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

Hydrogen Energy Earthshot

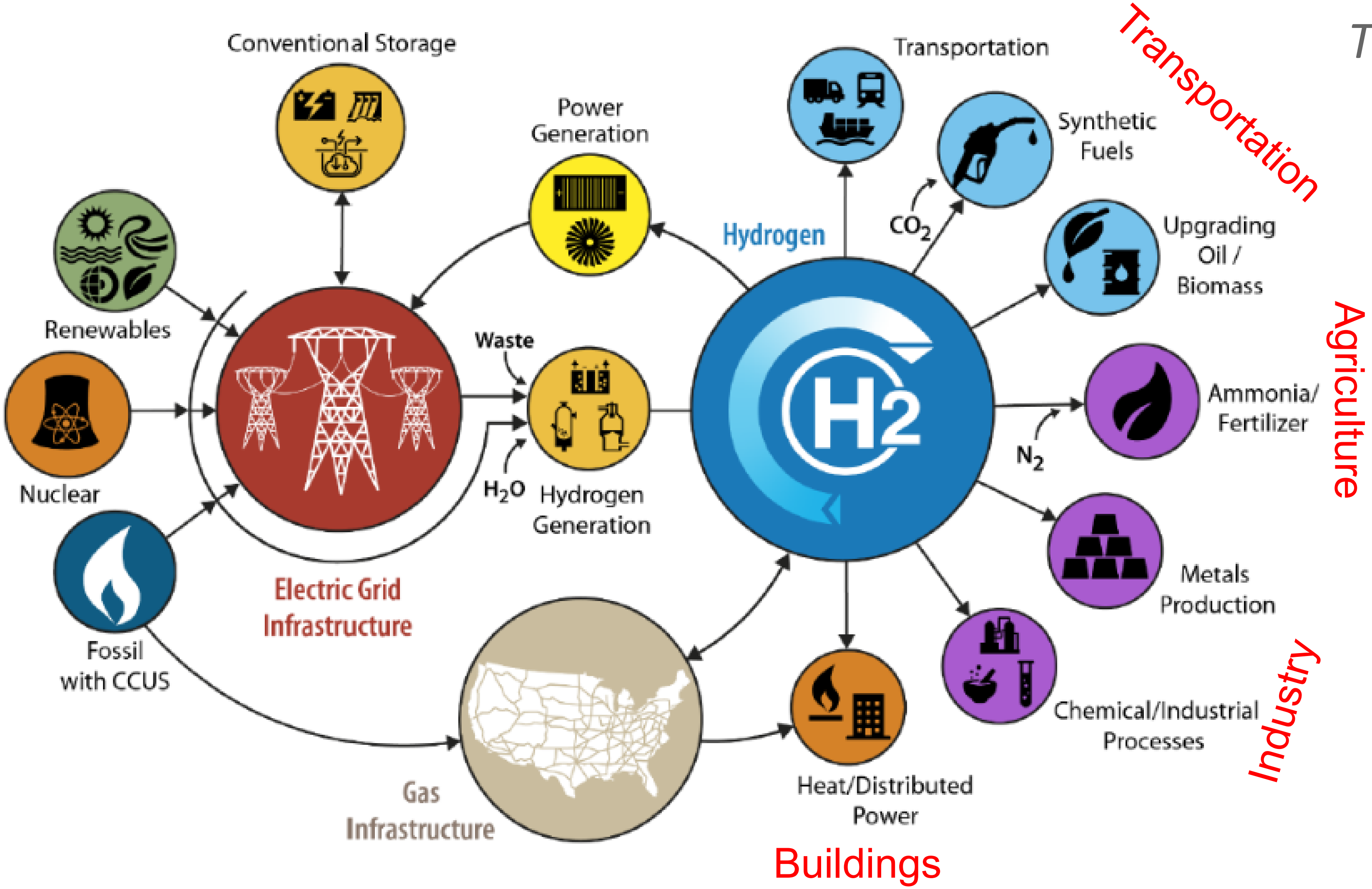
"Hydrogen Shot"

"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

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



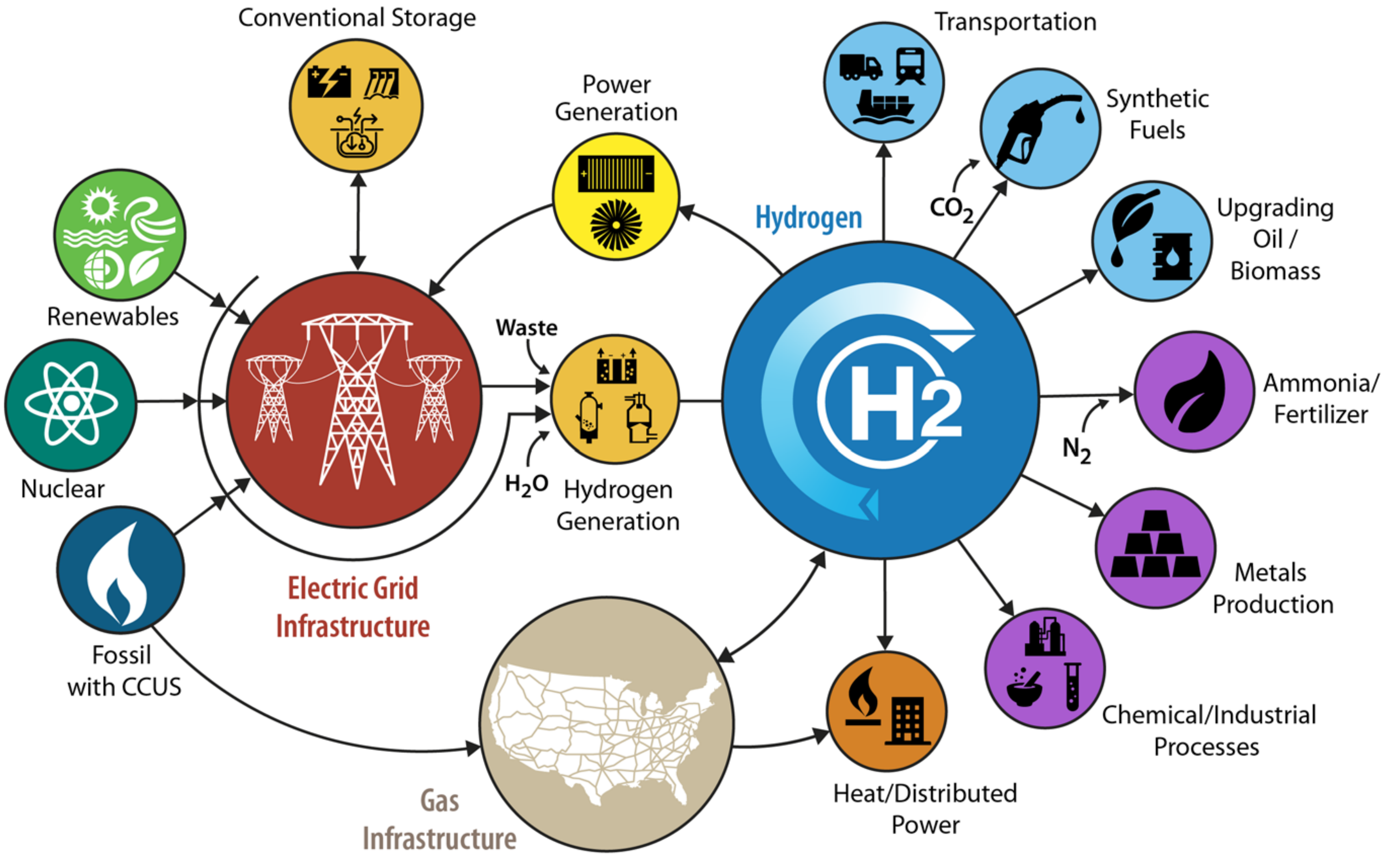
Illustrative example, not comprehensive
https://www.energy.gov/eere/fuelcells/h2-scale

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

Timeframe is short, competition intense, coordinated effort critical for domestic competitiveness.

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

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

3 Key Strategies of the DOE Clean H_2 Strategy & Roadmap

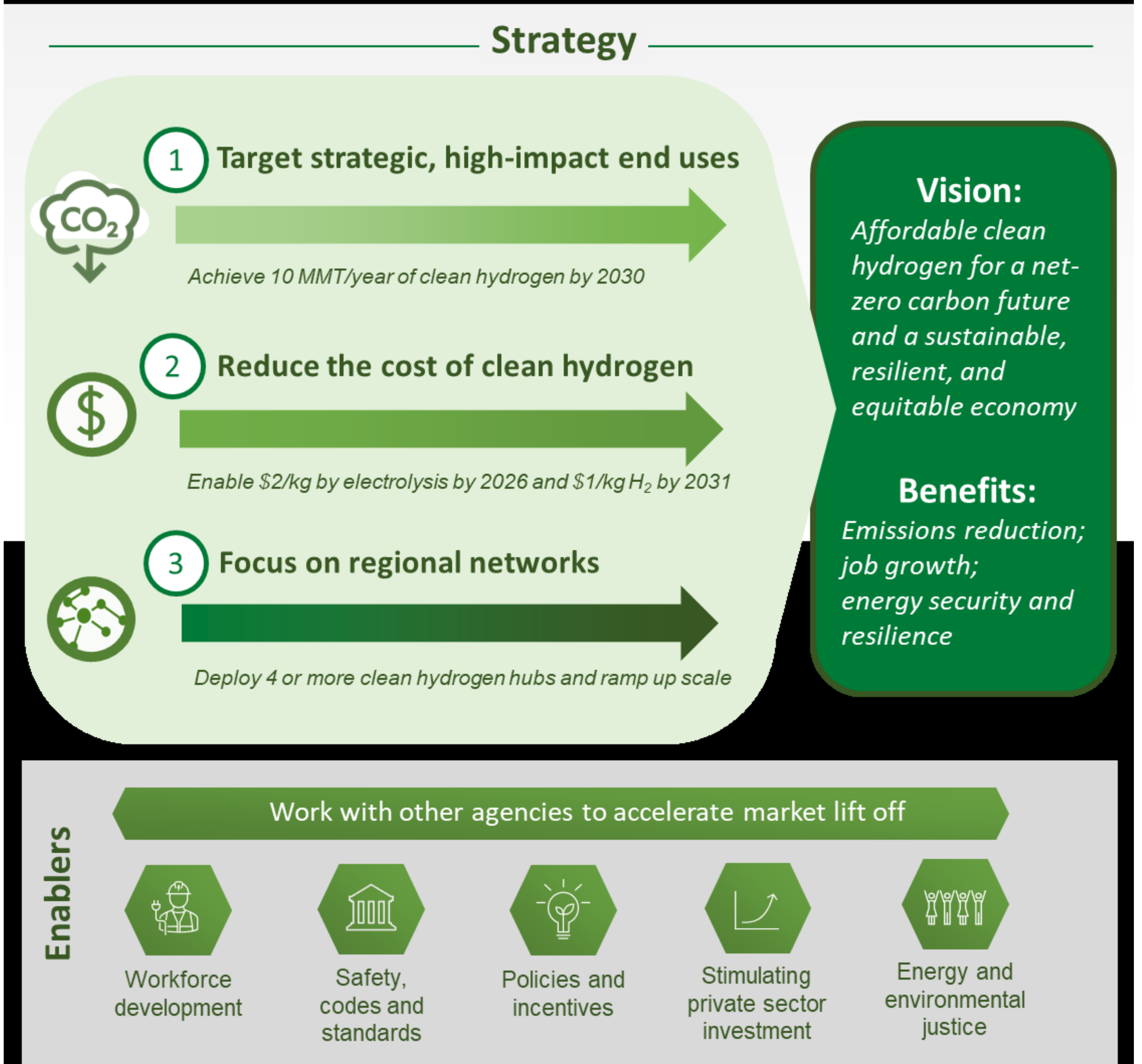


Figure 16 The national strategies for clean hydrogen and the Department of Energy's Hydrogen Program mission and context

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

Willingness to pay for clean hydrogen

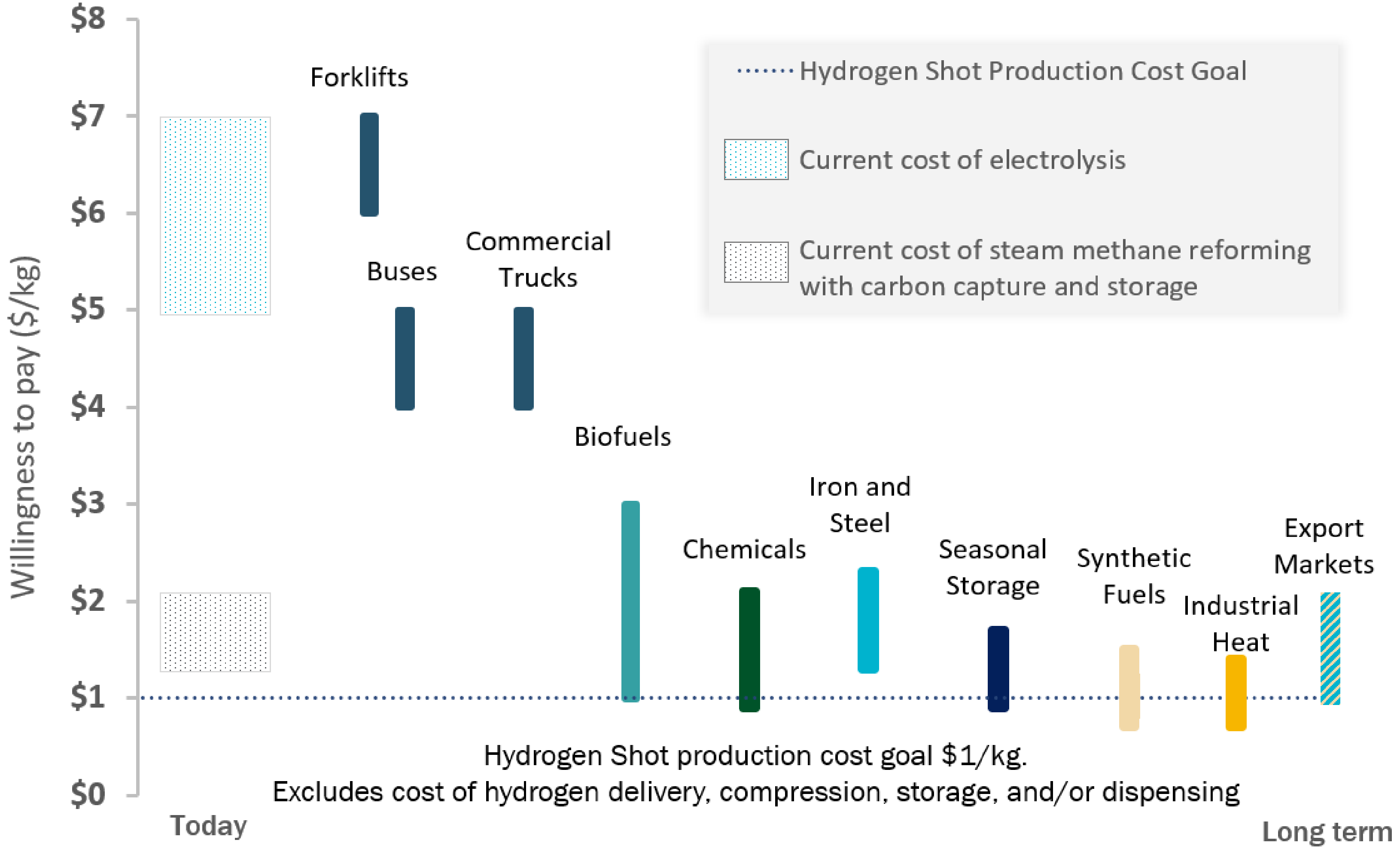


Figure 10: Willingness to pay, or threshold price, for clean hydrogen in several current and emerging sectors (including production, delivery, and conditioning onsite, such as additional compression, storage, cooling, and/or dispensing).

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

Potential of Clean H_2 Demand in Key Sectors

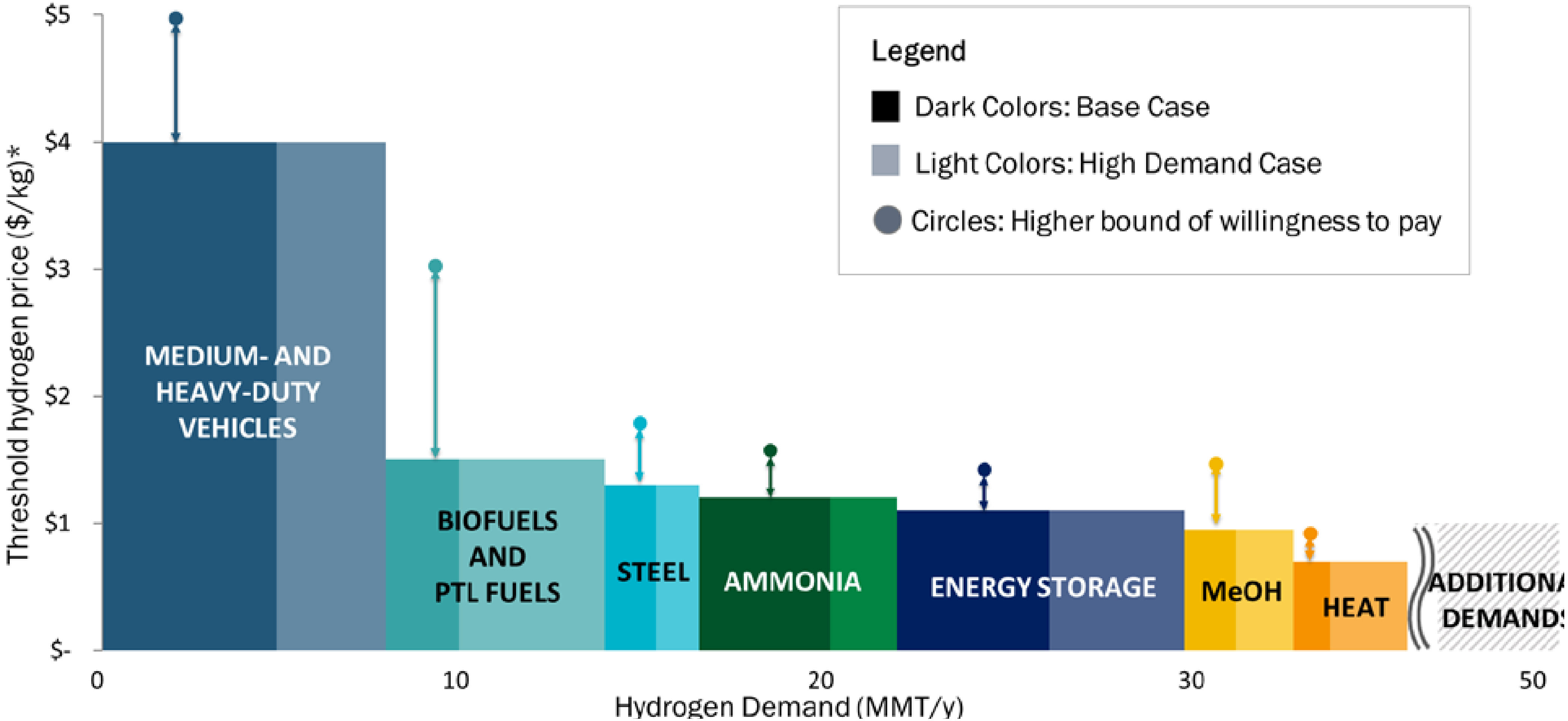
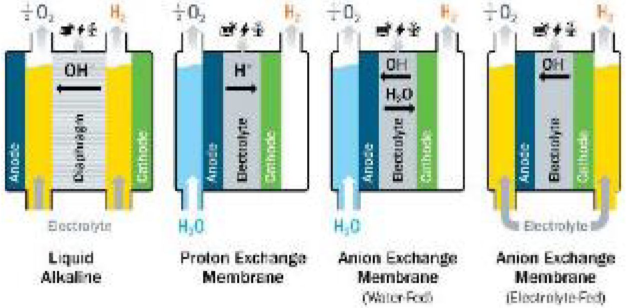


Figure 11: Scenarios showing estimates of potential clean hydrogen demand in key sectors of transportation, industry, and the grid, assuming hydrogen is available at the corresponding threshold cost.

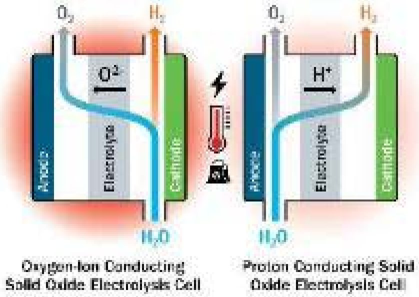
U.S. D.O.E National Clean Hydrogen Strategy and Roadmap Draft (September 2022)

R&D on Advanced Production Technologies

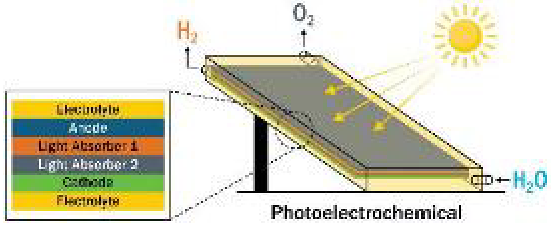
- **Near-term:** focus on electrolysis (water splitting with electricity and nuclear)
  - Accelerate **research on advanced water-splitting** technologies – take advantage of today’s renewable and nuclear power
  - Achieve $100/kW electrolyzer stack goal in just 5 years through **H2NEW** consortium
  - 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) H_2 production
  - Incubate and support promising technology development through **HydroGEN** consortium



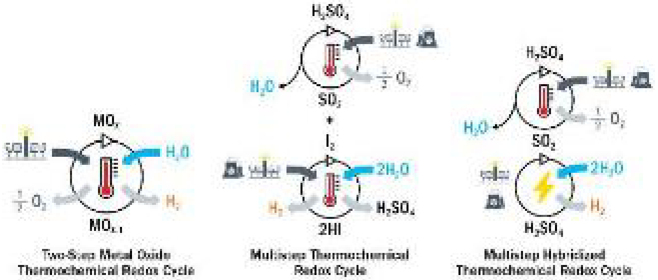
LTE



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.***

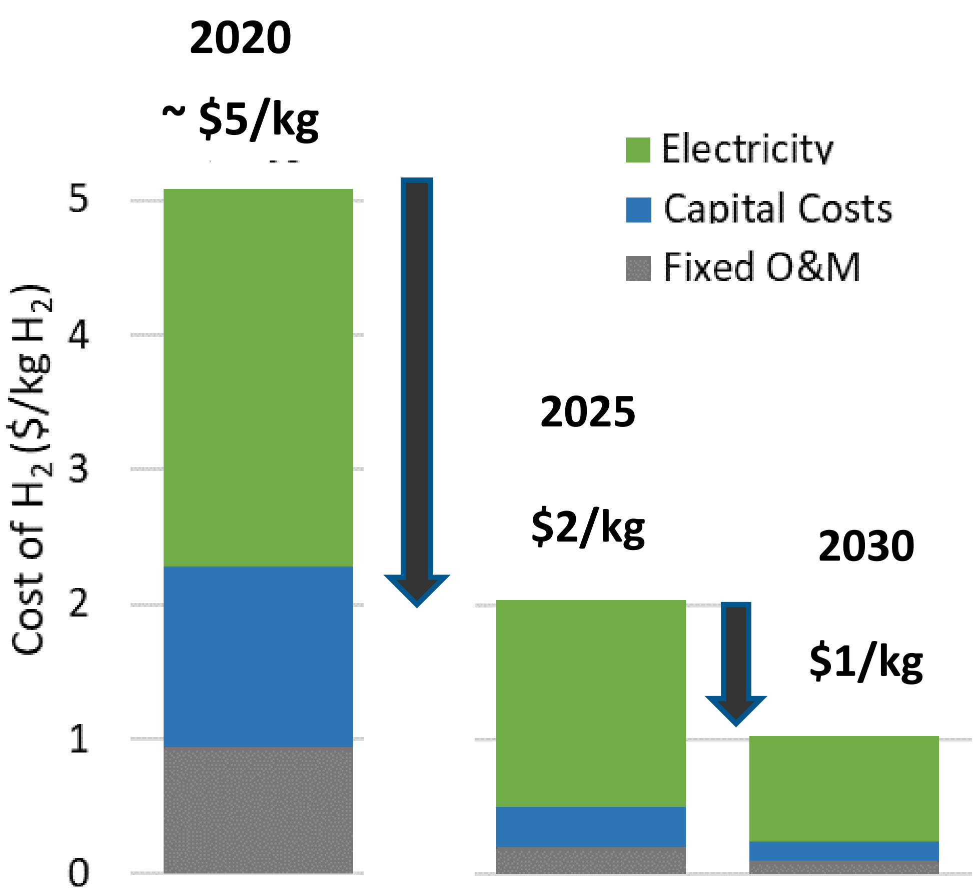
Hydrogen Shot: "1 1 1"

$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

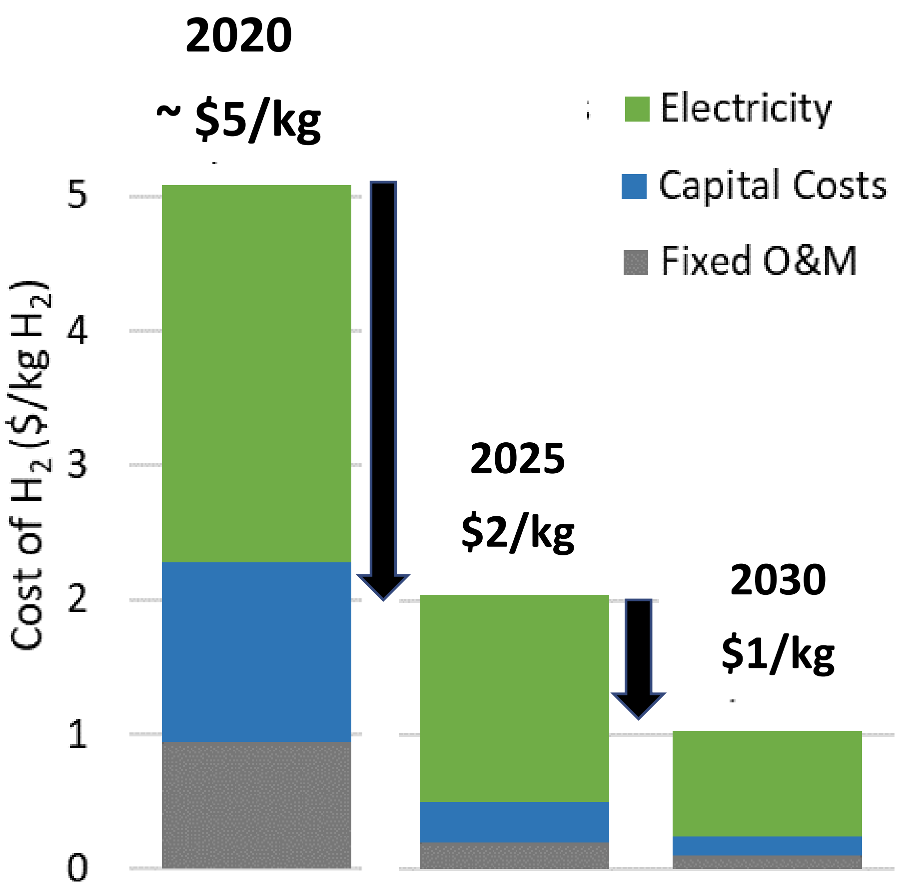
- Reduce electricity cost from >$50/MWh to
  - $30/MWh (2025)
  - $20/MWh (2030)
- Reduce capital cost >80%
- Reduce operating & maintenance (O&M)cost >90%

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)

Pathways to Reduce the Cost of Electrolytic H_2

Example: Cost Reduction of Clean Electrolytic H_2



Key enablers for lower cost electrolytic H_2:

- **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	Unit	PEM	SOEC
Higher electrical efficiency	% (LHV)	≥ 70	≥ 98
Lower stack costs	$/kW	≤ 100	≤ 100
Increased durability	hours	80,000	60,000
Lower system CAPEX	$/kW	≤ 250	≤ 300

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

https://www.hydrogen.energy.gov/pdfs/review21/plenary7_stetson_2021_o.pdf

H2NEW : H2 from Next-generation Electrolyzers of Water

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

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

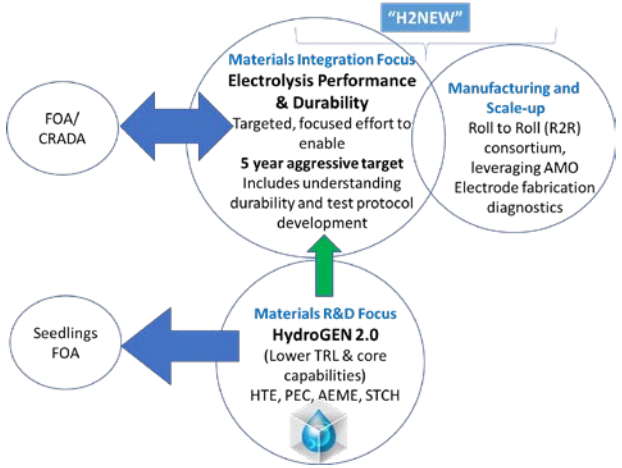
National Lab Consortium Team

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; National Energy Technology Laboratory

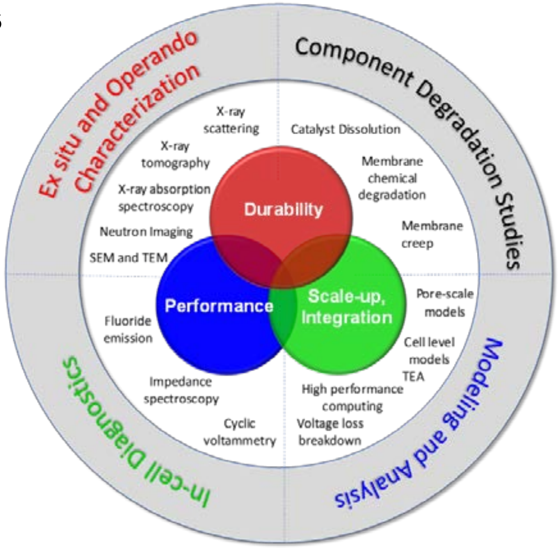
Clear, well-defined stack metrics to guide efforts.

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

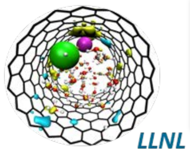
HydroGEN Advanced Water Splitting (AWS) Materials Consortium

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

Accelerating AWS Materials R&D to Enable <$2/kg H_2

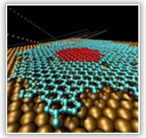
- Leveraging & streamlining access to world-class capabilities & expertise
- Providing a robust, secure, searchable, & sharable Data Hub
- Developing universal standards & best practices for benchmarking & reporting
- Fostering cross-cutting innovation

Theory & Computation



LLNL

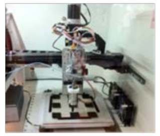
Bulk & interfacial models of aqueous electrolytes



SNL

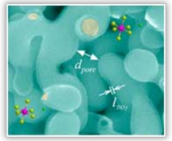
LAMMPS classic molecular dynamics modeling

Materials Synthesis



NREL

High-throughput spray for electrode fabrication



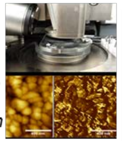
LLNL

Conformal ultrathin TiO_2 ALD coating on bulk nanoporous Au

Characterization & Analytics

LBNL

Atomic force microscopy: in-situ & operando material characterization



INL

TAP reactor: extracting quantitative kinetic data

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

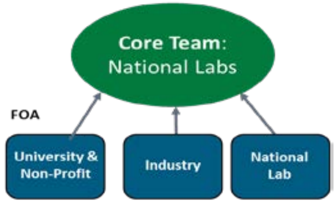
HydroGEN 2.0 Focus Areas

LTE: Enable high efficiency, durable AEMWE without supporting electrolytes

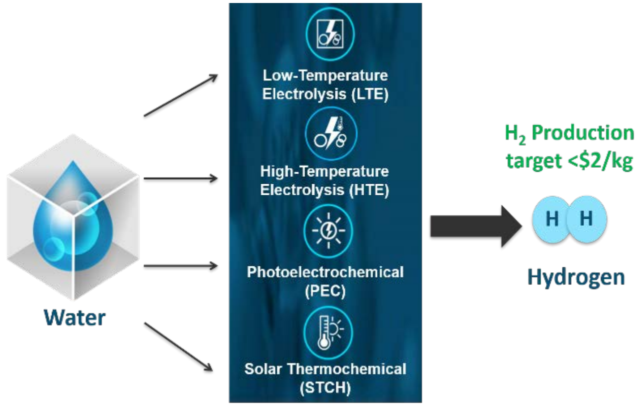
HTE: Identify electronic leakage mechanisms in p-SOEC for higher cell performance at lower temperatures

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



11 National Labs
10 Companies
39 Universities
2 Funding Agencies

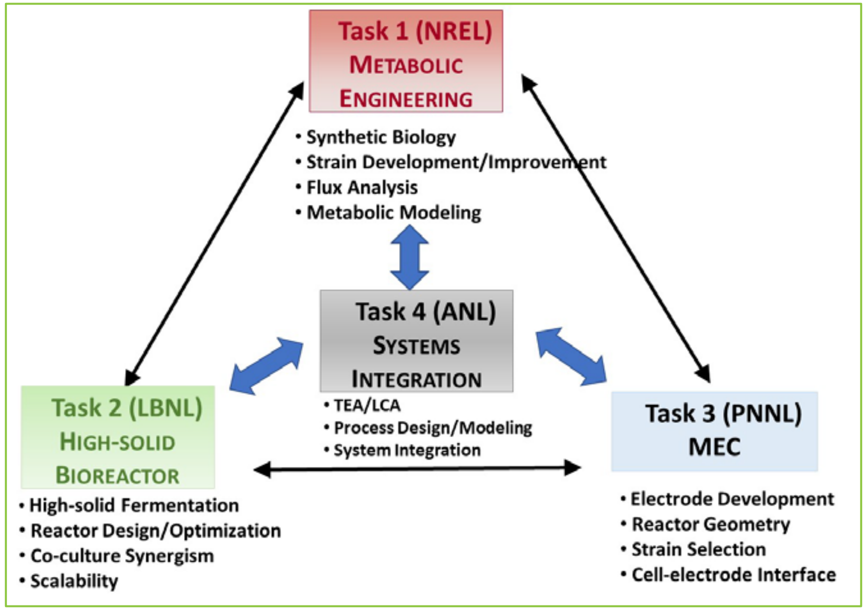


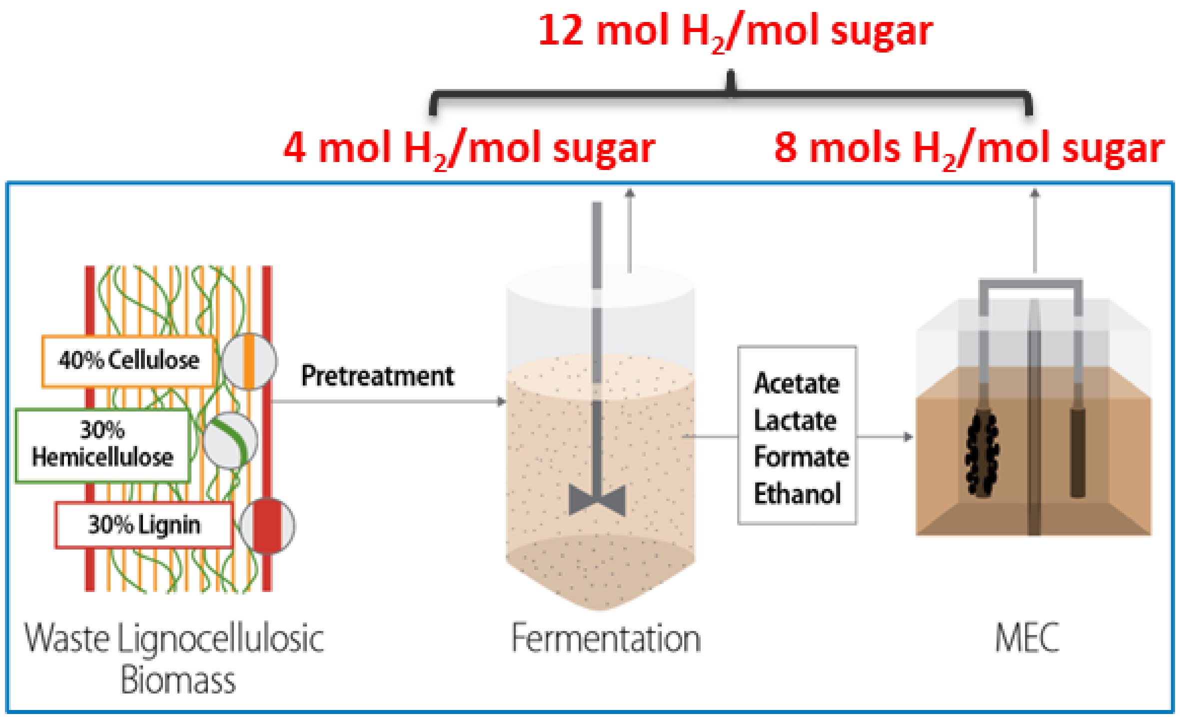
Key Technical Accomplishments

- Achieved high PGM-free (lower cost) AEME performance (< 1.75 V at 500 mA/cm^2) and durability (<40 mV/kh)
- Achieved >90% Faradaic efficiency at 1 A/cm^2, 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

BioH2 Consortium

Overall Objective: Develop a high-solids microbial fermentation technology to convert renewable lignocellulosic biomass resources into H_2 via strain engineering and integrate microbial electrolysis cell (MEC) to meet DOE H_2 production cost goal of < $2/kg-$H_2$



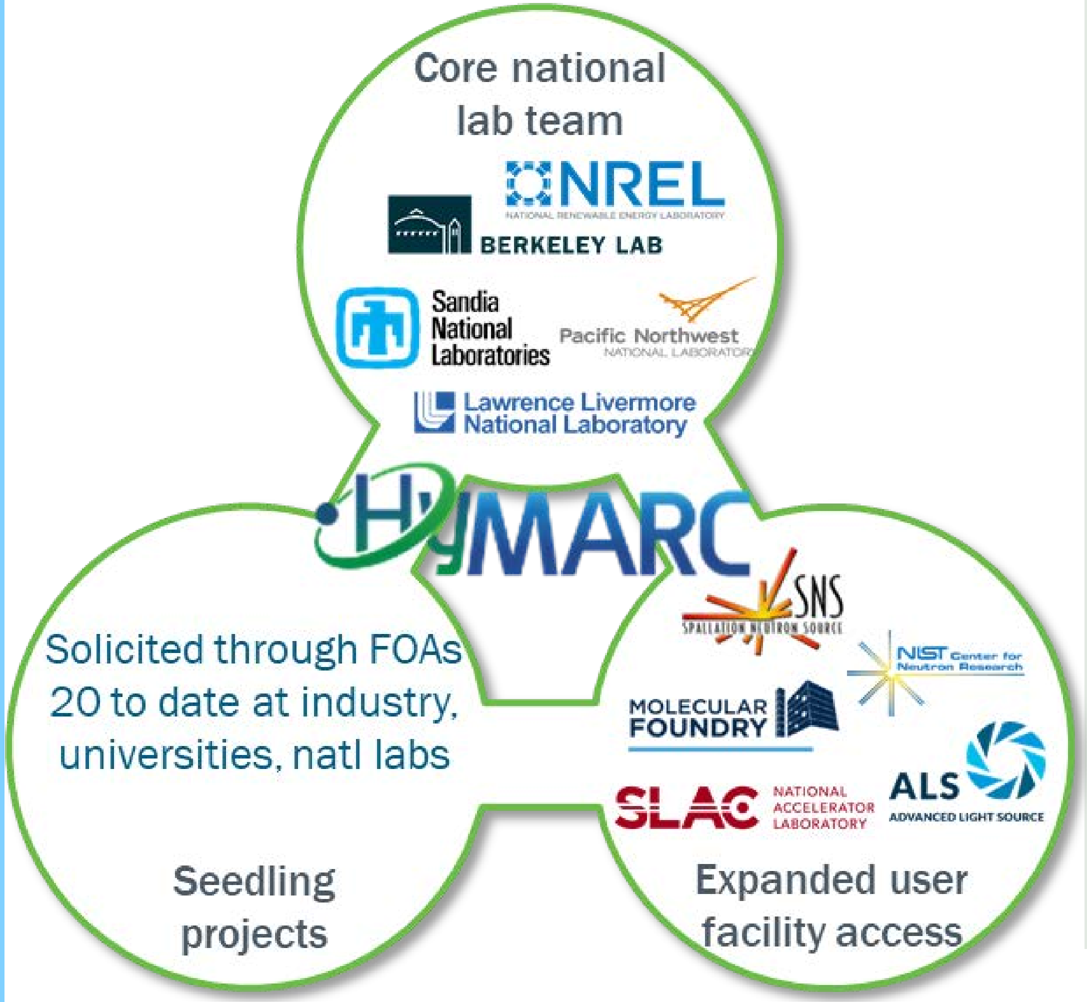


HyMARC: Hydrogen Materials Advanced Research Consortium

Accelerating Hydrogen Storage Material Design, Development and Deployment

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



- **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/

MILLION MILE
FUEL CELL TRUCK

U.S. DEPARTMENT OF ENERGY

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.

Main Laboratories

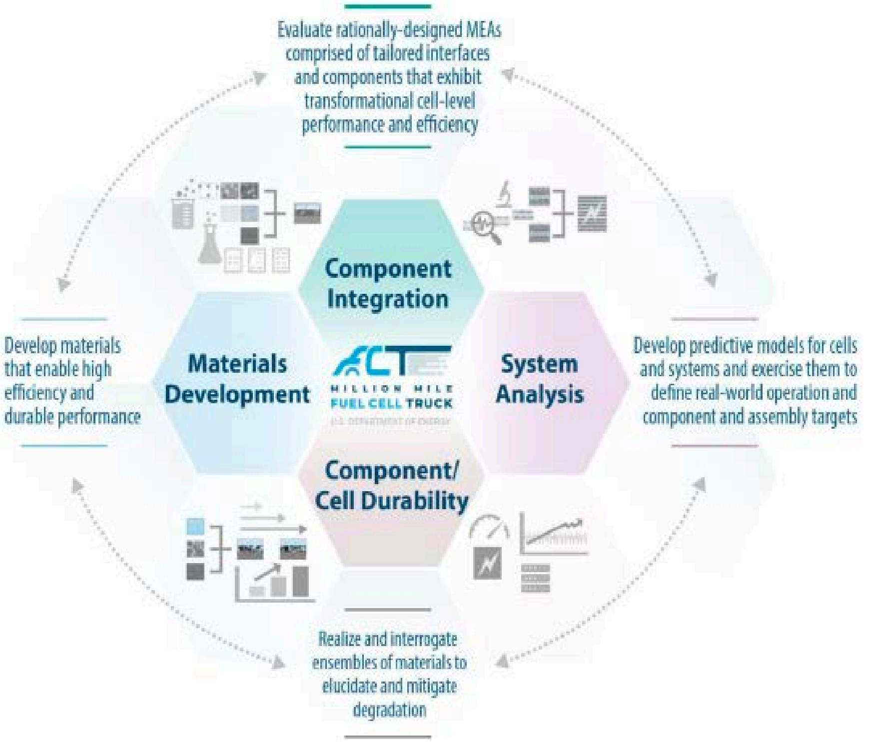
Los Alamos National Laboratory
Berkeley Lab
Argonne National Laboratory
Oak Ridge National Laboratory
NREL

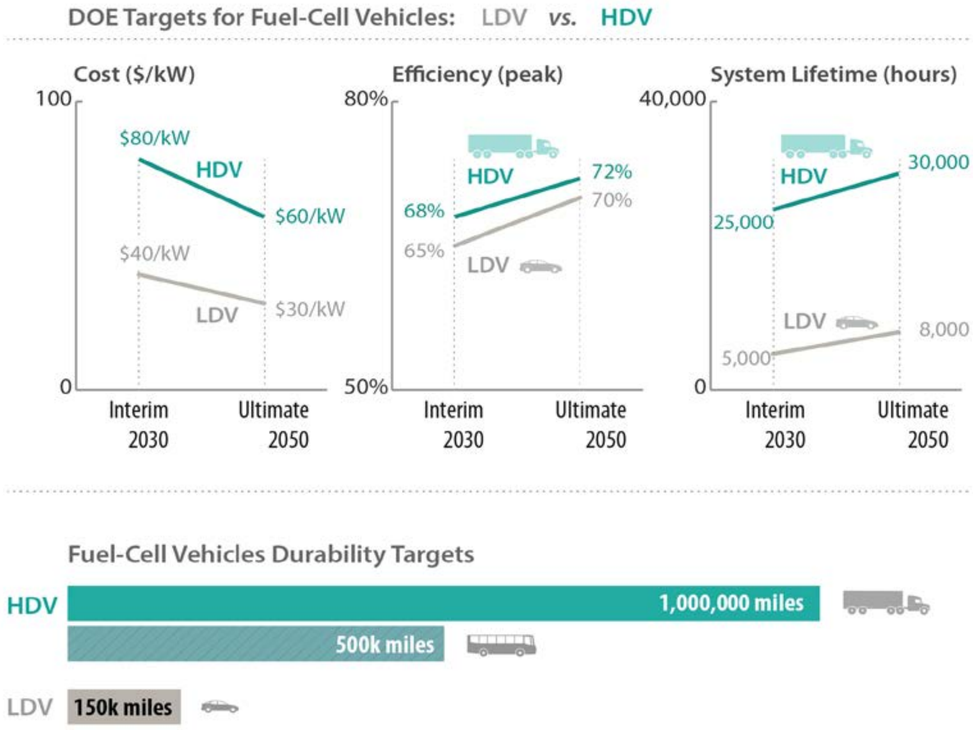
M2FCT Approach

Million Mile Fuel Cell Truck (M2FCT) aims to tackle challenges through a "team-of-teams" approach featuring main teams in analysis, durability, integration, materials development.

By coming together as sets of dynamic teams, the integrated consortium will provide rapid feedback, idea development, and information exchange, resulting in an effort that is more than the sum of its parts.

Approach





Sources:
Notes:
Current target of $50/kW for LDV is based on 100,000 units/year. HDV Targets are for Class 8 Tractor-Trailers.
Ultimate targets are based on simple cost of ownership assumptions and reflects anticipated timeframe for market penetration.

National Laboratory Collaboration is Critical for Success

Hydrogen Production

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

- 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
- National Energy Technology Laboratory
- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

Hydrogen Storage

HyMARC — Hydrogen Materials Advanced Research Consortium

- Sandia National Laboratories
- NREL — Transforming ENERGY
- Pacific Northwest National Laboratory
- Lawrence Livermore National Laboratory
- Berkeley Lab — Bringing Science Solutions to the World

Hydrogen Production

HydroGEN — Advanced Water Splitting Materials

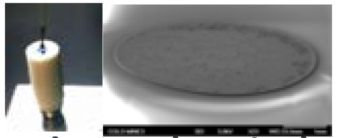
- NREL — Transforming ENERGY
- Berkeley Lab — Bringing Science Solutions to the World
- Sandia National Laboratories
- Lawrence Livermore National Laboratory
- INL — Idaho National Laboratory

Fuel Cells

M2FCT — Million Mile Fuel Cell Truck
U.S. DEPARTMENT OF ENERGY

- Berkeley Lab — Bringing Science Solutions to the World
- Los Alamos National Laboratory — EST. 1943
- Argonne National Laboratory
- NREL — Transforming ENERGY
- Oak Ridge National Laboratory

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



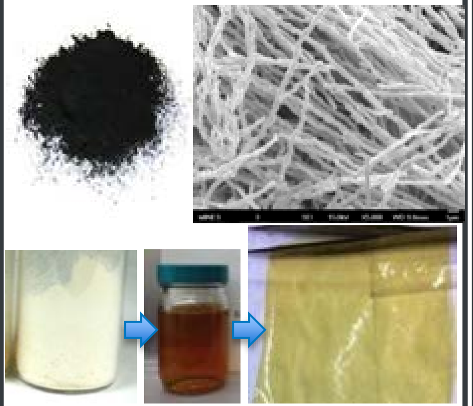
Electrochemical Characterization:
RDE & RRDE stations for Mass & Specific Activity, ECA, ORR; EQCMB, Seiras

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

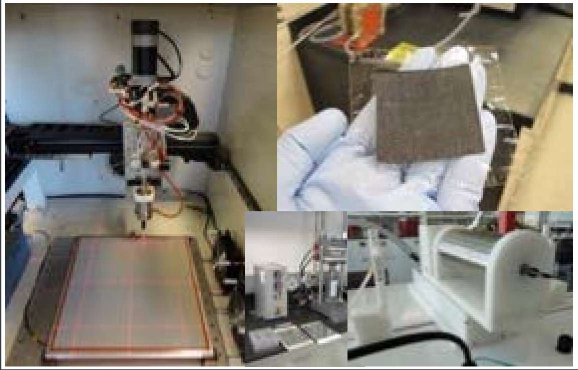
Manufacturing Lab
QC Diagnostic Development, Areal characterization, Roll-to-roll demonstration

Powders → Power

Material Synthesis:
Catalyst & Membrane Development



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



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

Systems Integration

Systems-focus ANALYSIS-driven R&D

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

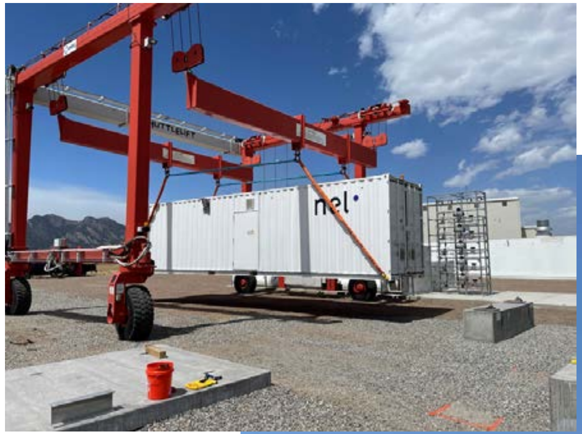
Full Stack

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

System

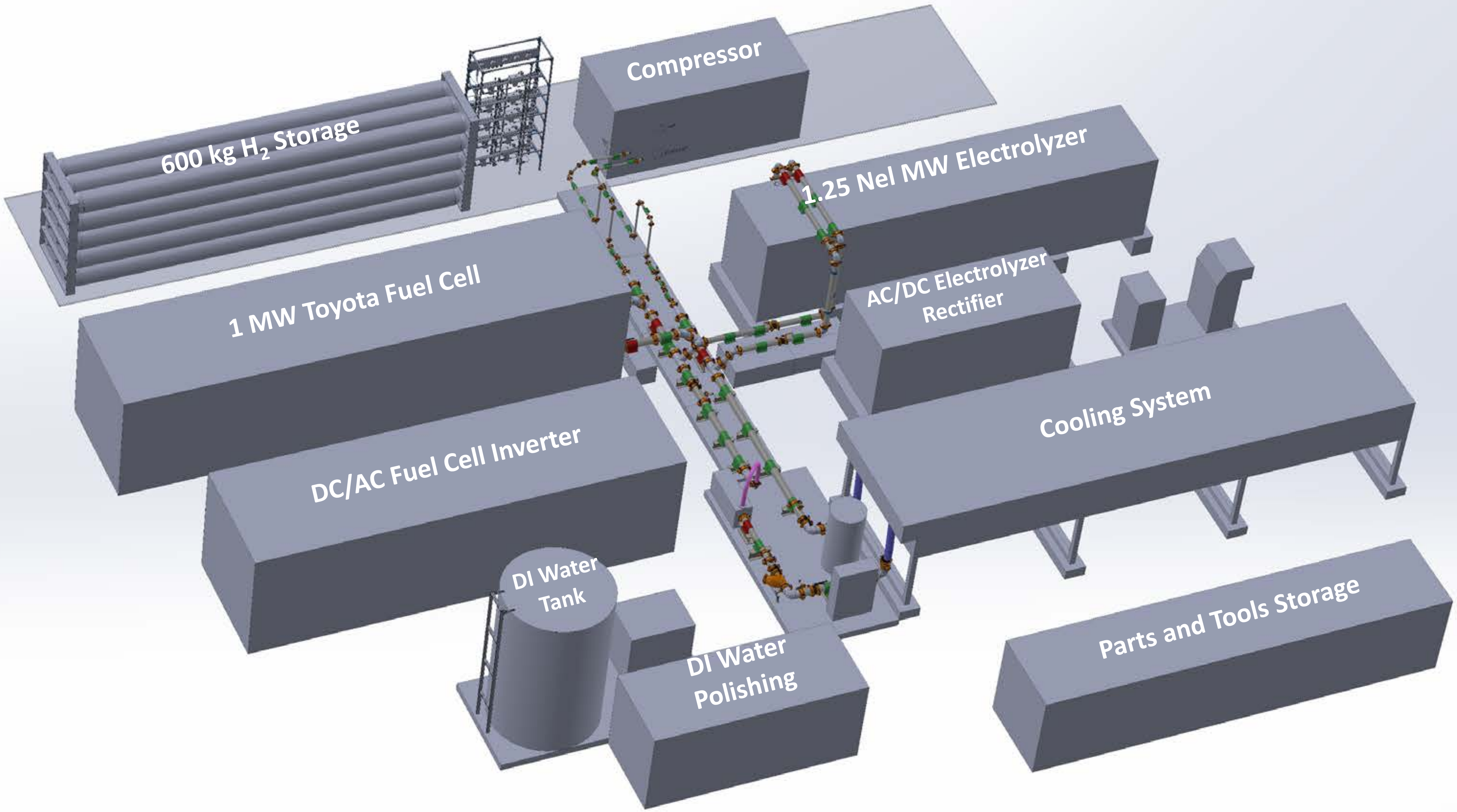
- 1.25 PEM system at Flatirons
- System integration with ARIES platform
- BOP for 2 x 1.25 MW stacks

The Role of Large-Scale Validation and Demonstration



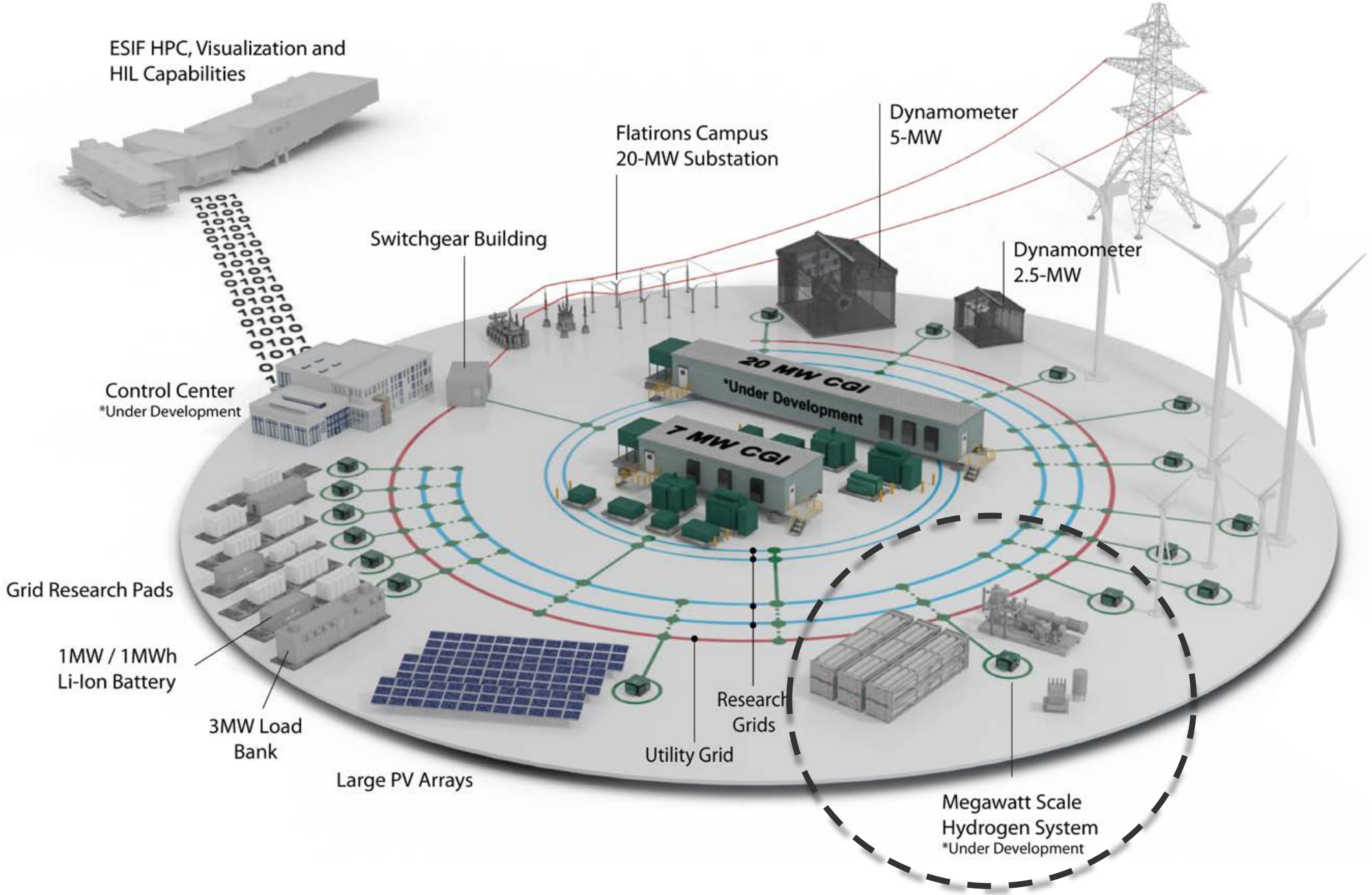
- Prior to investment, investors, utilities, and other stakeholders need to **de-risk H_2 systems** through operating in real-life industrial environments
- Large-scale deployments (~100MW) need to be **de-risked** through smaller scale validation (1-5MW) with analysis to extrapolate to larger systems
- NREL's **Flatirons Campus** has this capability

3D Layout of Flatirons Campus Hydrogen System

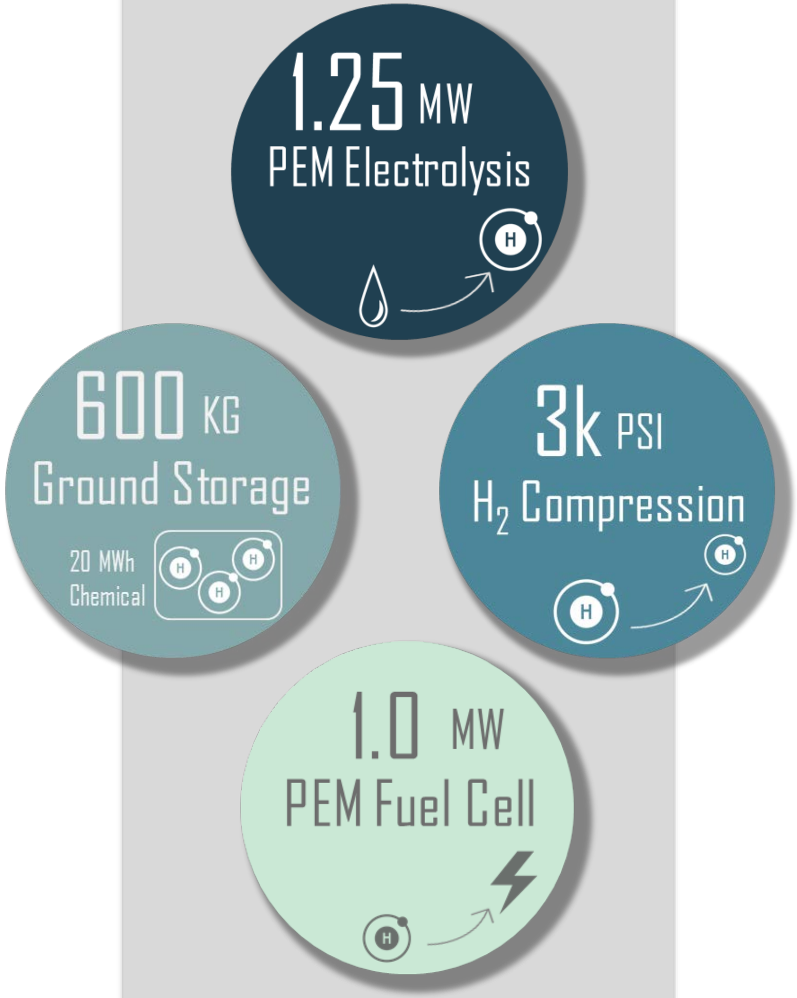


Recent View of Flatirons Campus H2 System

ARIES Hydrogen System Integration



Integrated Megawatt Scale Hydrogen System



ARIES Advanced Research on Integrated Energy Systems

Upcoming ARIES Demonstration of Materials-based H_2 Storage Technology

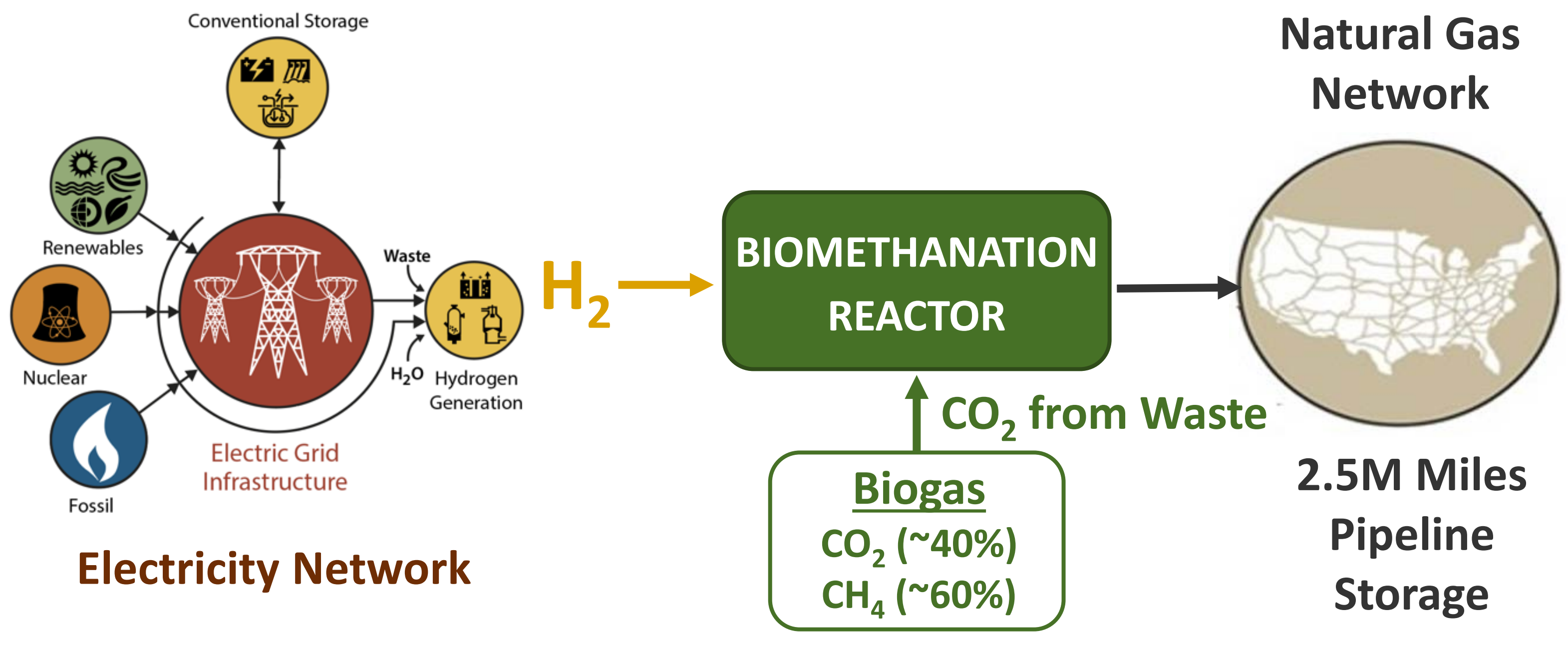
2 X 260 kg H_2 = 520 kg storage

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



Example of Where We're Going in H2 Systems Research: Hybrid Renewable Energy → H_2 → Green Steel / Ammonia

Exciting *new* project jointly funded by DOE Wind and Hydrogen Offices: NREL (lead) + ANL, LBNL, ORNL, & SNL

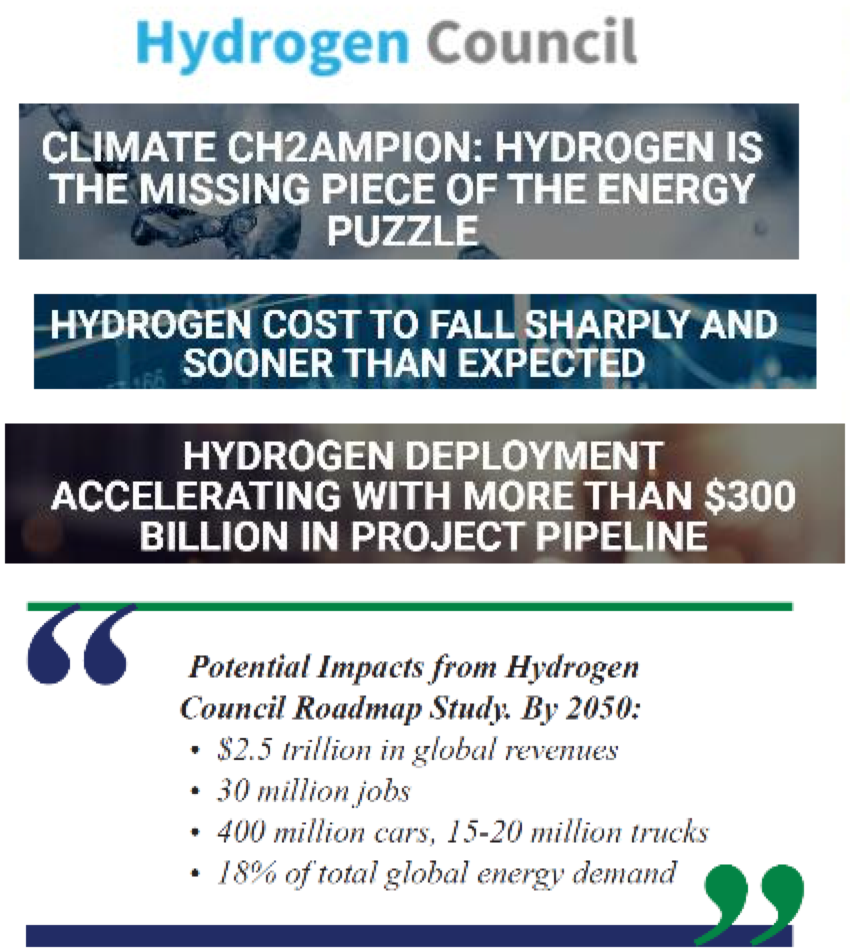
Vision: GW-scale off-grid, purpose-built systems composed of wind/PV/storage tightly coupled electrolyzers (DC/DC), optimized for levelized cost of H2 (LCOH), co-located with steel/ammonia production facilities.

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.

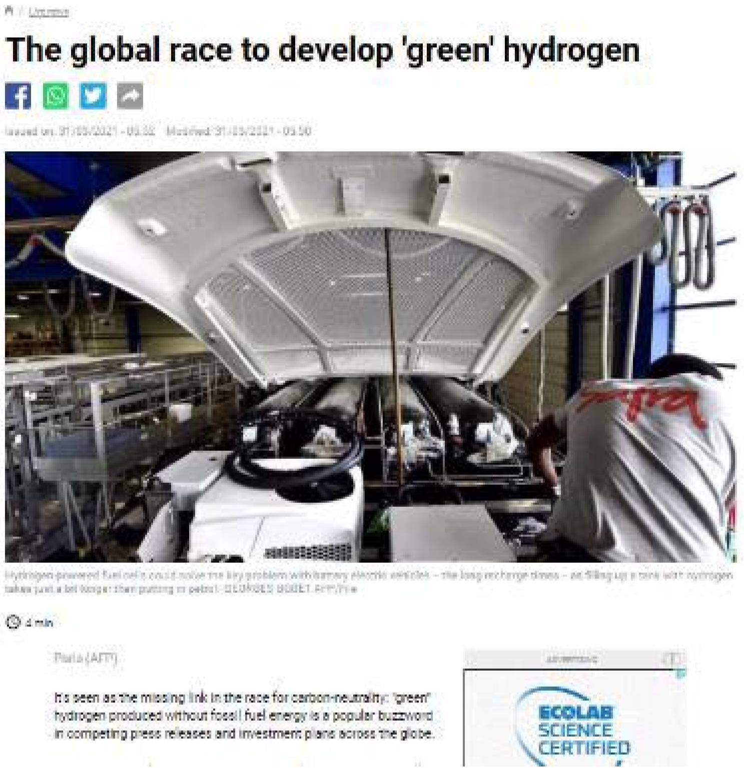
Preparing plans for **~10MW NREL ARIES demonstration** project.
Show **feasibility of 1GW** HES → H2 → green steel/ammonia

Reduce risks and accelerate pathways to industrial decarbonization.

2020's Decade of Hydrogen



https://hydrogencouncil.com/en/



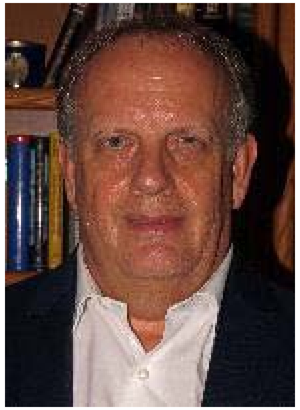
https://www.france24.com/en/live-news/20210331-the-global-race-to-develop-green-hydrogen

https://www.bloomberg.com/news/articles/2021-03-02/hydrogen-is-jump-ball-in-global-clean-energy-race-kerry-says

Now is the time for hydrogen and the "global race" is on

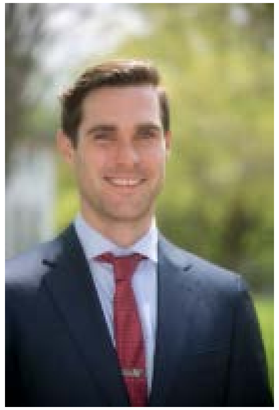
Acknowledgements

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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Thank You

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