Transforming ENERGY

Berkeley Lab
Bringing Science Solutions to the World

INL
Idaho National Laboratory

Argonne National Laboratory

Los Alamos National Laboratory

Oak Ridge National Laboratory

Pacific Northwest National Laboratory

HydroGEN
Advanced Water Splitting Materials

Hydrogen Production

ACT
MILLION MILE FUEL CELL TRUCK
U.S. DEPARTMENT OF ENERGY

Hydrogen Storage

HyMARC
Management-Intensive R&D Concepts

NREL
Transforming ENERGY

Berkeley Lab
Bringing Science Solutions to the World

Sandia National Laboratories

NREL
Transforming ENERGY

Oak Ridge National Laboratory

Lawrence Livermore National Laboratory

Berkeley Lab
Bringing Science Solutions to the World

Los Alamos National Laboratory

Argonne National Laboratory

Fuel Cells
Powders-to-Power for Electrolysis (Fuel Cell shown below)

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

**Systems Integration**

**Systems-focus ANALYSIS-driven R&D**
NREL Current Electrolyzer Research/Validation Capability Summary: From kW to MW

**Single Cell 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**
- 1.25 PEM system at Flatirons
- System integration with ARIES platform
- BOP for 2 x 1.25 MW stacks
The Role of Large-Scale Validation and Demonstration

- Prior to investment, investors, utilities, and other stakeholders need to **de-risk H₂ 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 H2 System
ARIES Hydrogen System Integration

ARIES Advanced Research on Integrated Energy Systems
Upcoming ARIES Demonstration of Materials-based H₂ Storage Technology

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

2 X 260 kg H₂ = 520 kg storage
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 H₂ and waste CO₂ from dairies, landfills, wastewater treatment plants. RNG:

- Has an energy density ~3x that of H₂
- 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
Exciting new project jointly funded by DOE Wind and Hydrogen Offices: NREL (lead) + ANL, LBNL, ORNL, & SNL

Vision: GW-scale off-grid, purpose-built systems composed of wind/PV/storage tightly coupled electrolyzers (DC/DC), optimized for levelized cost of H2 (LCOH), co-located with steel/ammonia production facilities.

Novelty and Advantages:
• Optimized LCOH for the specific end use,
• Holistic approach, increased efficiency, & reduced capital costs,
• Independence from natural gas price volatility, grid connection permits and new large-scale transmission build outs.

Preparing plans for ~10MW NREL ARIES demonstration project. Show feasibility of 1GW HES → H2 → green steel/ammonia

Reduce risks and accelerate pathways to industrial decarbonization.
2020’s Decade of Hydrogen

Hydrogen Council

CLIMATE CH2AMPION: HYDROGEN IS THE MISSING PIECE OF THE ENERGY PUZZLE

HYDROGEN COST TO FALL SHARPLY AND SOONER THAN EXPECTED

HYDROGEN DEPLOYMENT ACCELERATING WITH MORE THAN $300 BILLION IN PROJECT PIPELINE

Potential Impacts from Hydrogen Council Roadmap Study. By 2050:

- $2.5 trillion in global revenues
- 30 million jobs
- 400 million cars, 15-20 million trucks
- 18% of total global energy demand

Now is the time for hydrogen and the “global race” is on

https://hydrogencouncil.com/en/
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).

Ned Stetson  Katie Randolph  David Peterson  James Vickers  William Gibbons  Eric Miller
Thank You

www.nrel.gov

Huyen.dinh@nrel.gov

NREL/PR-5900-85768

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. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.