Overview of Clean Hydrogen Program at NREL

Huyen N. Dinh (She/Her/Hers)
Director of HydroGEN, NREL

45 Years of NREL Virtual Event,
Organized by Wiley Advanced Energy Materials
June 26, 2023


NREL
Transforming ENERGY

Biden Administration Energy Goals

2035

Carbon-free U.S. electricity generation

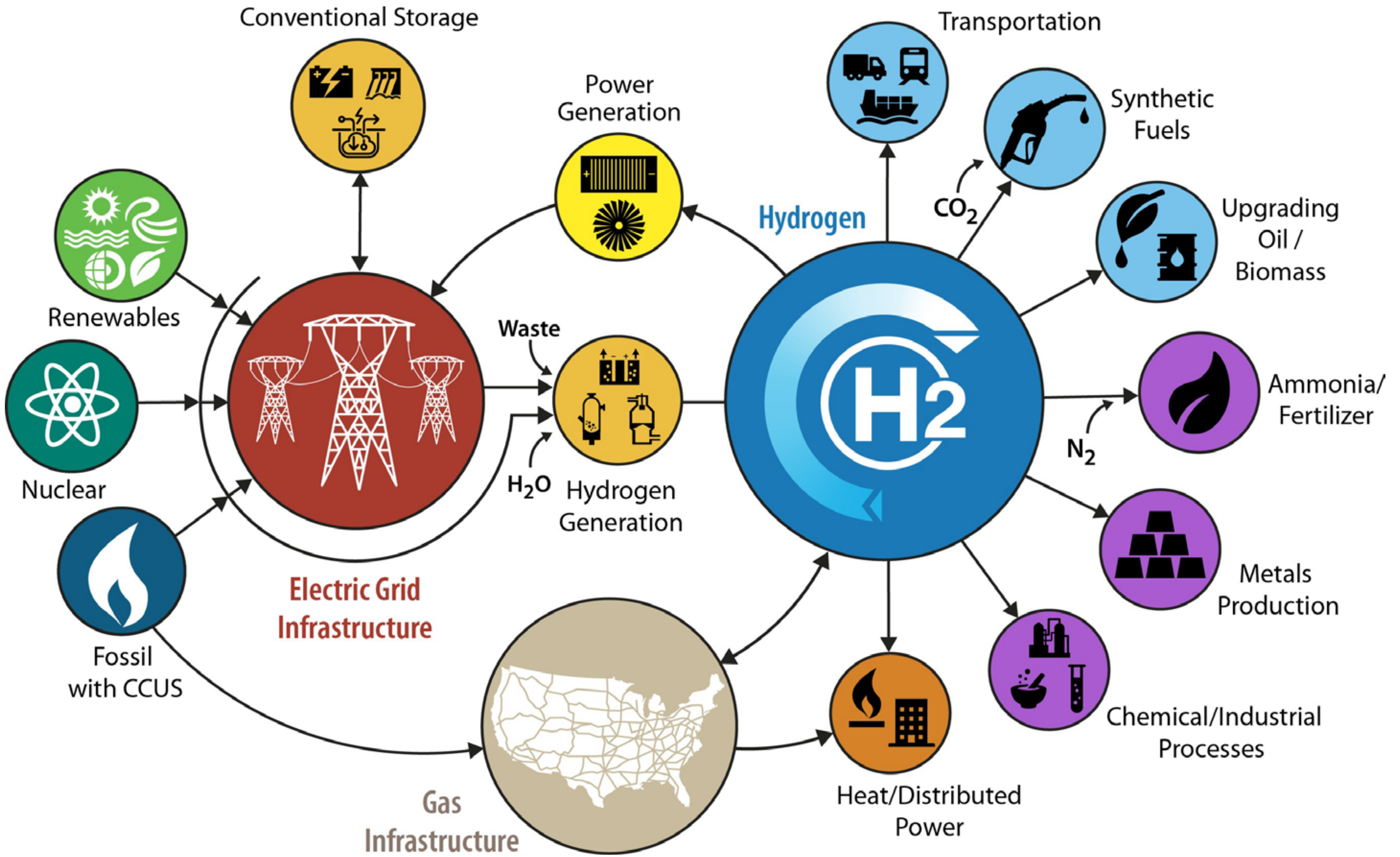
2050

Net zero greenhouse gas (GHG) emissions—including transportation, buildings, industry, and agriculture

Environmental Justice

Diversity, equity, and inclusion for energy jobs, manufacturing, and supply chain all over the United States

H2@Scale: Our Vision and Enduring North Star



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

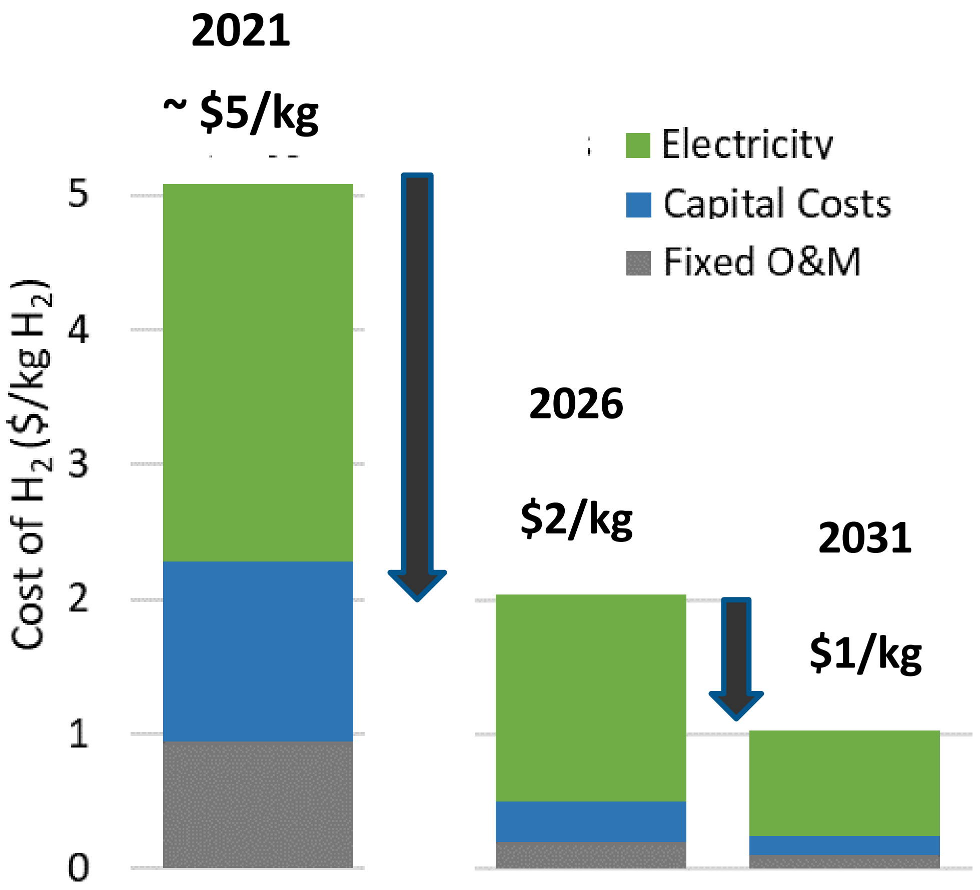
Context: Hydrogen Shot: "1 1 1"

$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 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 cost >90%

Bipartisan Infrastructure Law – $9.5B H2 Highlights

- **$8B** for at least 6-10 regional clean H2 Hubs
- **$1B** for electrolysis (and related H2) RD&D
- **$0.5B** for clean H2 technology mfg. & recycling R&D
- Aligns with H2 Shot priorities by directing work to reduce cost of clean H2 to $2/kg by 2026
- National H2 Strategy & Roadmap

Inflation Reduction Act

- Up to **$3/kg H2** Production Tax Credit for producing clean hydrogen (<0.45 kg CO2eq/kg H2)

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)

NREL Research Spans MAKE/MOVE/STORE/USE

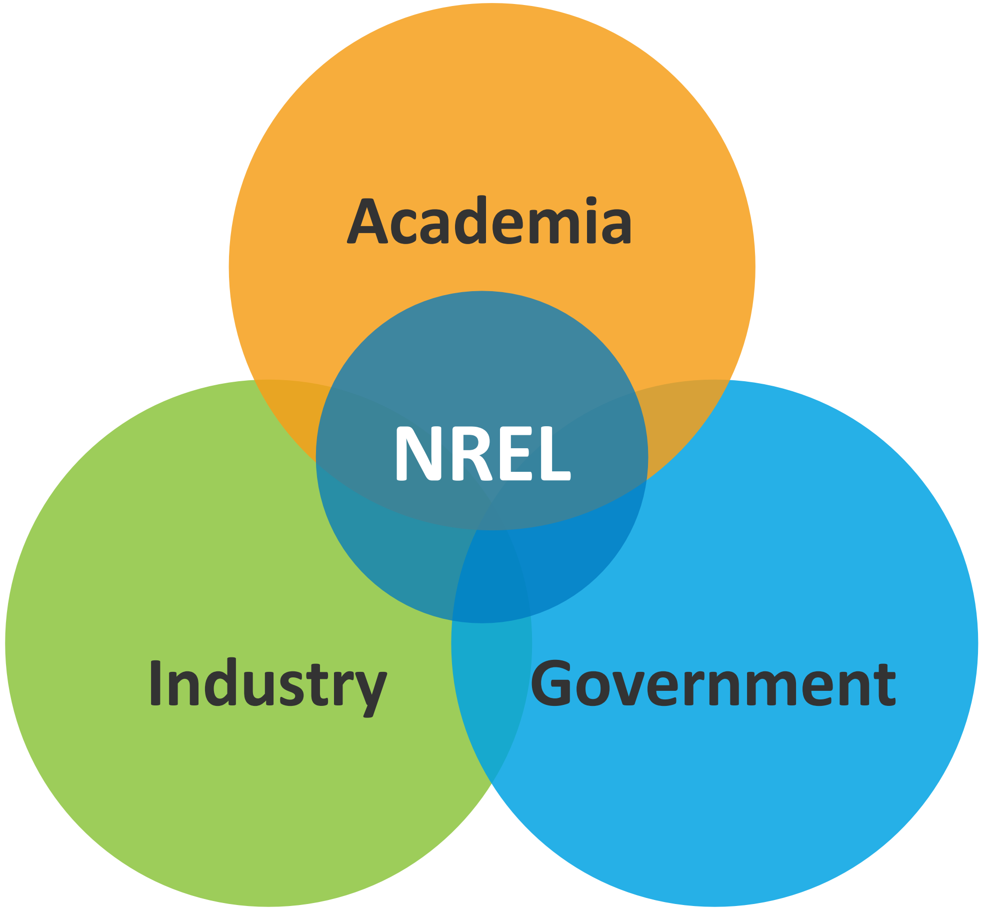
Make	Move	Store	Use
R&D on Advanced Production Technologies	Infrastructure Research & Large Scale Demonstration and Deployment	Hydrogen Storage Materials and Systems Research	Hydrogen Penetration into Heavy-Duty Transportation Sector Expanding Green Hydrogen Into New End-Use Cases

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

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

Partnerships Key for Larger Impact

- **Funding doubled** from FY20 to FY 21
- **35 new** strategic partnership projects in FY22
- **$23.7M total value** ($7.4M cash to NREL)



Recent NREL Agreements in the News

- September 2022: Fortescue Future Industries, $80M over 10 years
- October 2021: Electric Hydrogen, $3.6M over 3 years

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
- National Energy Technology Laboratory (NETL)
- 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

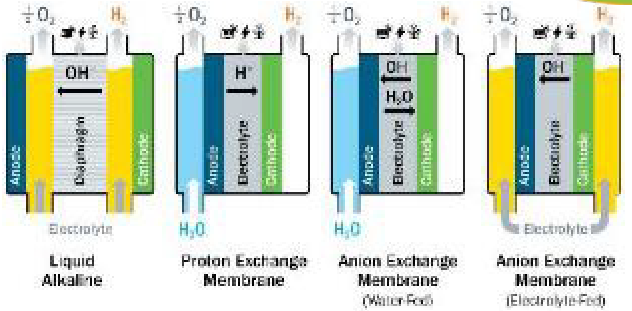
Fuel Cells

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

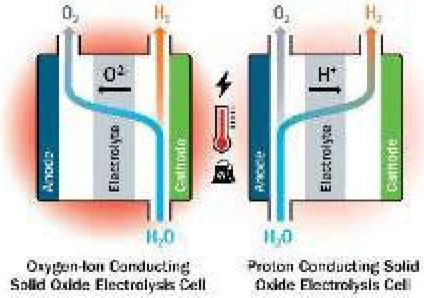
R&D on Advanced Production Technologies

R&D on Advanced Production Technologies

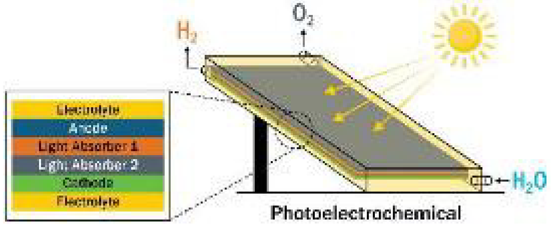
- **Near-term:** focus on electrolysis (water splitting with electricity and nuclear)
  - Accelerate **research on advanced water-splitting** technologies – take advantage of today's renewable and nuclear power
  - Achieve $100/kW electrolyzer stack goal in just 5 years through **H2NEW** consortium
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



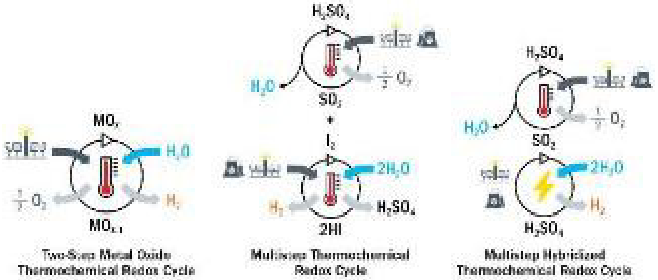
LTE



HTE



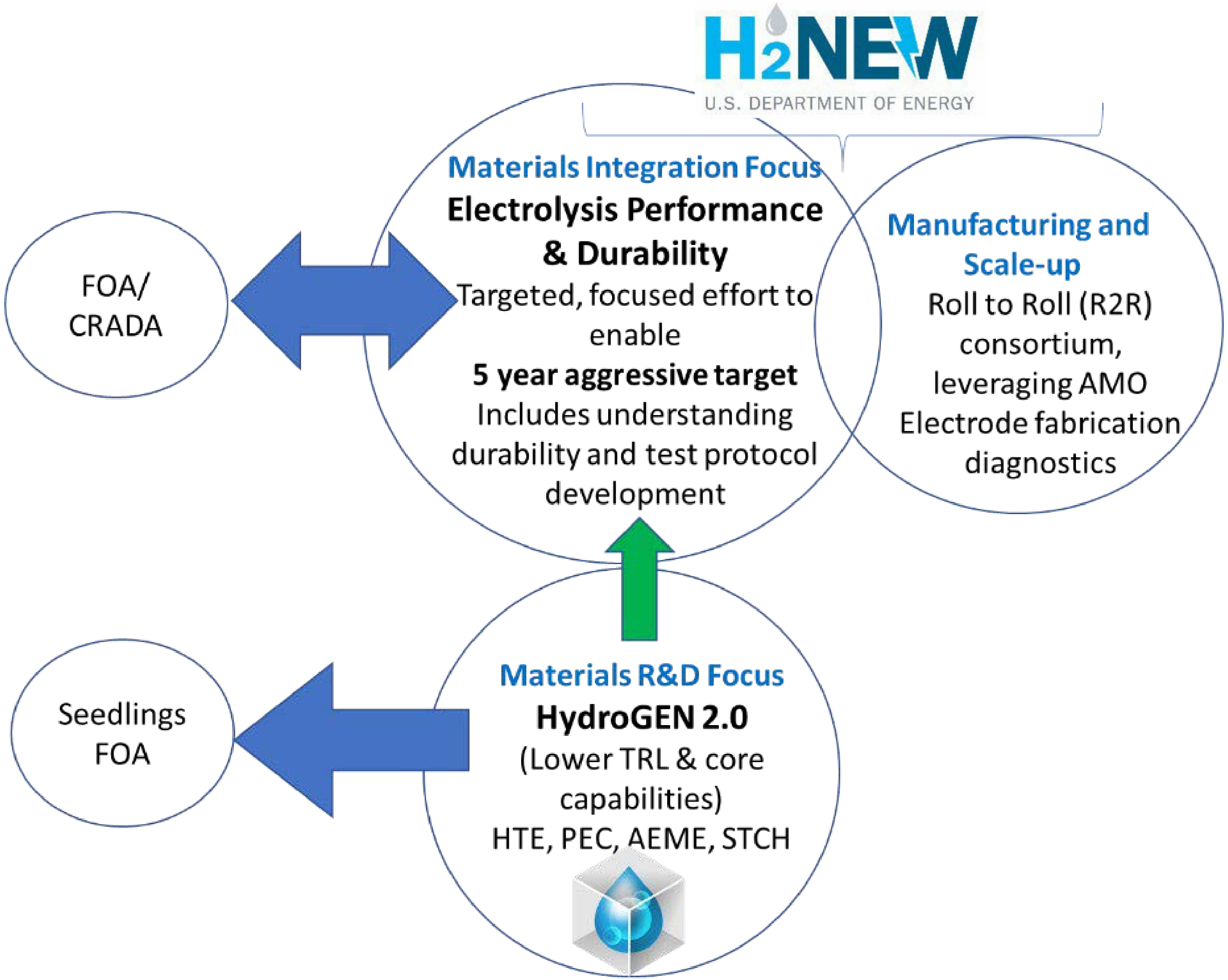
PEC



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 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)

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: \$28M

National Lab Consortium Team

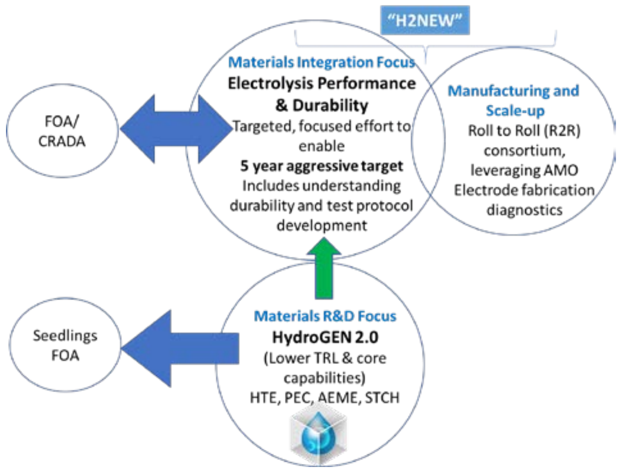
NREL — National Renewable Energy Laboratory; INL — Idaho National Laboratory; Argonne National Laboratory; Berkeley Lab; Pacific Northwest National Laboratory; Los Alamos National Laboratory; Lawrence Livermore National Laboratory; Oak Ridge National Laboratory; National Energy Technology Laboratory

Clear, well-defined stack metrics to guide efforts.

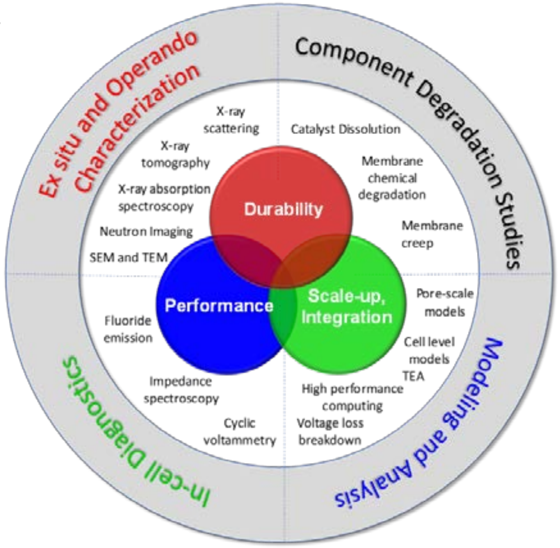
Draft Electrolyzer Stack Goals by 2025

	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



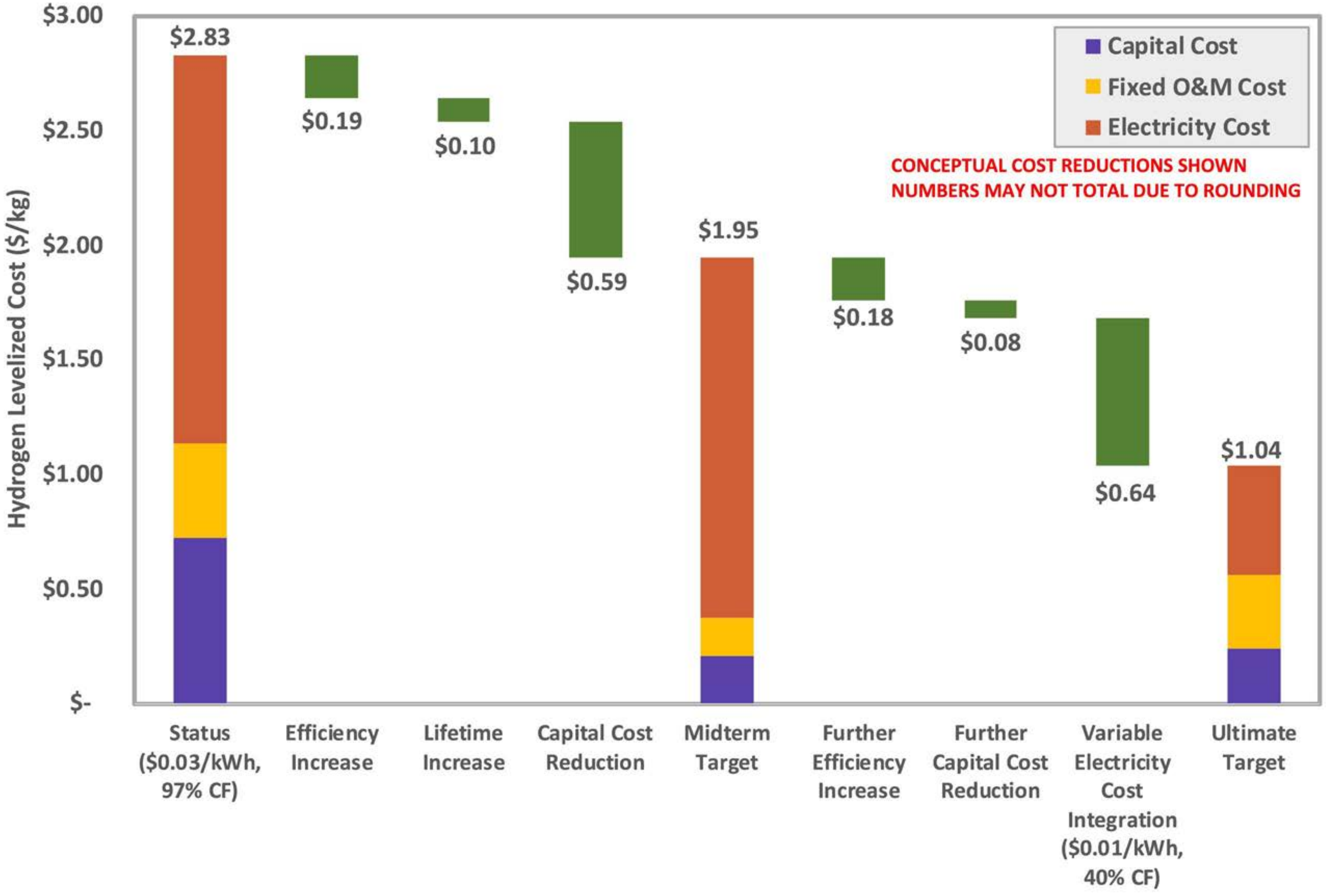
Utilize combination of world-class experimental, analytical, and modeling tools



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.

Potential Impact: Hydrogen Levelized Cost (HLC)



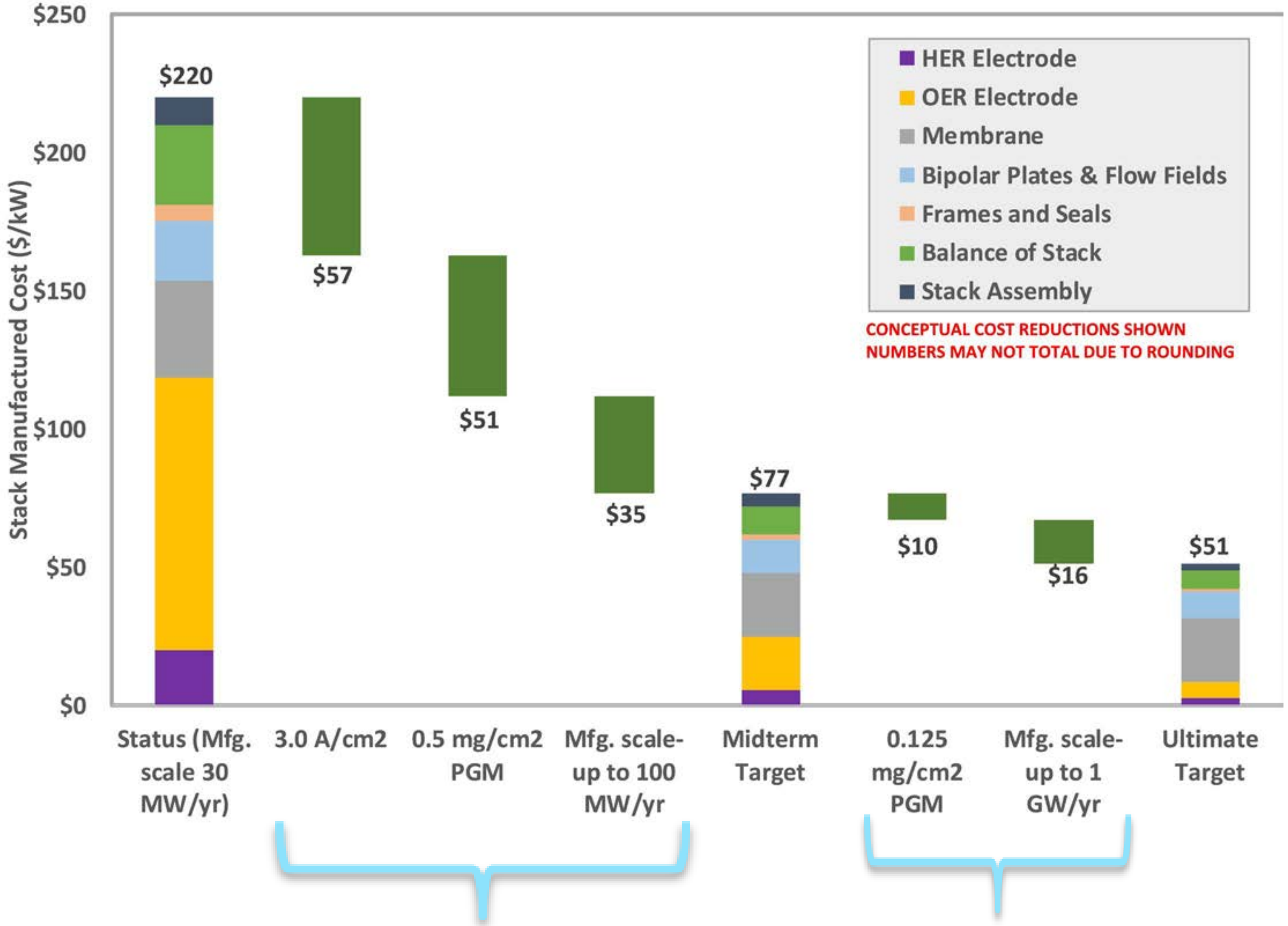
Select pathway to $2/kg and $1/kg identified.

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.

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

Potential Impact: Stack Costs (PEM)



Stack Targets	Status	2026	Ultimate
Cell (A/cm²)	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/cm²)	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

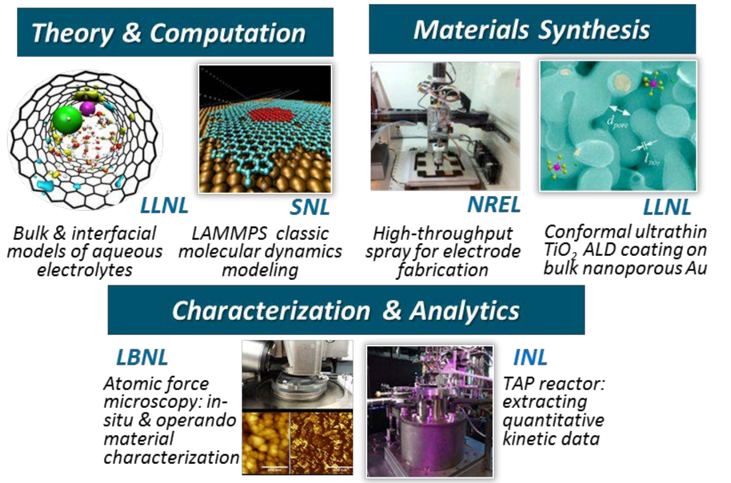
Are the strongest levers for addressing stack costs and primary focus of H2NEW.

HydroGEN 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



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

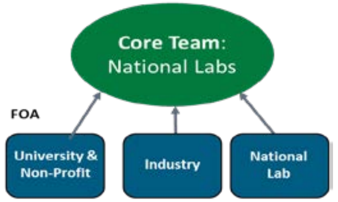
HydroGEN 2.0 Focus Areas

LTE: Enable high efficiency, durable AEMWE without supporting electrolytes

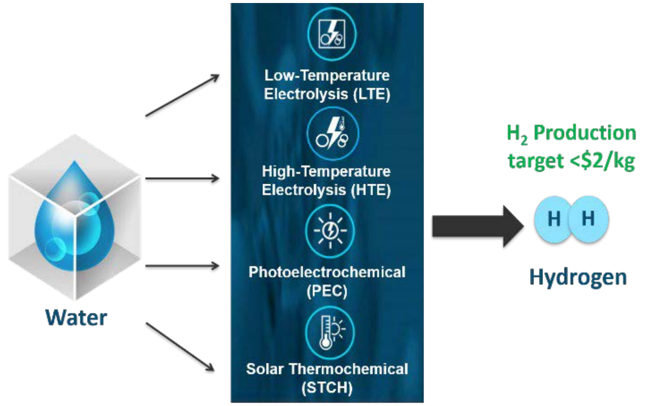
HTE: Identify electronic leakage mechanisms in p-SOEC for higher cell performance at lower temperatures

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



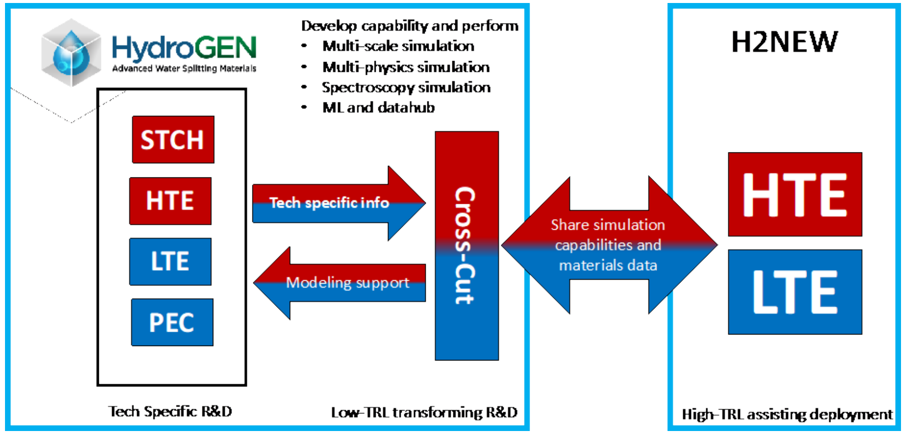
Key Technical Accomplishments

- Achieved high PGM-free (lower cost) AEME performance (< $1.56_{HFR\text{-}free}$ V at 1 A/cm^2) with LANL NiFe 8:1 catalyst.
- Achieved 2.8 A/cm^2 at 1.3V @ 600°C 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

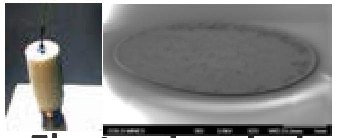
Science Challenges for HydroGEN 2.0:

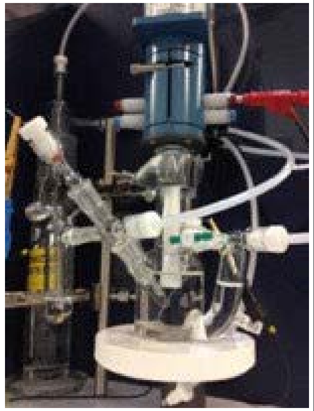
- ***LTE***: improve AEM electrolysis performance and durability by determining the role of supporting electrolyte and the limiting factors behind DI water operation
- ***HTE***:
  - **MS-SOEC**: improve performance and durability with a scale-up cell
  - **p-SOEC**: understand the proton conduction and electronic leakage mechanisms of electrolyte materials in proton-conducting SOEC
- ***PEC***: materials stability and device durability
- ***STCH***: identify and understand how structural features, composition, and defect dynamics engender high capacity–high yield behavior in materials

Cross-Cutting Modeling: theory-guided design to analyze performance and durability of materials under simulated operating conditions



From Powders to Power
— Program Spans Fundamental Science to Large-Scale Validation





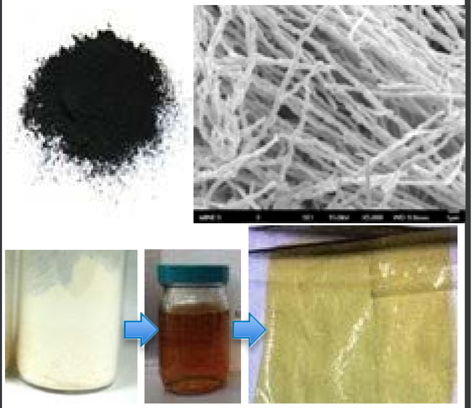
Electrochemical Characterization:
RDE & RRDE stations for Mass & Specific Activity, ECA, ORR; EQCMB, Seiras

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

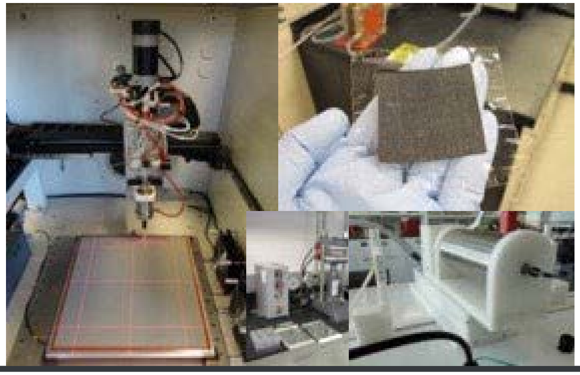
Manufacturing Lab
QC Diagnostic Development, Areal characterization, Roll-to-roll demonstration

Powders → Power

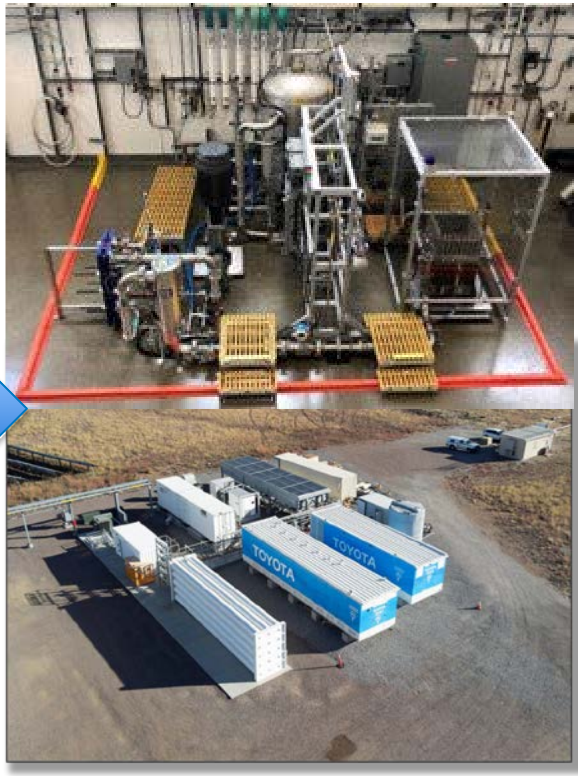
Material Synthesis:
Catalyst & Membrane Development



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



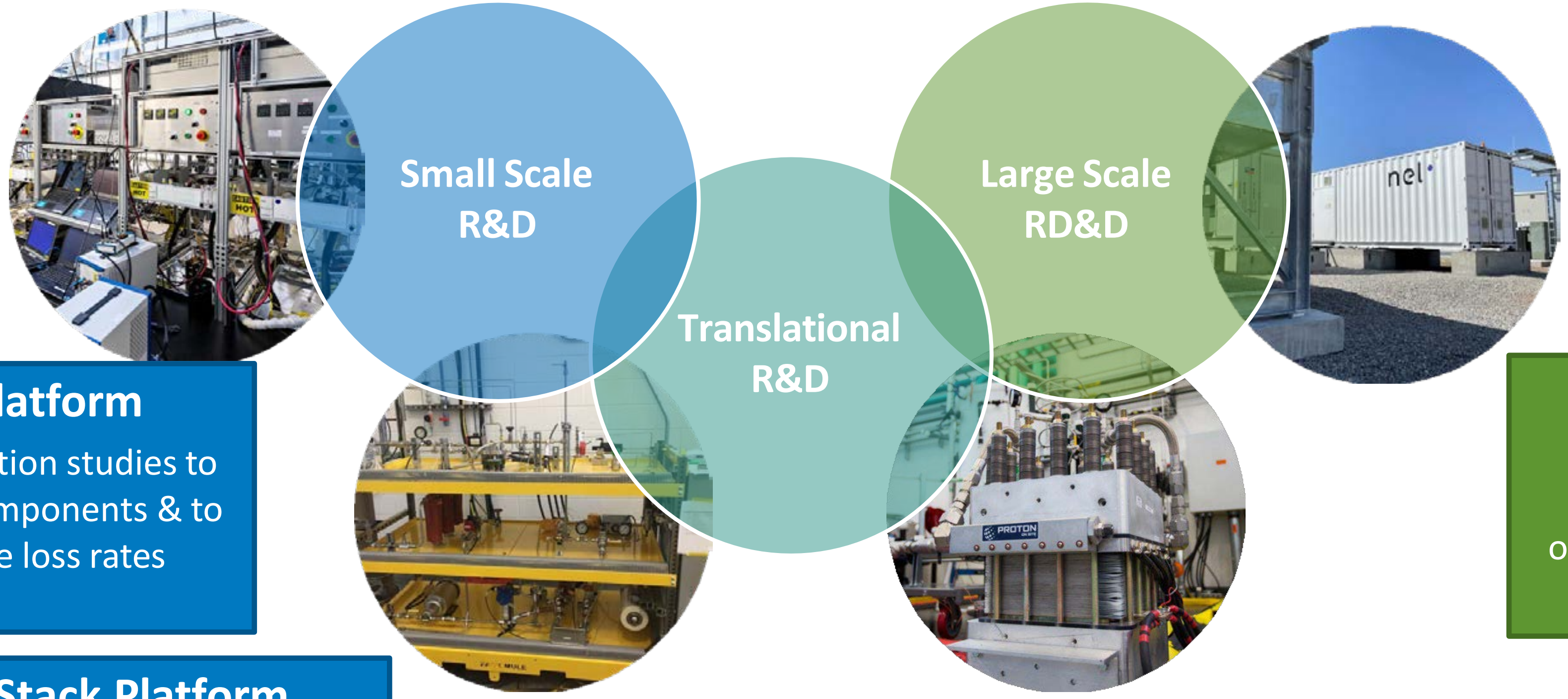
Performance and Durability Evaluation
In-situ Diagnostics, PEMFC, AEMFC, Electrolyzer; Single Cell, Stacks, Spatial



Systems Integration

Systems-focus ANALYSIS-driven R&D

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 Stack Platform

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

Full System Platform

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

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

Images: NREL

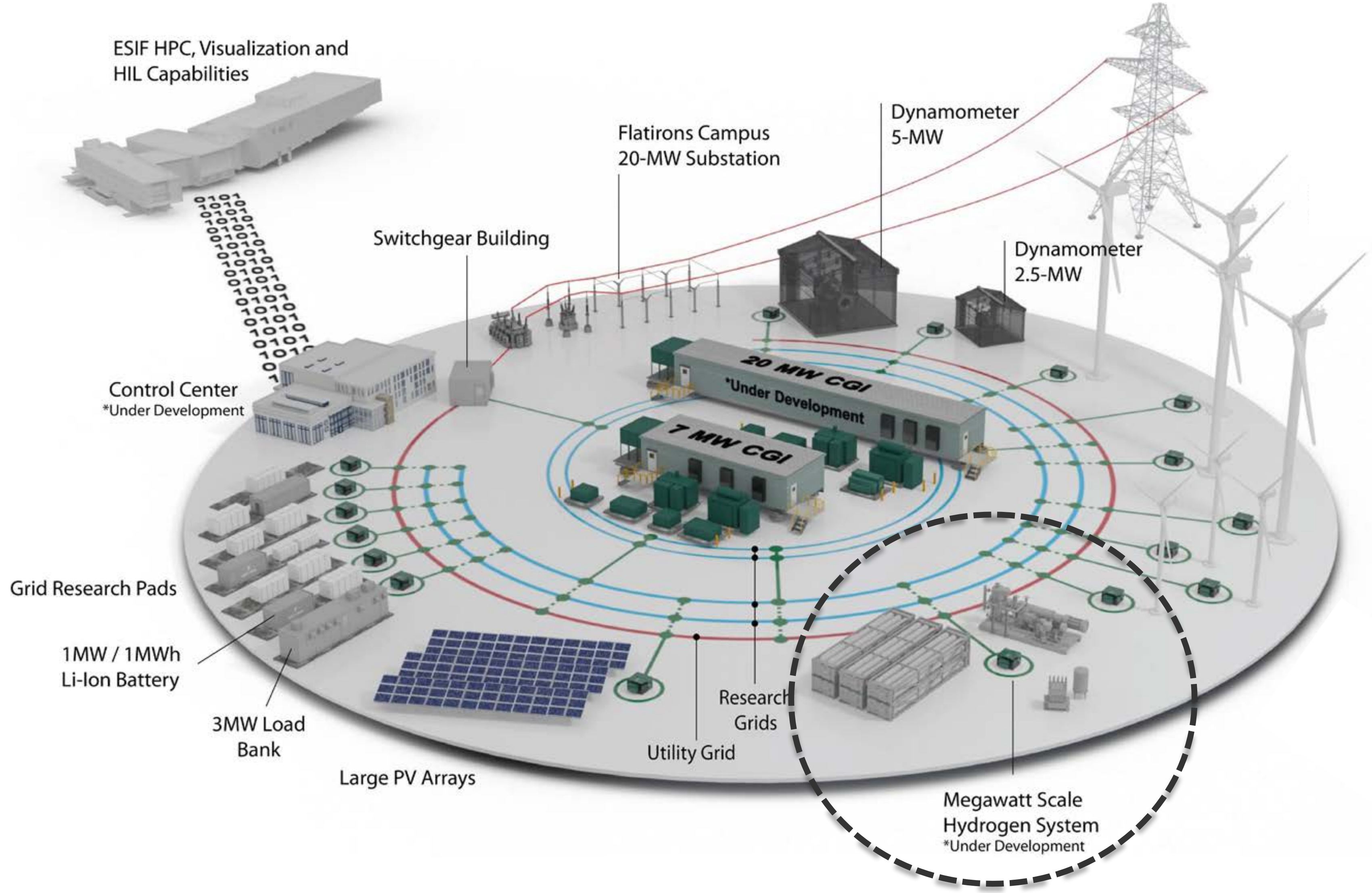
The Role of Large-Scale Validation and Demonstration

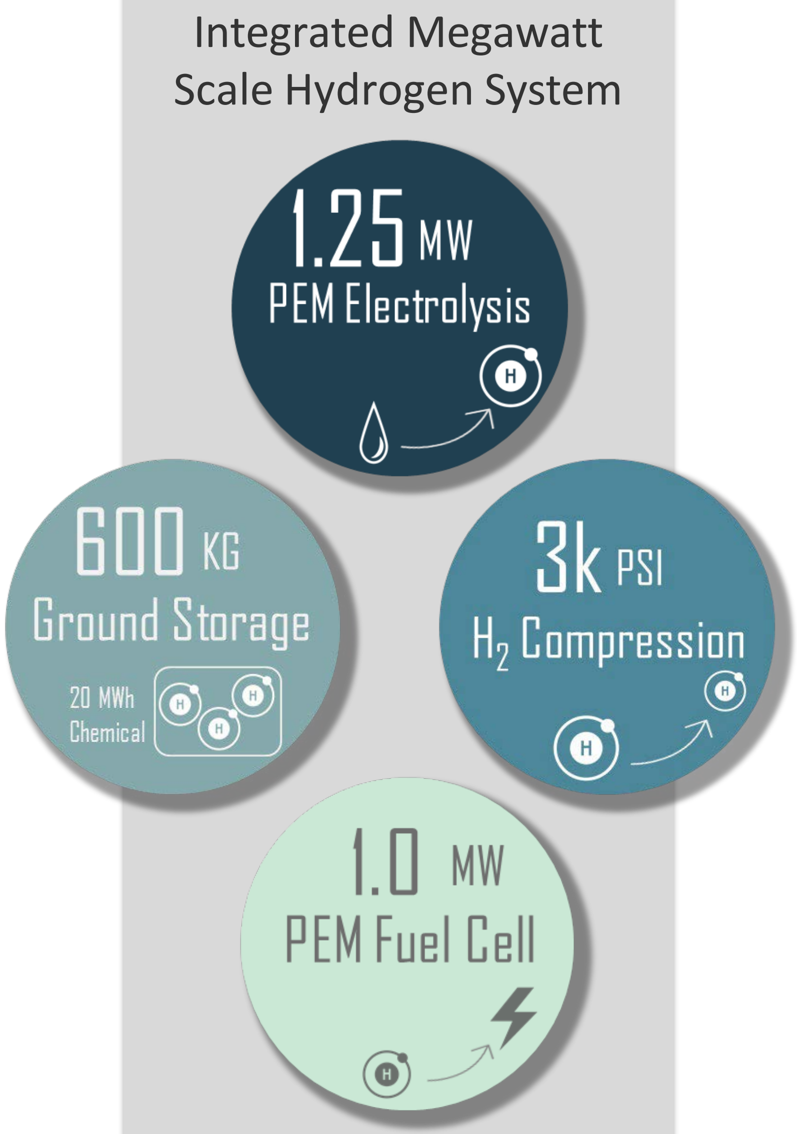
- Prior to investment, investors, utilities, and other stakeholders need to **de-risk H_2 systems** through operating in real-life industrial environments

- 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

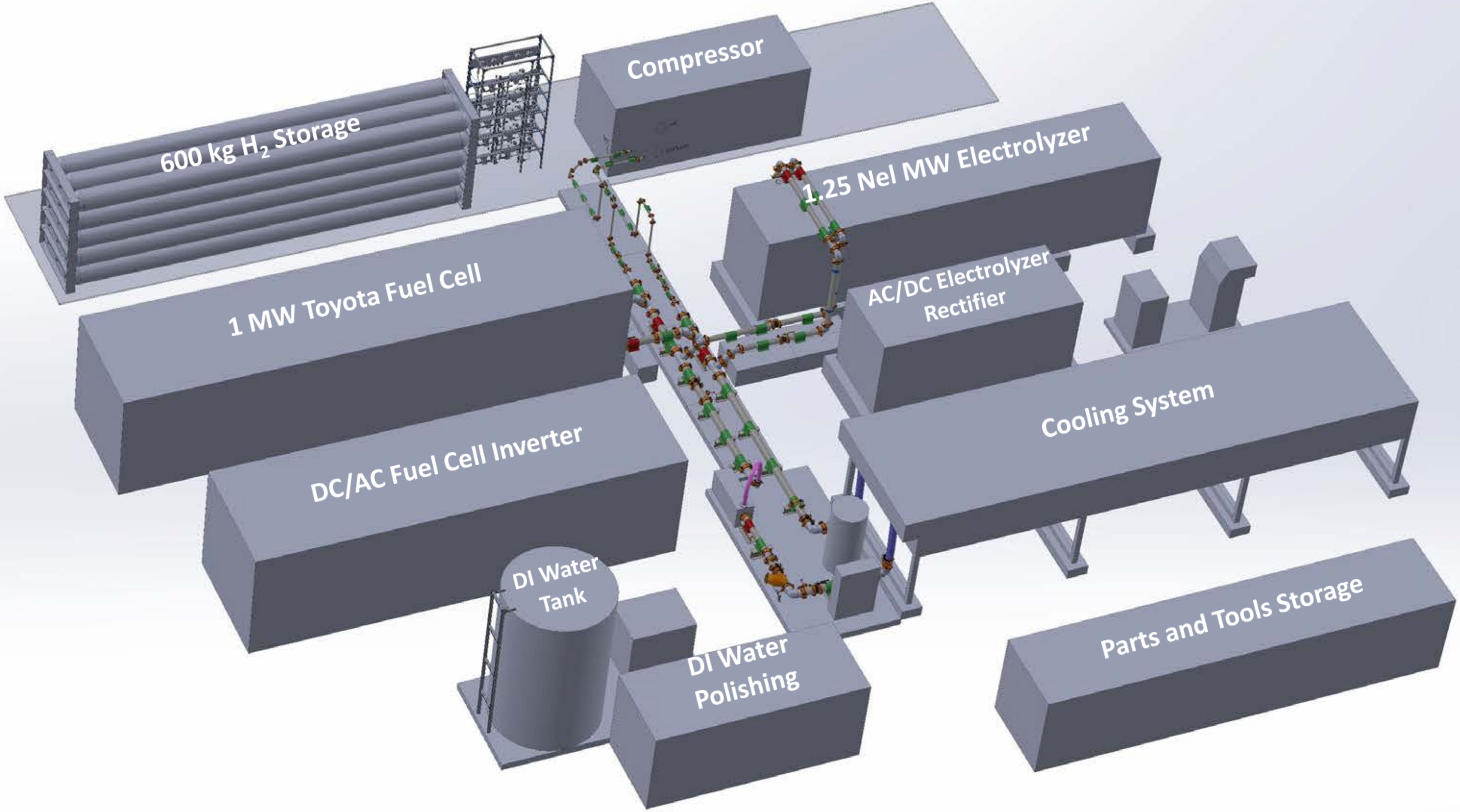
ARIES Hydrogen System Integration





ARIES: Advanced Research on Integrated Energy Systems

3D Layout of Flatirons Campus Hydrogen System



Recent View of Flatirons Campus H_2 System

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

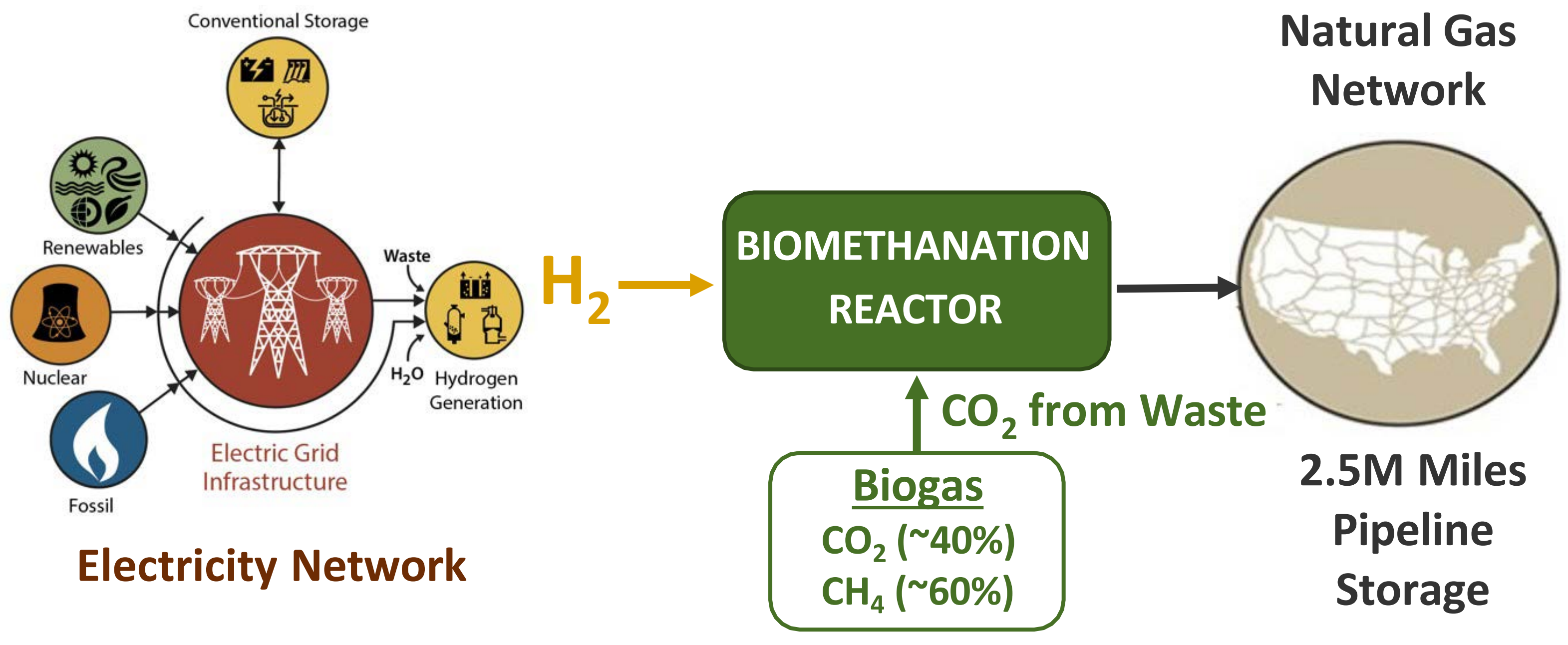
2 X 260 kg H_2 = 520 kg storage

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



Example of Where We're Going in H_2 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 H_2 (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 → H_2 → green steel/ammonia

Reduce risks and accelerate pathways to industrial decarbonization.

Acknowledgements

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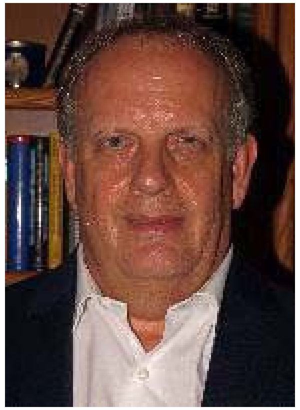
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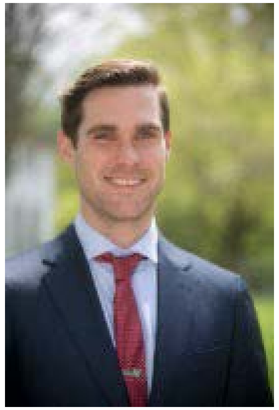
Katie Randolph


David Peterson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