U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

U.S. DOE Hydrogen and Fuel Cell Activities

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U.S. Department of Energy

Hydrogen Online Conference

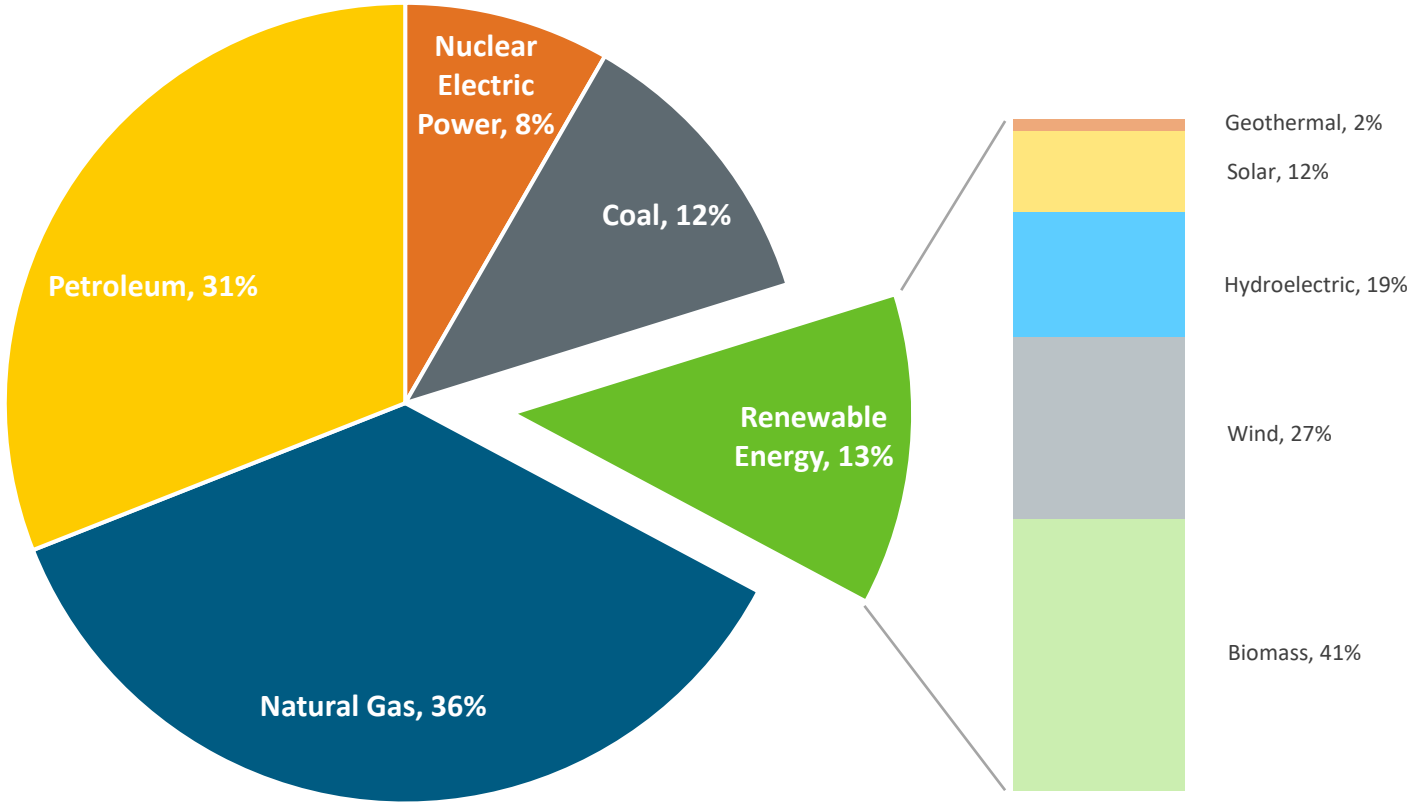
November 7, 2022

Introduction – Energy, Market, and Policy Context

U.S. Energy Landscape and Key Goals

U.S. primary energy consumption by energy source, 2021

Total = 97.8 quadrillion British thermal units (Btu)



Total = 12.3 quadrillion Btu

Note: Sum of components may not equal 100% because of independent rounding
Source: Data collected from U.S. Energy Information Administration, April 2022, *Monthly Energy Review,* preliminary data

Administration Goals include:

- Net-zero emissions economy by 2050 and 50–52% reduction by 2030
- 100% carbon-pollution-free electric sector by 2035

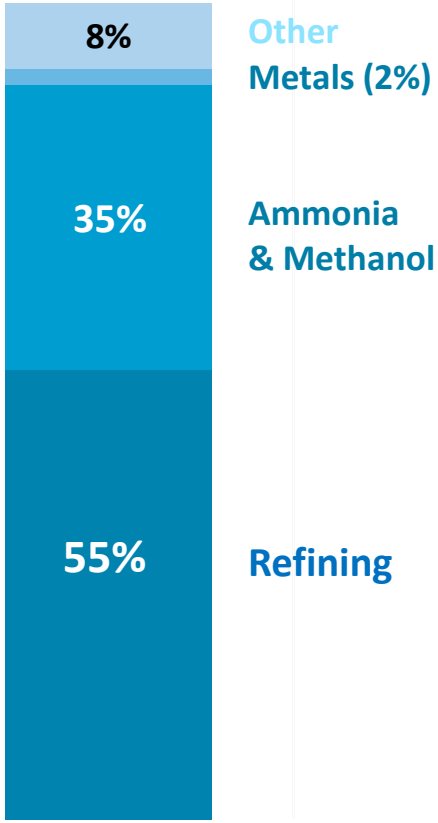
Priorities: Ensure benefits to all Americans, focus on jobs, EJ40: 40% of benefits in disadvantaged communities

EJ: Environmental Justice

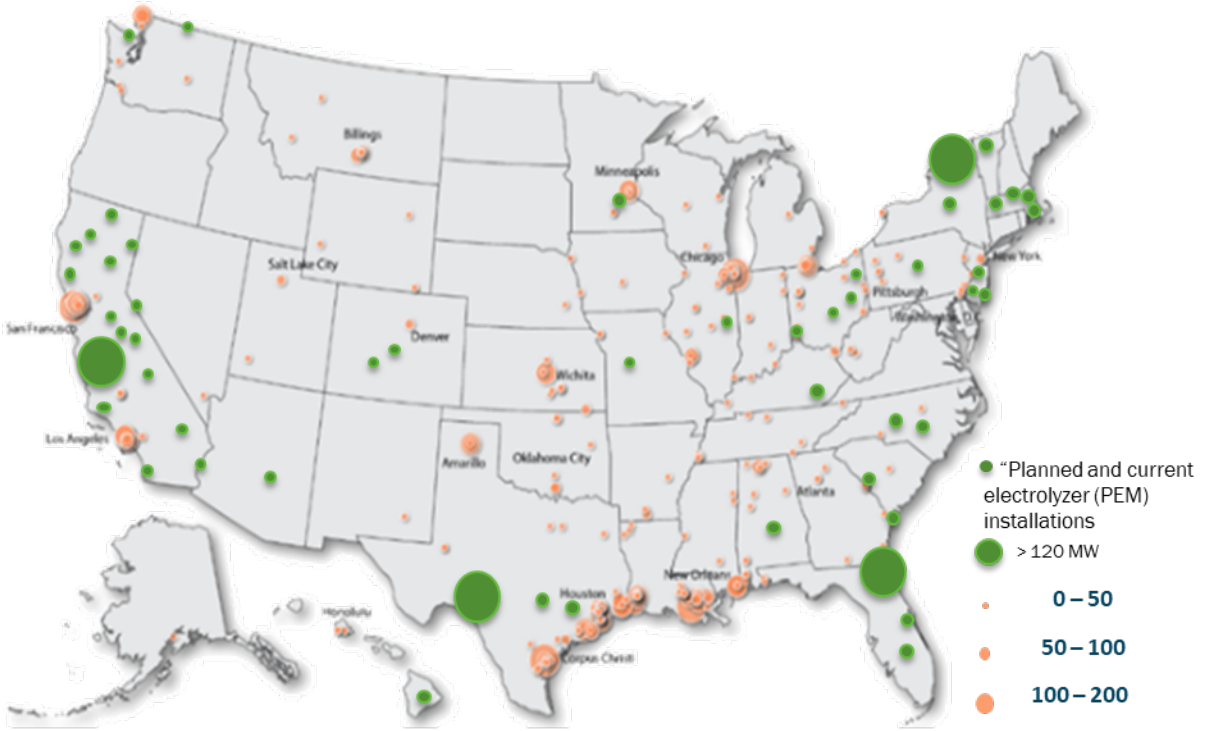
Snapshot of Hydrogen and Fuel Cells in the U.S.

- 10 million metric tons produced annually
- More than 1,600 miles of H_2 pipeline
- World's largest H_2 storage cavern

Use of Hydrogen in the U.S. Today

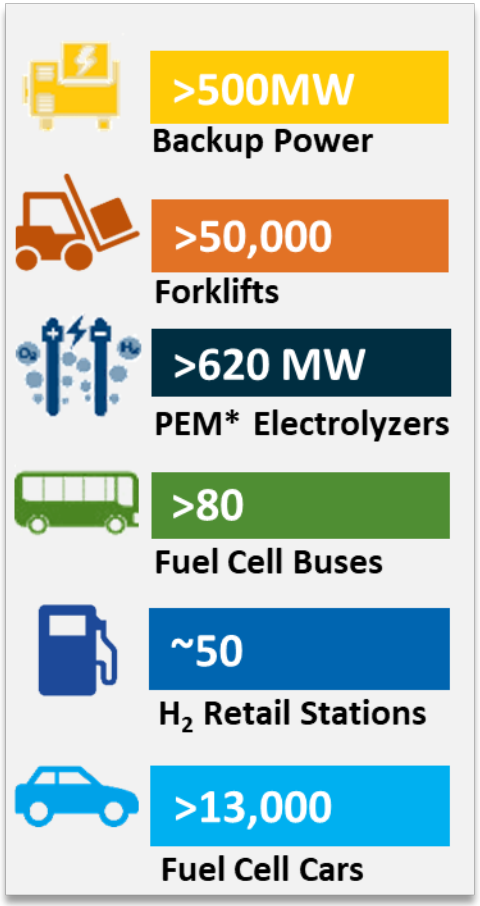


Examples of Hydrogen Production Locations



>620 MW of PEM* electrolysis in the U.S.
>3X increase since 2021

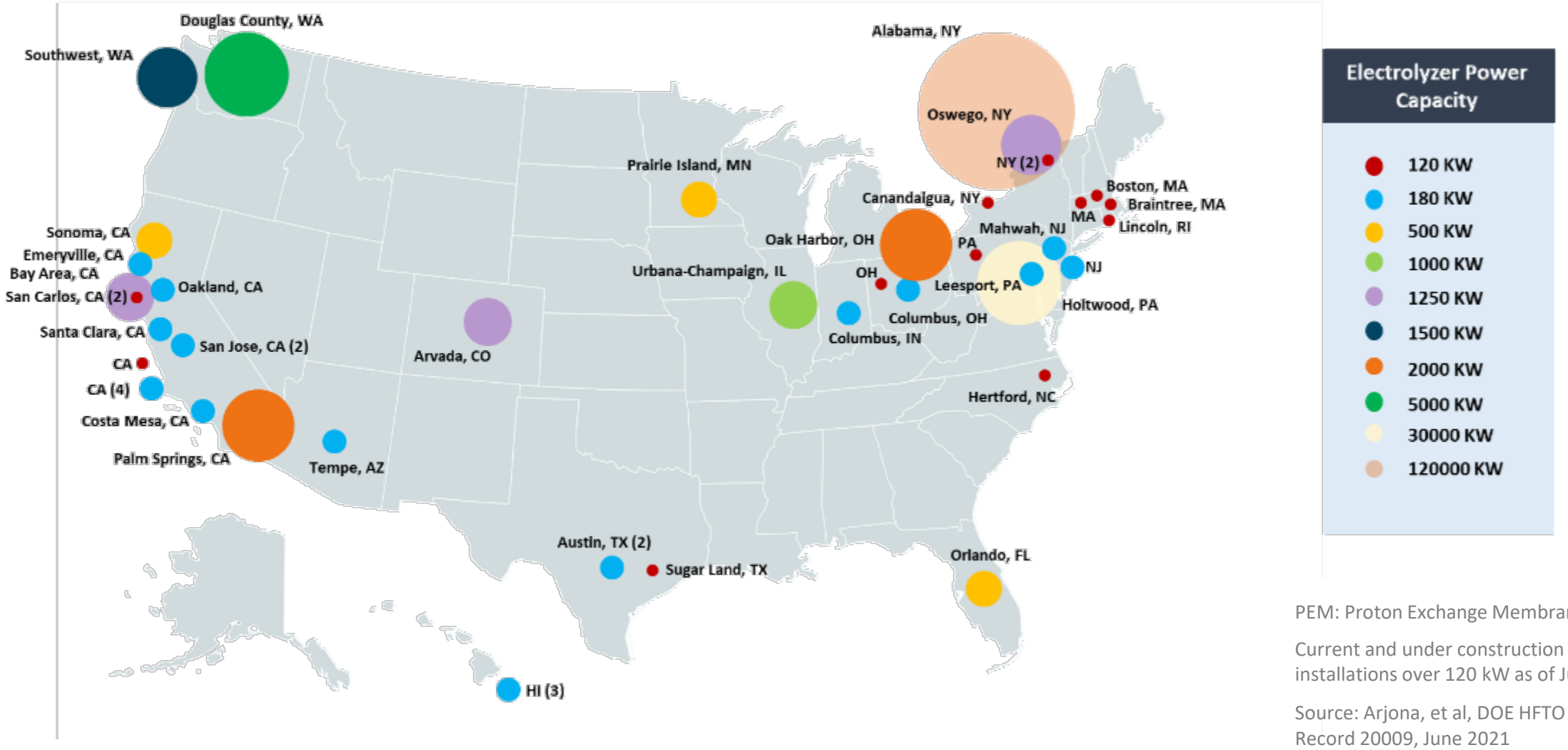
Examples of Deployments



*Proton exchange membrane

PEM Electrolyzer Locations and Capacity – 2021 Snapshot

Operational and Under Construction: 172 MW Capacity



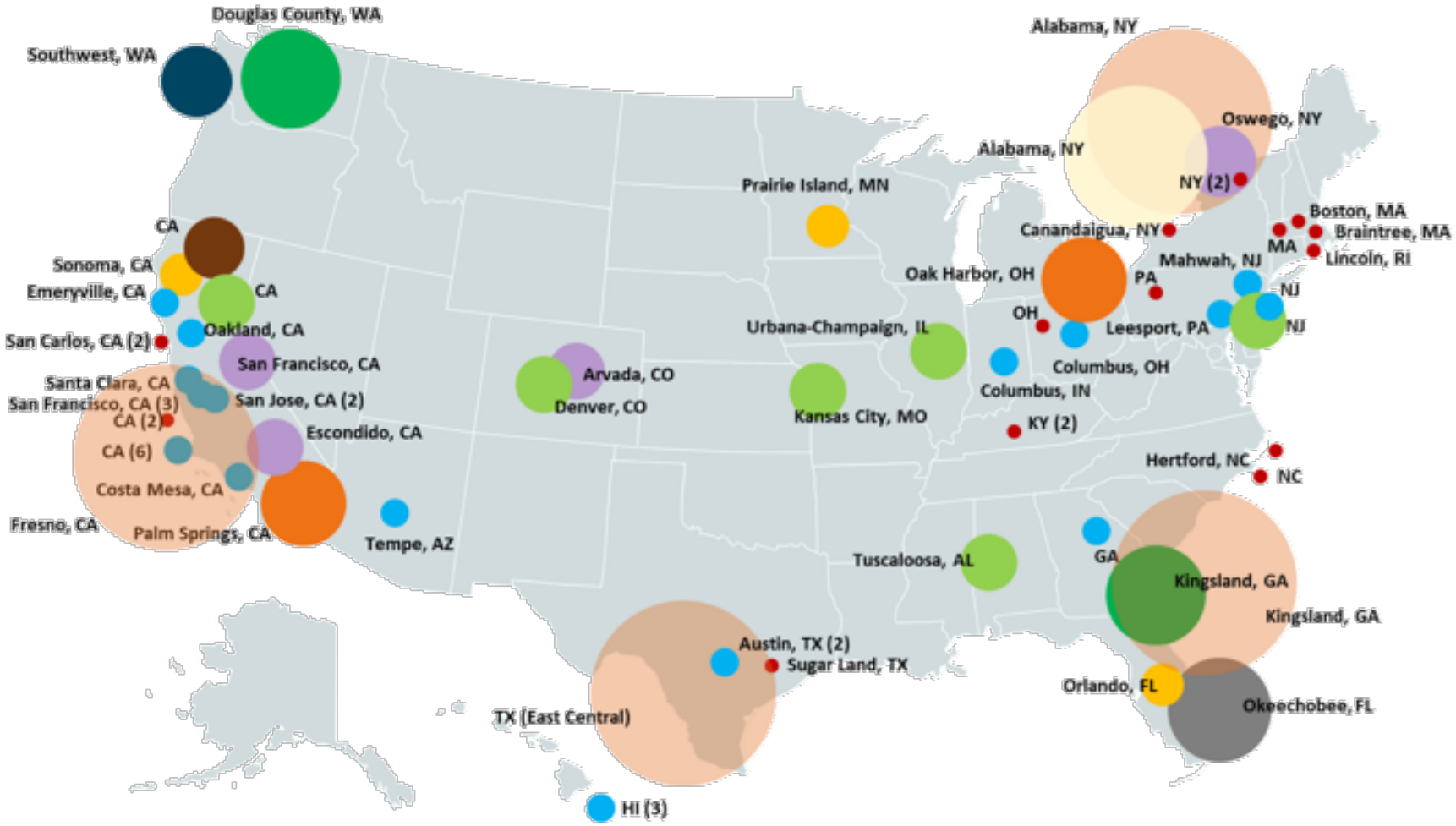
PEM: Proton Exchange Membrane

Current and under construction installations over 120 kW as of June 2021

Source: Arjona, et al, DOE HFTO Program Record 20009, June 2021 hydrogen.energy.gov/program_records.html

PEM Electrolyzer Locations and Capacity – 2022 Snapshot

Operational and Under Construction: > 620 MW Capacity



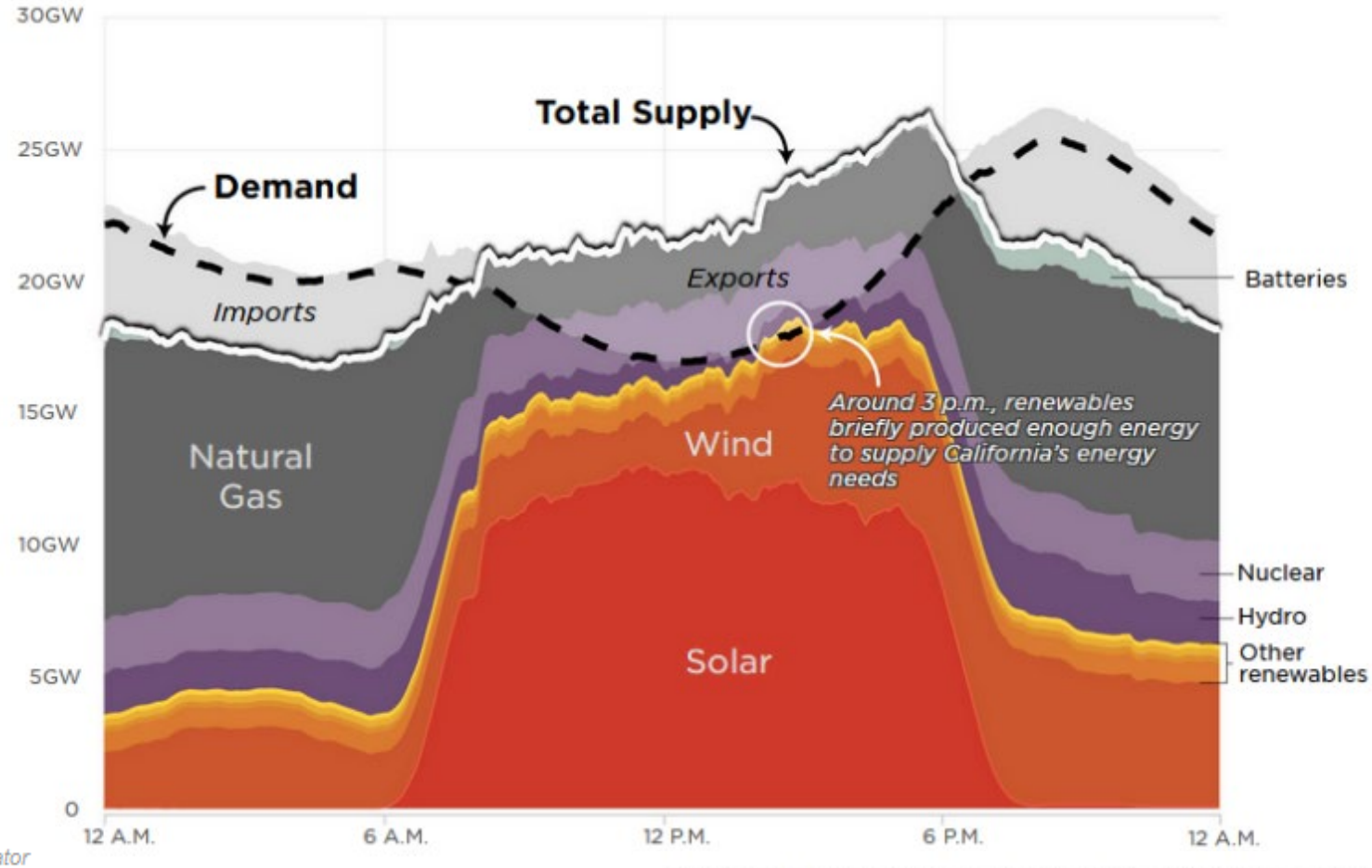
PEM: Proton Exchange Membrane

Current and under construction installations over 120 kW as of May 2022

Source: Arjona, V., DOE HFTO Program Record 22001 , June 2022

Penetration of Renewables Drives the Need for Energy Storage

For the first time in history, in May 2022, renewable power in California exceeded demand



Source: California Independent System Operator

Credit: Daniel Wood and Lauren Sommer/NPR

Other renewables include geothermal, biomass, biogas and small hydroelectric power. Large hydroelectric and nuclear power are not considered renewable by the state of California. Total supply exceeds demand because some amount of electricity is lost in transmission and some is exported to other states.

Key Hydrogen Provisions in Recent Legislation

Bipartisan Infrastructure Law

- **Includes $9.5 billion** for clean hydrogen:
  - $1B for electrolysis research, development and demonstration
  - $500M for clean hydrogen technology manufacturing and recycling R&D
  - $8B for at least four regional clean hydrogen hubs
- **Aligns with Hydrogen Shot priorities by directing work to reduce the cost of clean hydrogen to $2 per kilogram by 2026**
- **Requires developing a National Hydrogen Strategy and Roadmap**

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

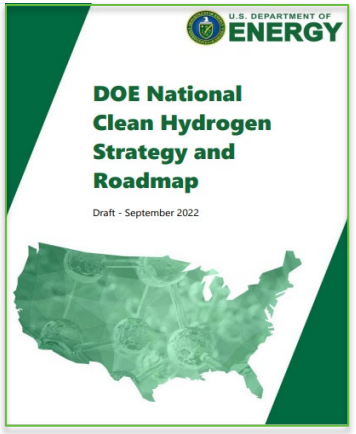
Inflation Reduction Act

- Includes **clean hydrogen production tax credit of up to $3 per kg**

Recent Announcements and BIL Deliverables

DOE National Clean Hydrogen Strategy and Roadmap

Draft Document Released



H2 Hubs Funding Opportunity Announcement (FOA)

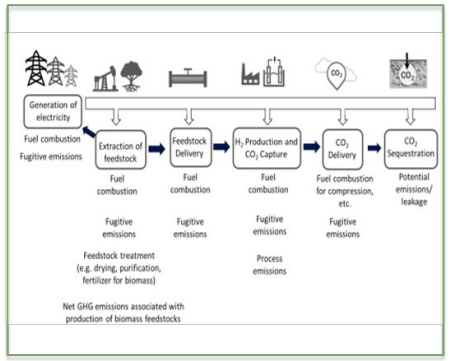
FOA Released

6 to 10 H2 Hubs for a combined total of $6B to $7B

Concept papers due 11/7/22
Full applications due 4/7/23

Clean Hydrogen Production Standard (CHPS)

Draft Guidance Document Released for Initial Standard



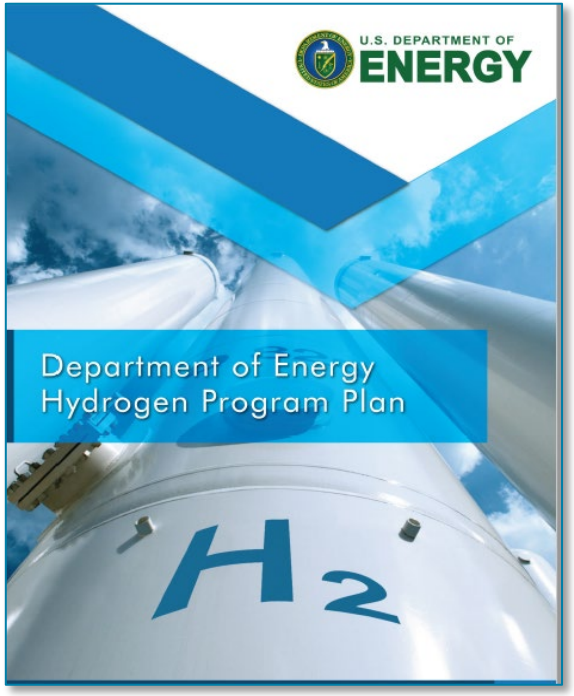
Request for Information released by U.S. Treasury on Production Tax Credit

Learn about DOE Life Cycle Emissions Analysis and GREET tool through DOE webinars:
https://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-technologies-office-webinars

Strategy & Goals

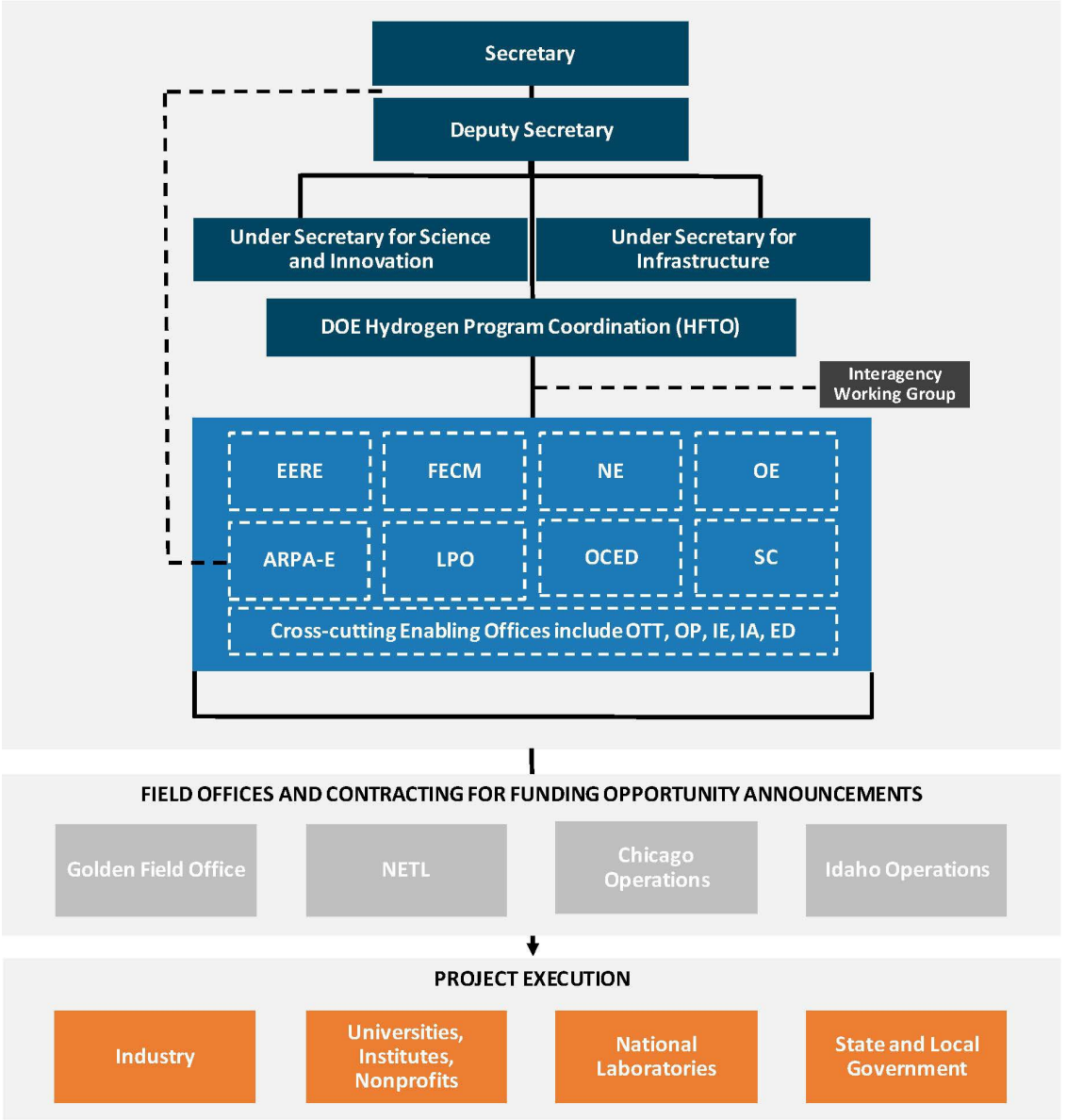
U.S. DOE Hydrogen Program

Hydrogen is part of a broad portfolio of activities. The Program includes multiple offices and addresses the entire RDD&D value chain from production through end use.



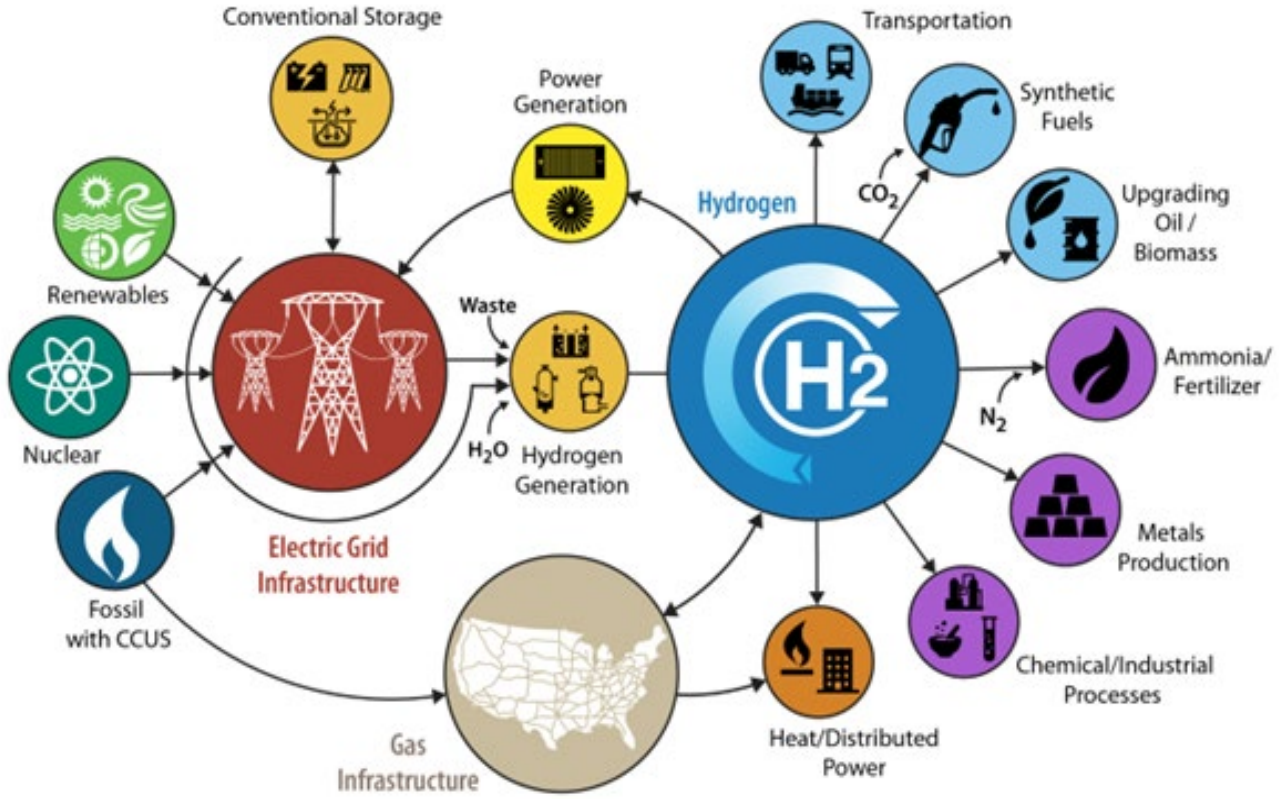
www.hydrogen.energy.gov

Includes multiple offices across DOE, led by DOE's Hydrogen and Fuel Cell Technologies Office



H2@Scale: Enabler for Deep Decarbonization across Sectors and Jobs

H2@Scale provides vision for how hydrogen can enable clean-energy pathways across applications and sectors.



Key Opportunities

- **Industry and Chemicals**

  Steel, ammonia, cement, syn-fuels (e.g., aviation), exports

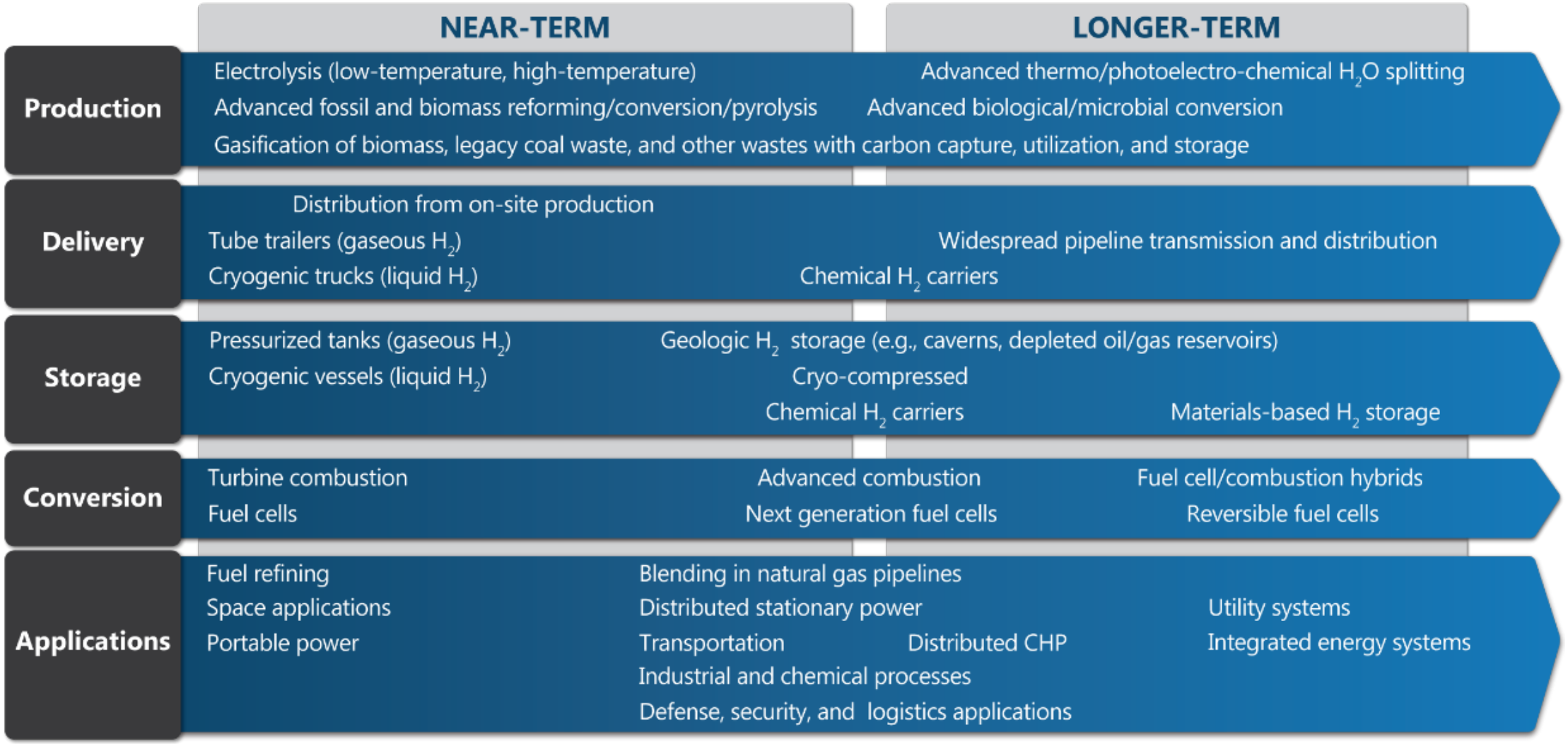
- **Transportation**

  Trucks, marine, buses, etc.

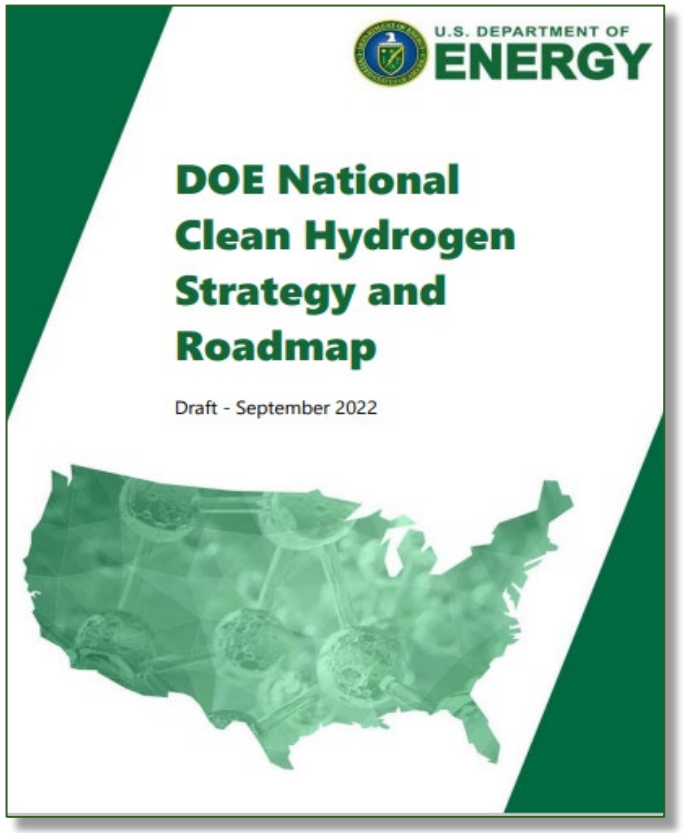
- **Power and Energy Storage**

  Long-duration storage, NG blending, turbines, fuel cells

Comprehensive DOE Strategy Across the Hydrogen Value Chain



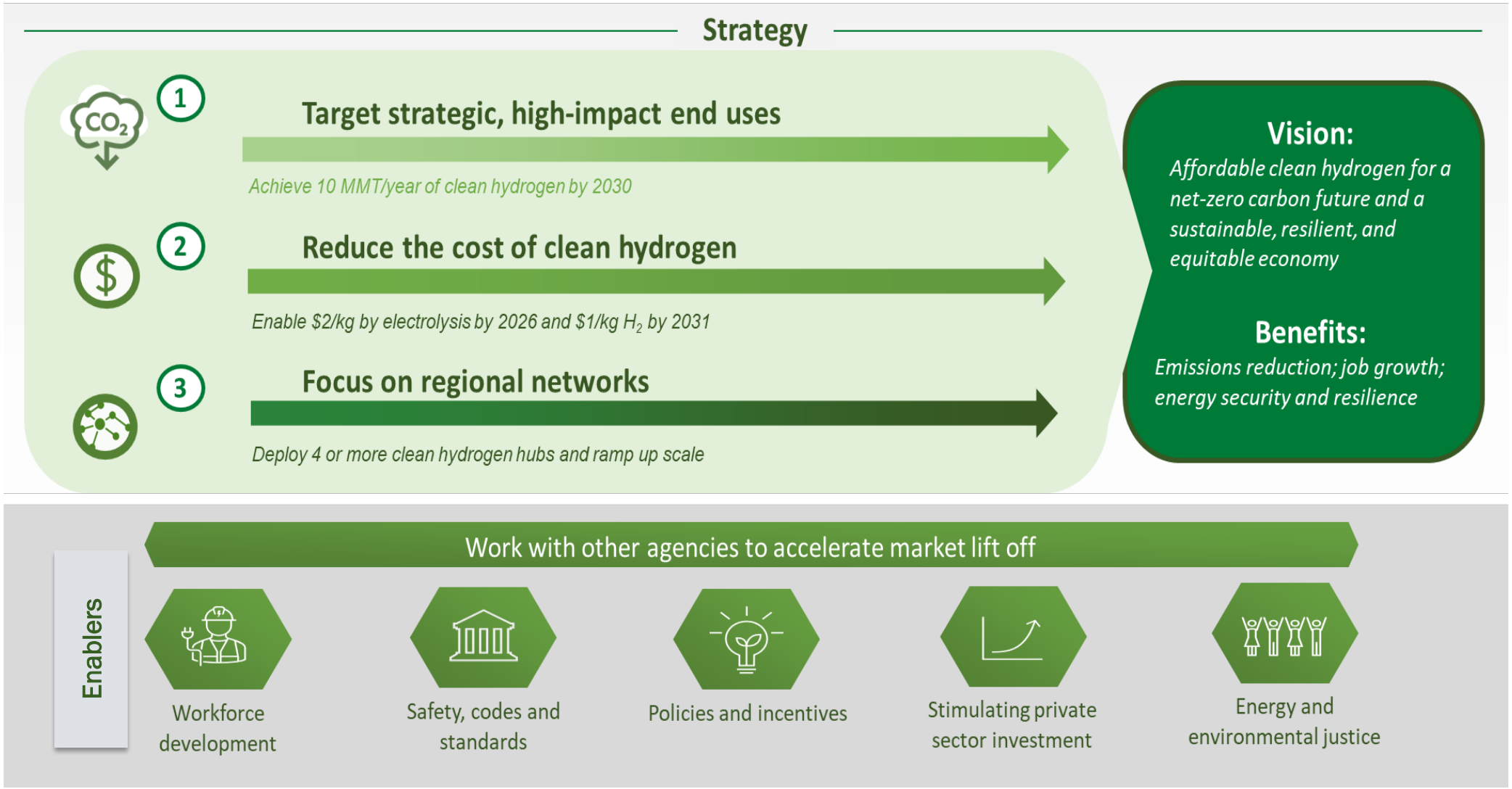
Draft *DOE National Clean Hydrogen Strategy and Roadmap*



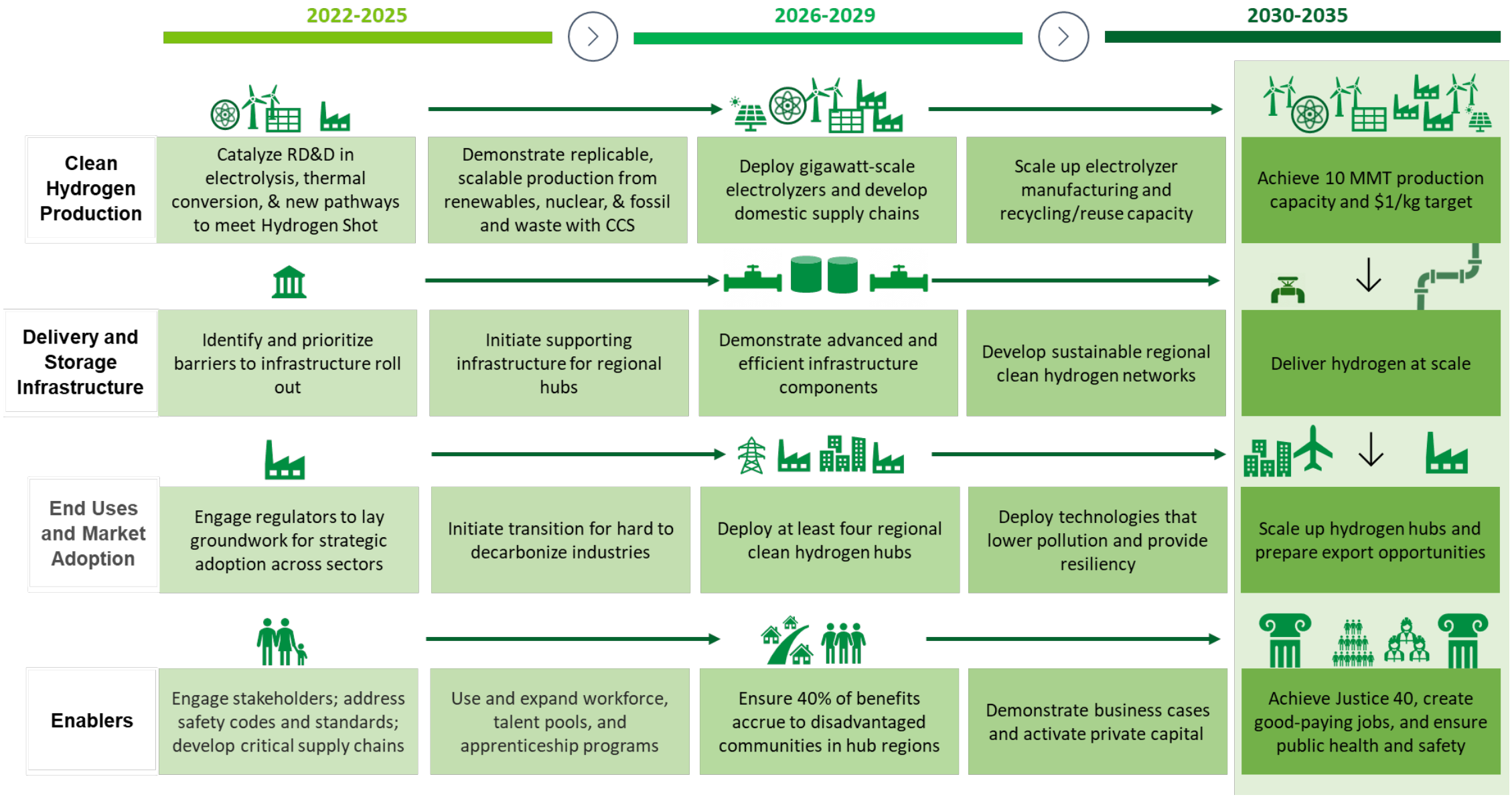
- Provides a snapshot of hydrogen production, transport, storage, and use in the United States today
- Explores the potential for clean hydrogen to contribute to national goals across multiple sectors
- **Identifies opportunities for domestic production of clean hydrogen:**
  - **10 million metric tons per year by 2030**
  - **20 MMT by 2040**
  - **50 MMT by 2050**
- The *Strategy and Roadmap will be finalized in early 2023* and updated per Bipartisan Infrastructure Law at least every 3 years.

https://www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html

Draft *DOE National Clean Hydrogen Strategy and Roadmap*

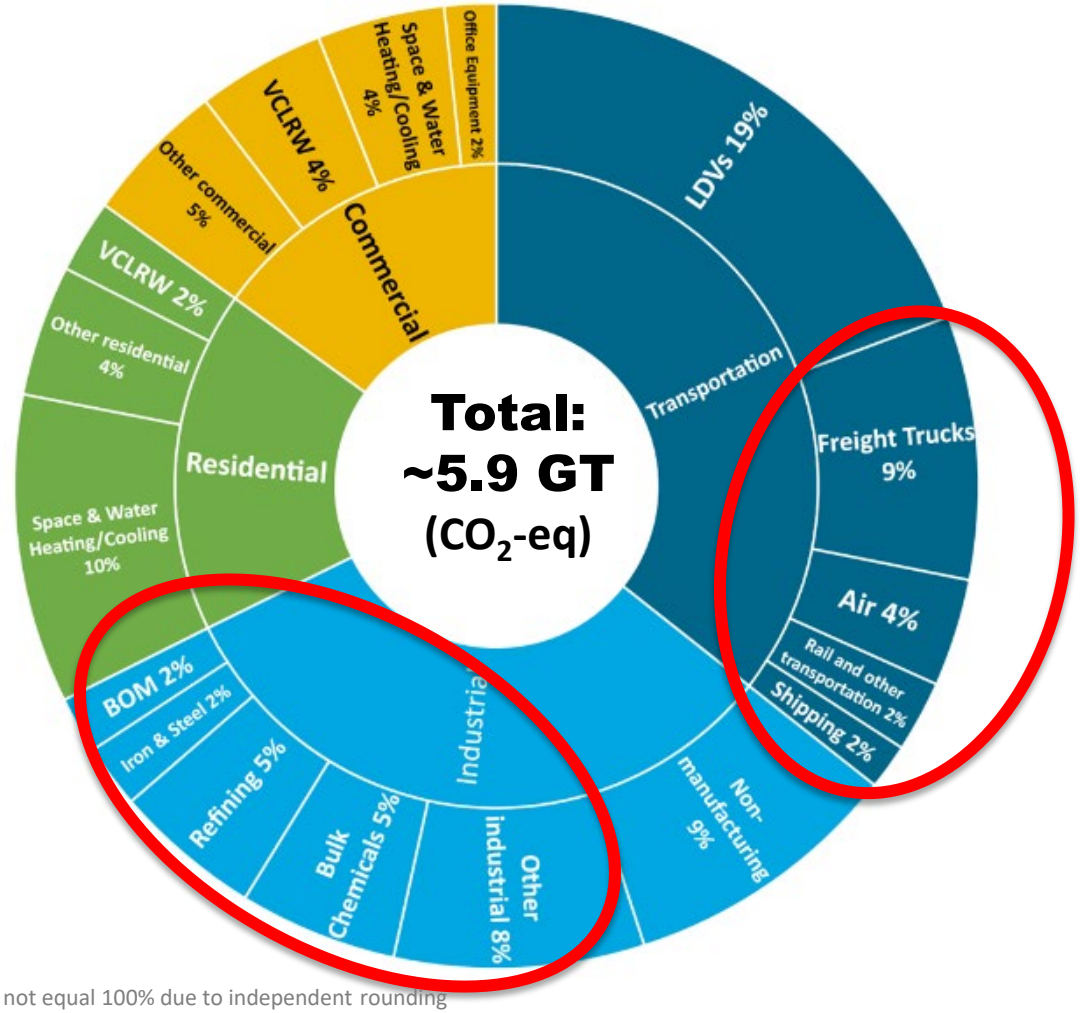


Actions from Draft DOE National Strategy and Roadmap



Strategy 1: Target High-Impact Uses of Hydrogen

U.S. Energy Related CO_2 Emissions by End-Use



Hydrogen can provide benefits particularly in hard to decarbonize sectors: industry, heavy duty transport and to enable energy storage

VCLRW - Ventilation, Cooking, Lighting, Refrigeration & Washing
BOM - Balance of Manufacturing

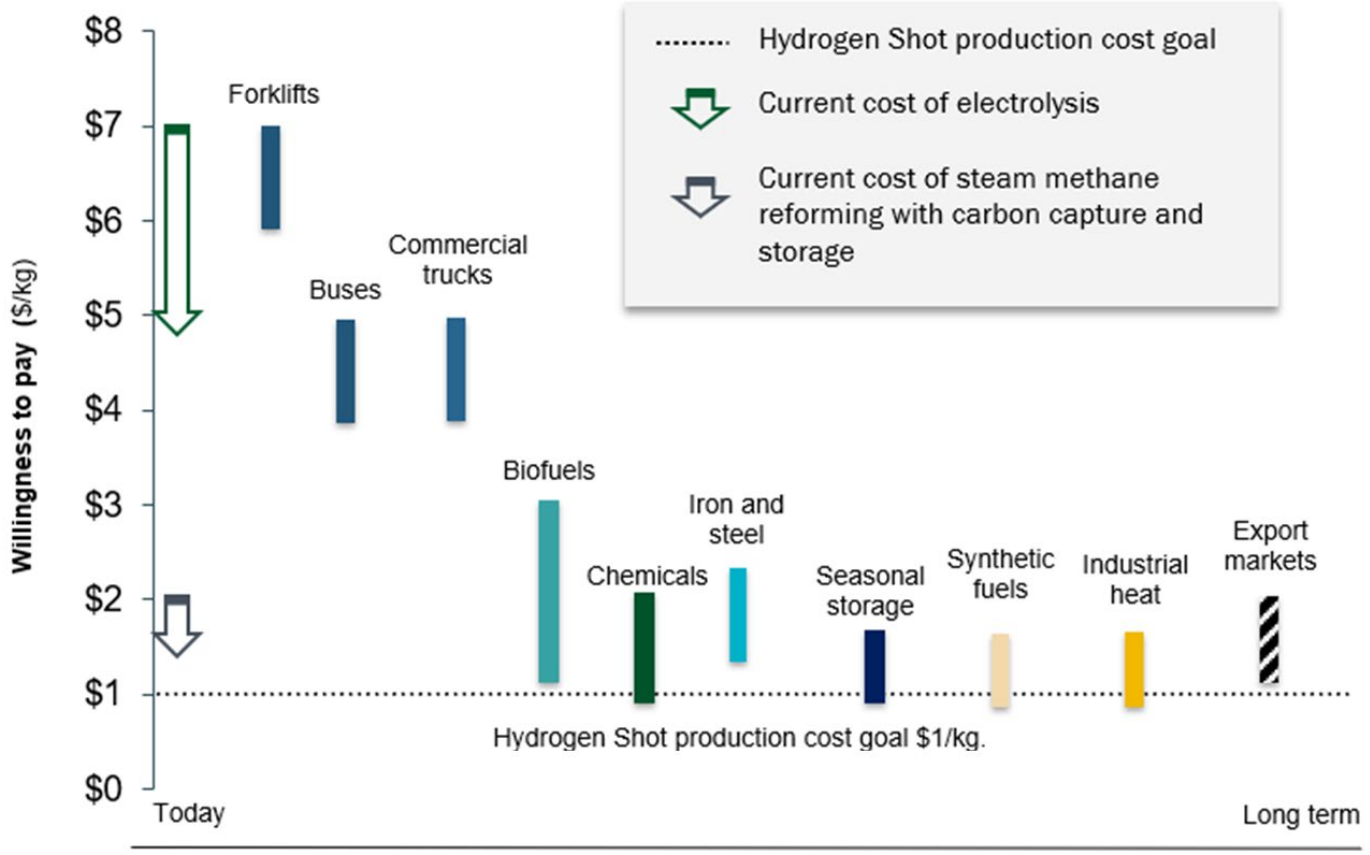
Other industrial: aluminum, cement and lime, construction, agriculture, plastics, wood, electrical equipment, transportation equipment, computing and electronics equipment, paper products, glass ,etc.

Note: Sum of sectors may not equal 100% due to independent rounding
Source: M. Koleva, DOE HFTO, NREL, adapted from EIA, 2020, U.S. Energy Information Administration - EIA - Independent Statistics and Analysis

Strategy 1: Target High-Impact Uses of Hydrogen

Threshold Costs for Hydrogen to be Competitive Across Sectors

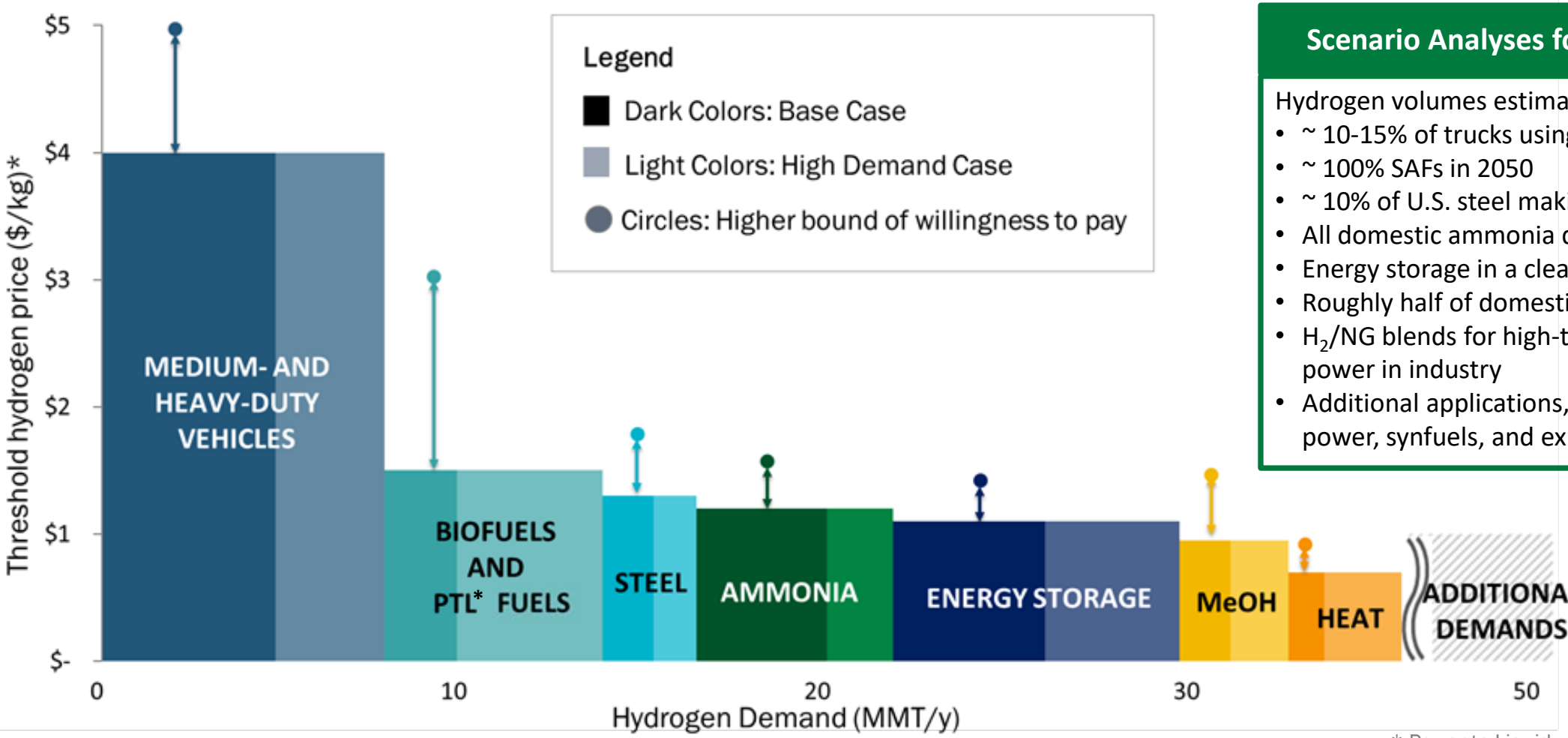
Some applications can start to be competitive at a higher threshold cost and can jumpstart the market



Threshold cost for each application includes cost of production, delivery, storage, compression/processing/dispensing, as required, to the point of use for each application

Strategy 1: Target High-Impact Uses of Hydrogen

Clean Hydrogen Demand and Costs for Market Penetration



Scenario Analyses for H_2 Demand**

Hydrogen volumes estimated for:

- ~ 10-15% of trucks using fuel cells
- ~ 100% SAFs in 2050
- ~ 10% of U.S. steel making
- All domestic ammonia demand
- Energy storage in a clean grid
- Roughly half of domestic methanol
- H_2/NG blends for high-temp heat and power in industry
- Additional applications, include stationary power, synfuels, and export potential

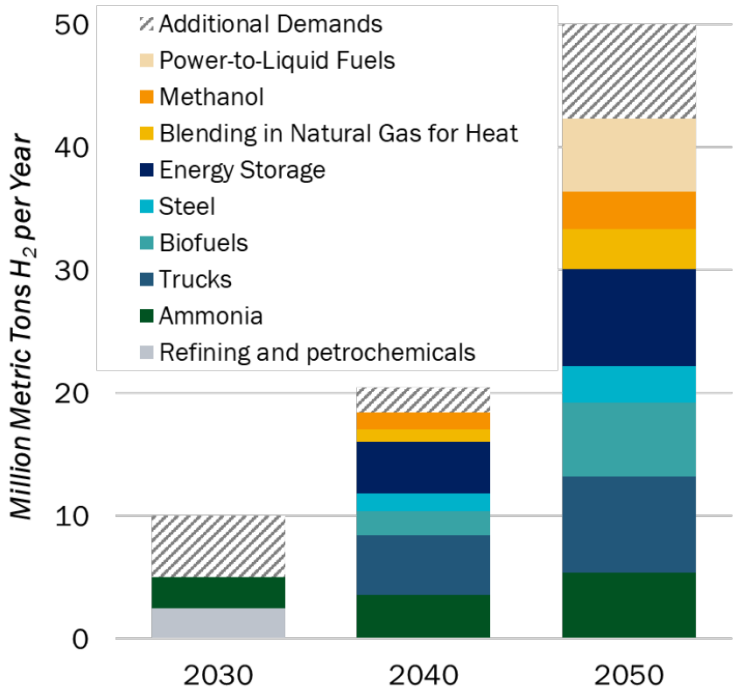
Costs include production, delivery, dispensing to the point of use (e.g., high-pressure fueling for vehicle applications)

* Power to Liquid

** Volumes dependent on multiple variables

Strategy 1: Target High-Impact Uses of Hydrogen

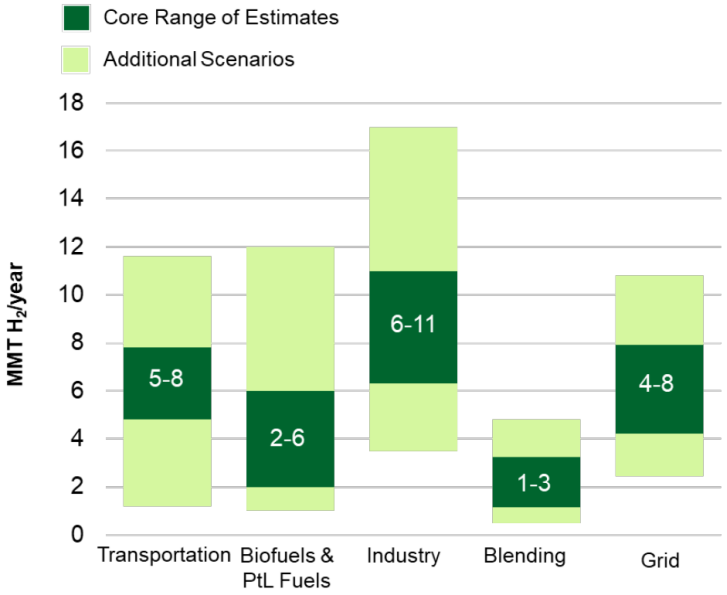
The Opportunity for Clean Hydrogen



Clean Hydrogen Use Scenarios

- Catalyze clean H_2 use in existing industries (ammonia, refineries), initiate use for sustainable aviation fuels (SAFs), steel, potential exports
- Scale up use for heavy-duty transport, industry, and energy storage
- Market expansion across sectors for strategic, high-impact uses

Range of Potential Demand for Clean Hydrogen in U.S. by 2050

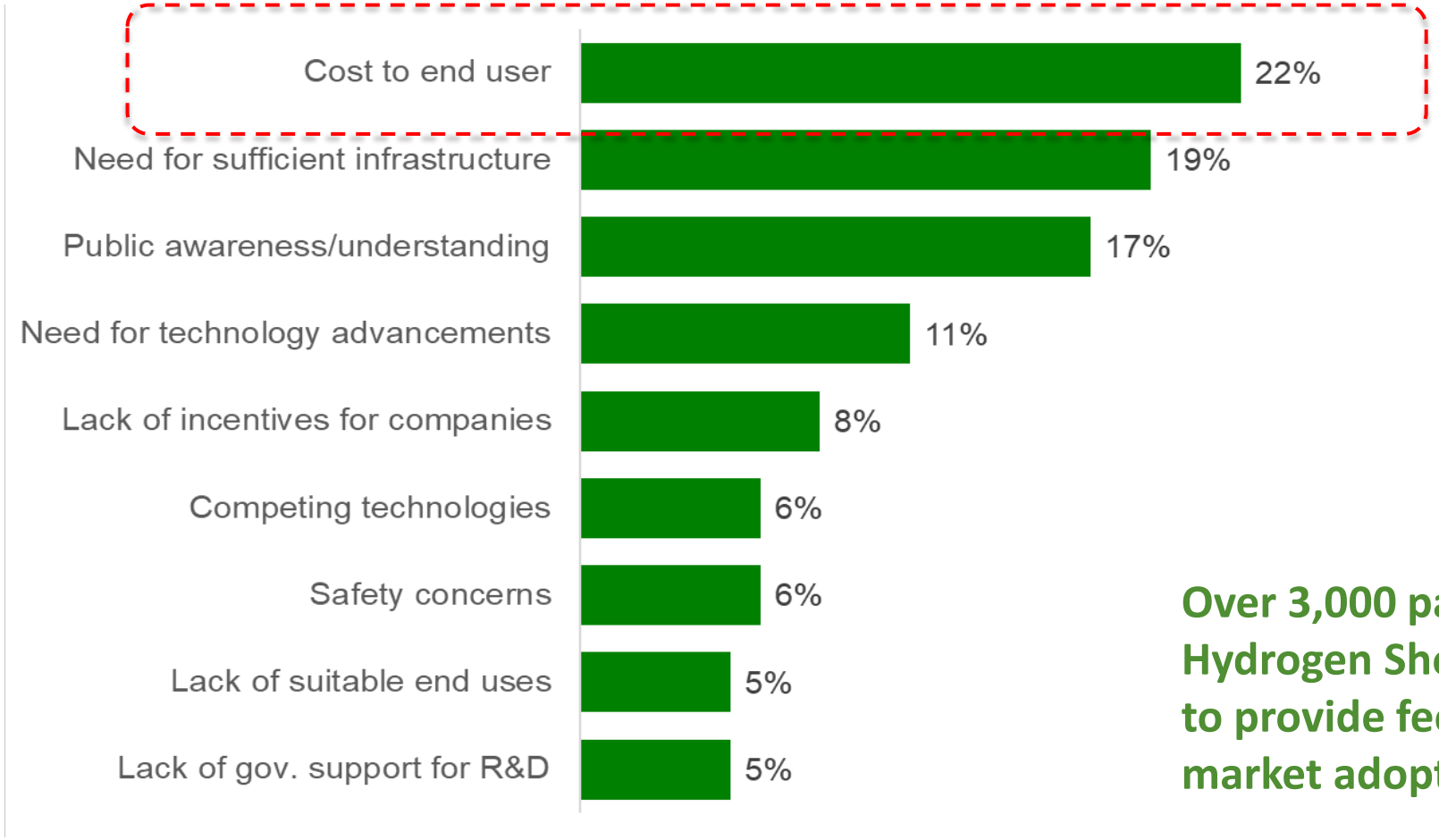


- **Core range: ~ 18–36 MMT H_2**
- **Higher range: ~ 36–56 MMT H_2**

Refs: 1. NREL MDHD analysis using TEMPO model; 2. Analysis of biofuel pathways from NREL; 3. Synfuels analysis based off H2@Scale ; 4. Steel and ammonia demand estimates based off DOE Industrial Decarbonization Roadmap and H2@Scale. Methanol demands based off IRENA and IEA estimates; 5. Preliminary Analysis, NREL 100% Clean Grid Study; 6. DOE Solar Futures Study; 7. Princeton Net Zero America Study

Strategy 2: Focus on Cost-Reduction

Stakeholder Reported Barriers to Hydrogen Market Adoption



Over 3,000 participants at DOE Hydrogen Shot Summit were requested to provide feedback on key barriers to market adoption of hydrogen

Source: Hydrogen Shot Summit, Sept 2021

https://www.energy.gov/eere/fuelcells/hydrogen-shot-summit

Hydrogen Energy Earthshot

“Hydrogen Shot”

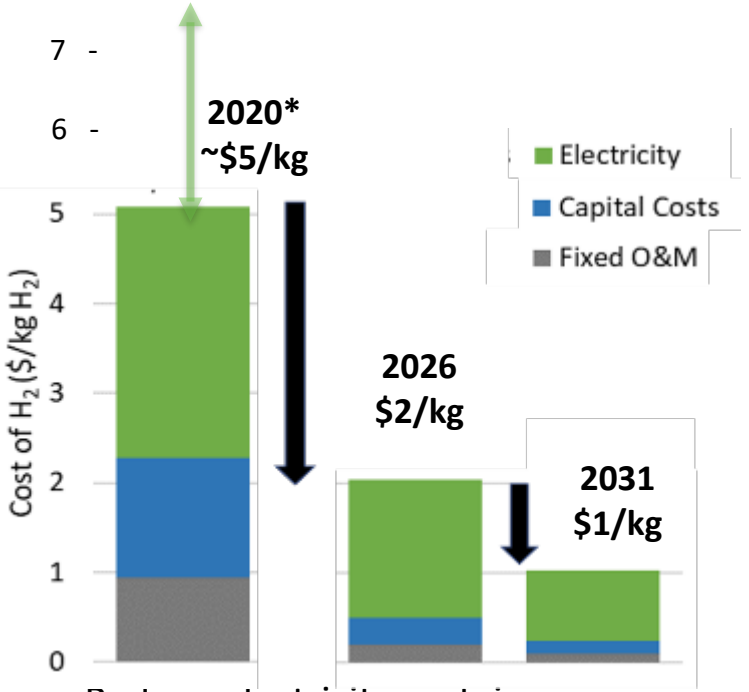
“1 1 1”
$1 for 1 kg clean hydrogen in 1 decade

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

How to reduce cost? Examples across multiple pathways

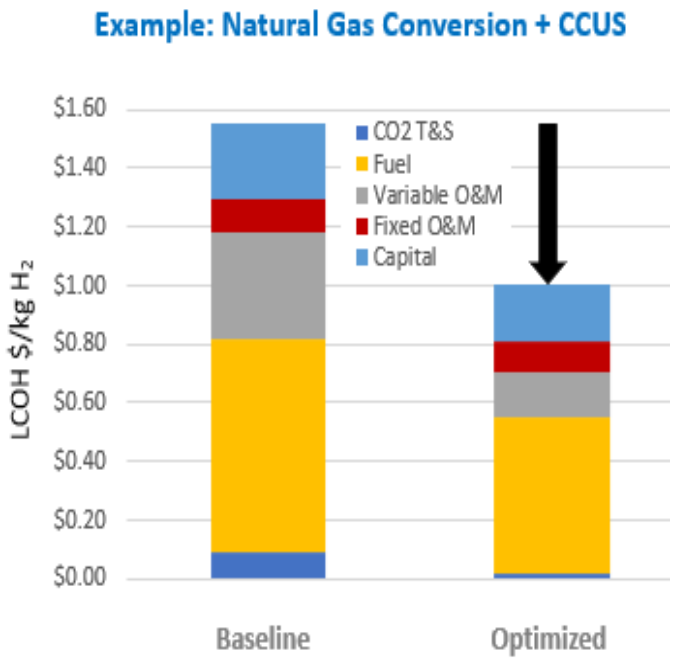
Strategies and scenarios being developed to reduce cost and emissions across pathways

H_2 from Electrolysis



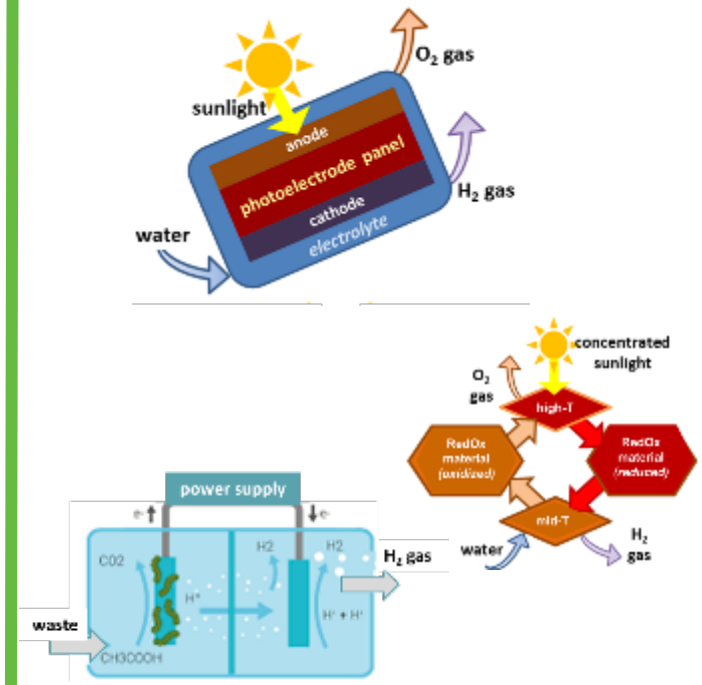
- Reduce electricity cost, improve efficiency and utilization
- Reduce capital cost >80%, operating & maintenance cost >90%

Thermal Conversion



- Reforming; pyrolysis; air separation; catalysts; carbon capture and storage (CCS); upstream emissions

Advanced Pathways

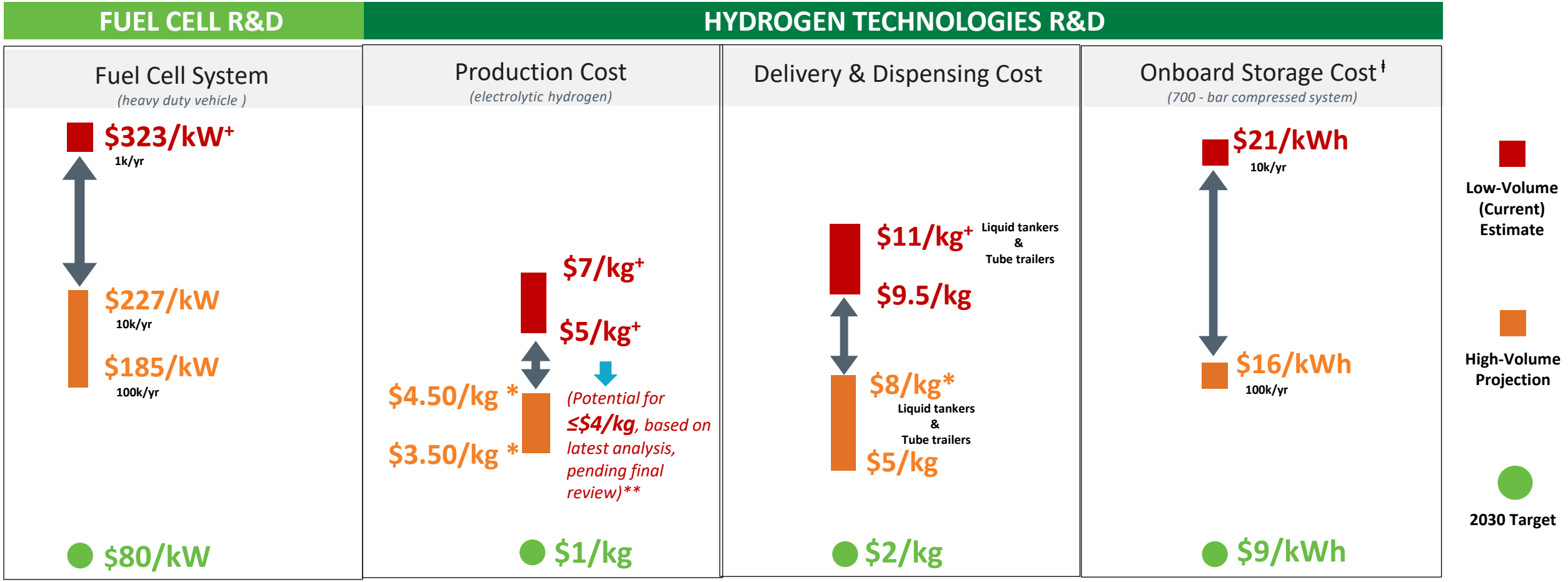


- Photelectrochemical (PEC), thermochemical, biological, etc.

*2020 Baseline: PEM (Polymer Electrolyte Membrane) low volume capital cost ~$1,500/kW, electricity at $50/MWh. Pathways to targets include capital cost <$300/kW by 2025, < $150/kW by 2030 (at scale). Assumes $50/MWh in 2020, $30/MWh in 2025, $20/MWh in 2030

Technology Targets Guide RD&D Activities

Key Goals: Reduce the cost of fuel cells and hydrogen production, delivery, storage, and meet performance and durability requirements – guided by applications specific targets



†Based on 275 kW Heavy Duty Fuel Cell System Cost Analysis (2021), adjusted to reflect cost of system that meets 25,000 hours durability

‡5 to 7 cents/kWh, 90% capacity factor at $1500/kW
*5 to 7 cents/kWh, 90% capacity factor at $460/kW
** See Hydrogen Technologies Plenary presentation for more information about pending Program Record

†For range: Delivery and dispensing at today's (2020) stations with capacity ~450 kg/day
*For range: Delivery and dispensing at today's (2020) stations with capacity 450-1,000 kg/day at high volume manufacturing

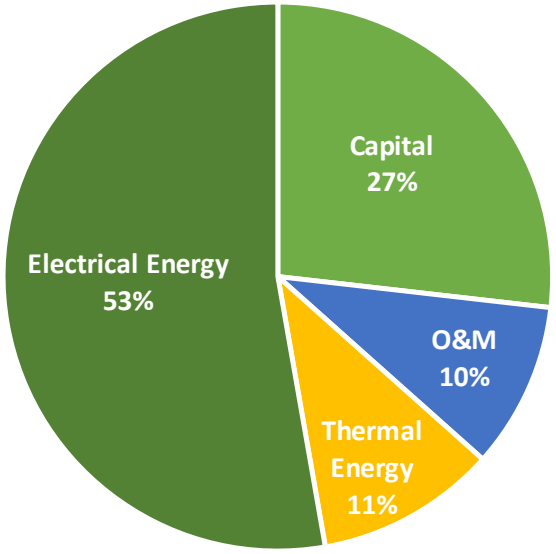
‡Storage costs based on 2019 storage cost record

All costs based on $2016

Note: Graph is not at scale. For illustrative purposes only

Examples of Cost Drivers and Focus Areas for Hydrogen Technologies

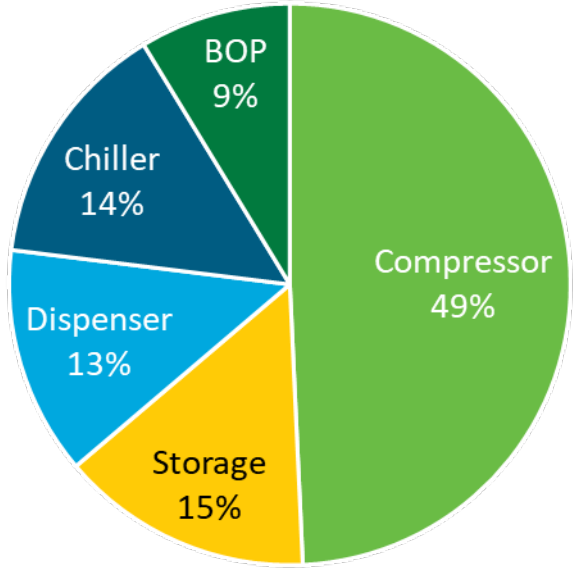
Hydrogen Production Cost
(High Temperature Electrolysis)



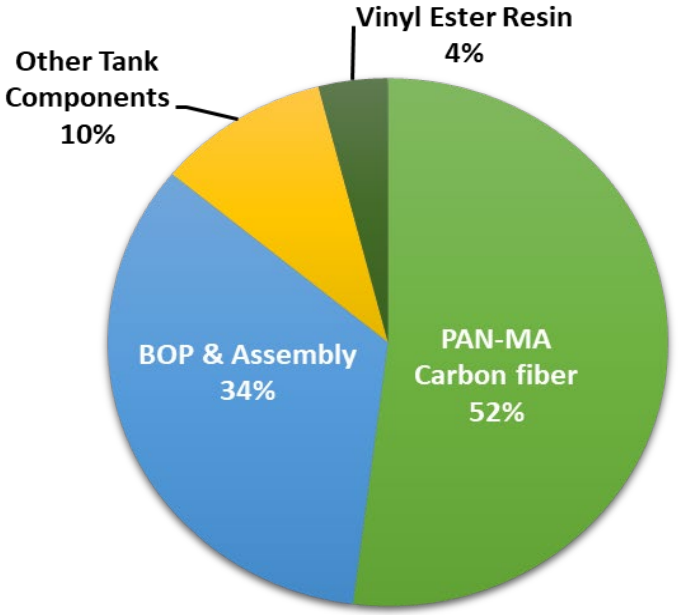
H_2 Production (Electrolysis) Cost Drivers:
Electrical energy and capital costs

H_2 Infrastructure Cost Drivers:
Compressors, Chiller, Dispenser and Storage

Hydrogen Fueling Station Levelized Cost
(700 Bar, 800 kg/day Station)



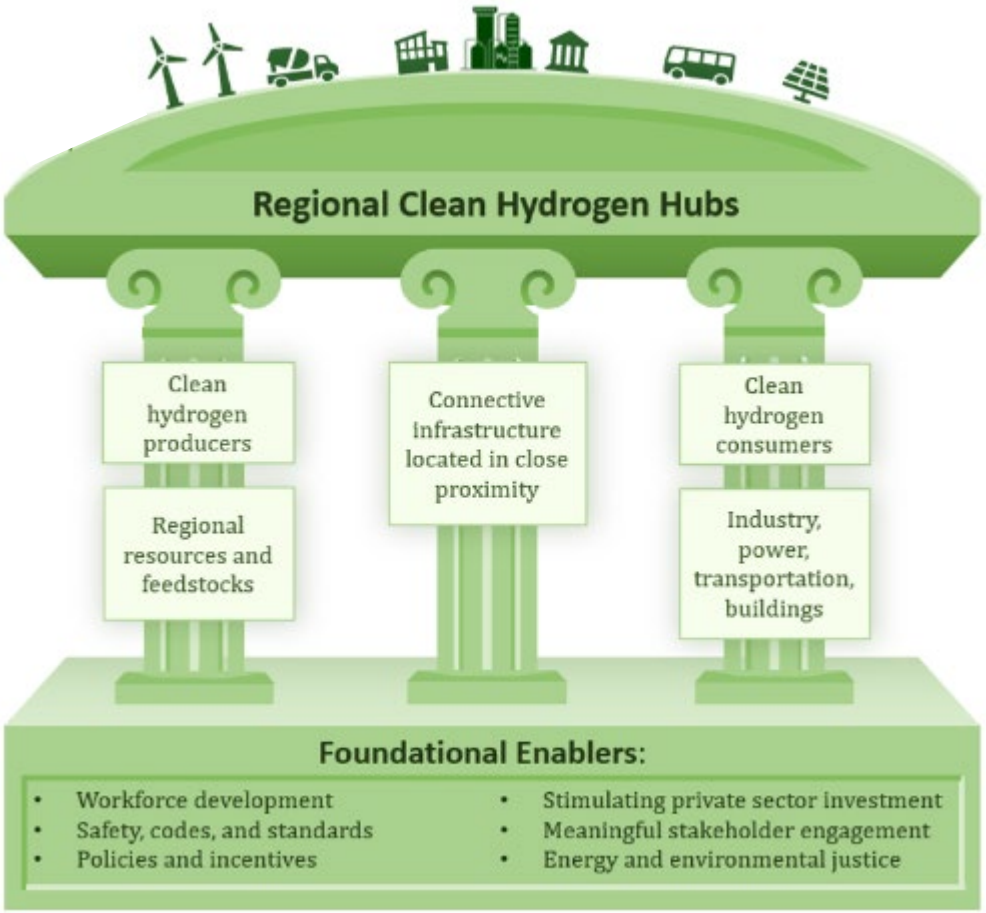
Hydrogen Storage Cost
(700 bar Type IV, 5.6 kg Hydrogen Storage System)



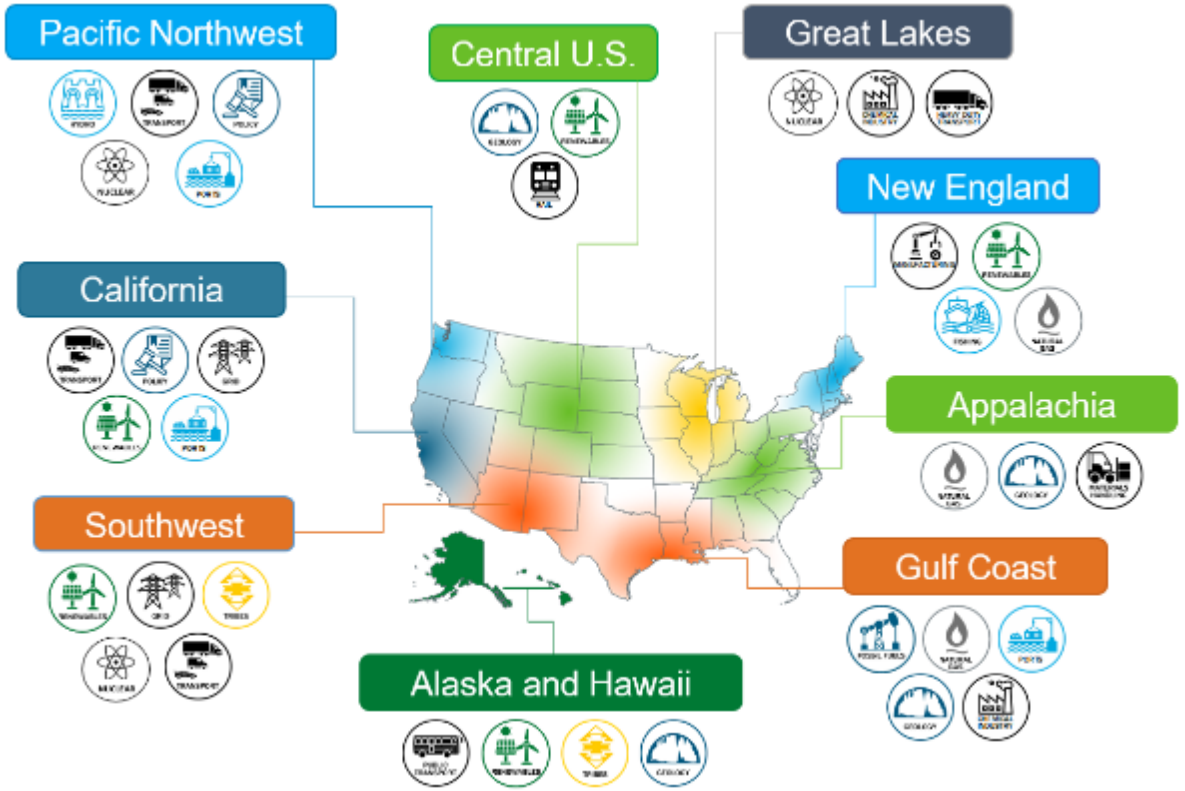
H_2 Onboard Storage Cost Drivers:
Carbon Fiber Precursors and Processing

Strategy 3: Focus on Regional Networks

Build Regional Networks through "Clean Hydrogen Hubs"



Examples of Stakeholder and RFI Input



Stakeholder Feedback Identified Opportunities for Regional Clusters

Pacific Northwest

- *Port communities*
- *Tribal communities*
- *Extensive renewables*
- *8 jobs per $1M invested in H_2*

California

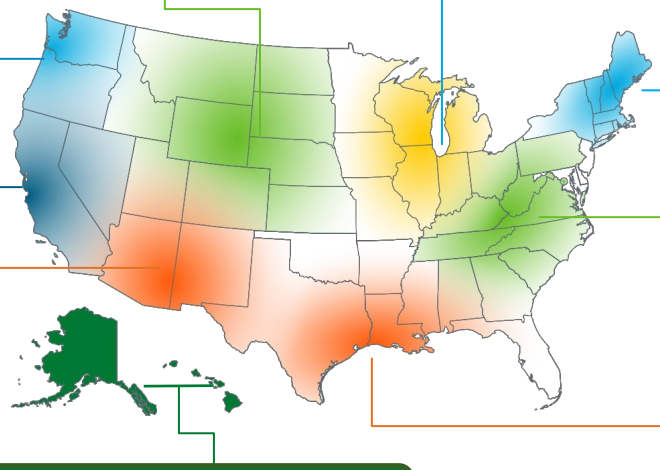
- *Diverse populations*
- *Extensive infrastructure*
- *Emissions regulations*
- *40,000+ jobs*

Southwest

- *Tribal and Hispanic communities*
- *Underutilized solar*
- *Nuclear power*
- *Up to 2B tonnes/yr emission reduction potential*

Central U.S.

- *Ample wind*
- *Geological storage*
- *Railway transport*
- *Nuclear resources*
- *>630,000 tonnes/yr CO_2 reduction*



Alaska and Hawaii

- *Extensive renewables – geothermal, solar, ocean*
- *Backup power*
- *Isolated communities*
- *86,000 tonnes/yr emission reduction*

Great Lakes

- *Major national corridors • Nuclear power • 60,000+ jobs*

New England

- *Offshore wind*
- *Fishing communities*
- *Backup power and winter heating*
- *~120K tons CO_2/year reduction*

Appalachia

- *Retiring fossil plants*
- *Mining, refining transferable skills*
- *Carbon capture and sequestration*
- *70,000 tons/yr H_2 production*

Gulf Coast

- *Existing infrastructure*
- *Multiple opportunity zones*
- *Renewable resources*
- *1,000s of jobs*
- *Chemical industry*

Example: Industrial Clusters to Enable Large-Scale Offtakers

Priority deployments for hydrogen in industry include sectors where other decarbonization pathways are challenging, such as high-temperature heat generation, steelmaking, and ammonia production.

National Distribution of **Industrial Sites**, **CO_2 Output**, and **CO_2 Sink Demand**

Industrial Sites

Aluminum	Lime
Ammonia	Magnesium
Carbonate Use	Petrochemicals
Cement	Pulp and Paper
Ethanol	Refining
Ferroalloy	Silicon Carbide
Glass	Soda Ash
Iron and Steel	Titanium Dioxide
Lead	Zinc

CO_2 Sources (kt/year)

- < 500
- 500.01 - 1250
- 1250.01 - 3000
- 3000.01 - 6250
- > 6250

CO_2 Sink Demand (kt)

500
250
0.0

Mapping industrial sites to CO_2 sources and demands can help identify **industrial clusters for potential decarbonization hubs**

Adapted from Carbon Capture and Utilization in the Industrial Sector | Environmental Science & Technology (acs.org)

Ongoing Work and Accomplishments to Address Key Priorities

Program Enabled Accomplishments

Innovation

1,256 Patents

in hydrogen and fuel cell technologies through HFTO funding from Labs, Industry and Academia

35% from National Labs

Technology-to-Market

30 Technologies Commercialized

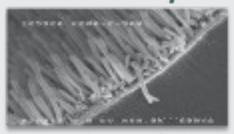
By private industry

65 With Potential to Enter Market

in the next 3-5 years

Examples of Technologies Enabled

Fuel Cell Catalysts



Catalyst and Supports for PEM Fuel Cells
3M

Hydrogen Tube Trailers

Hydrogen Tube Trailers
Hexagon Lincoln

Forklifts

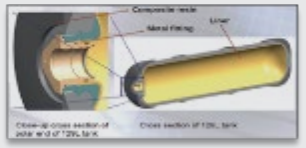
Class-1, -2, and -3 Forklifts
Plug Power (GenDrive FCs)

Electrolyzers

Electrolyzer System
Proton Series

PEM Electrolyzer System
Giner

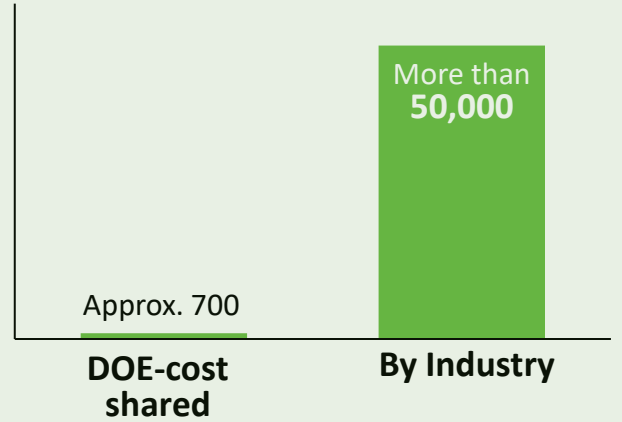
Hydrogen Tanks



Optimized 129L Tank
Quantum Technologies

Market Uptake

Hydrogen fuel cell forklifts in the U.S.



American-made small-scale hydrogen refueler

- Exported to Japan
- Uses electrolysis

DOE Hydrogen Activities across RDD&D – Examples

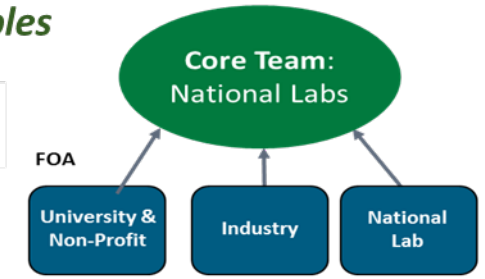
Research and Development

Basic and applied research through individual projects and consortia

Consortia Examples

HydroGEN Advanced Water Splitting Materials

H2NEW U.S. DEPARTMENT OF ENERGY



H-Mat Hydrogen Materials Compatibility Consortium

ElectroCat Electrocatalysis Consortium

HyMARC Hydrogen Materials Advanced Research Consortium

FCT U.S. DEPARTMENT OF ENERGY

MILLION MILE FUEL CELL TRUCK

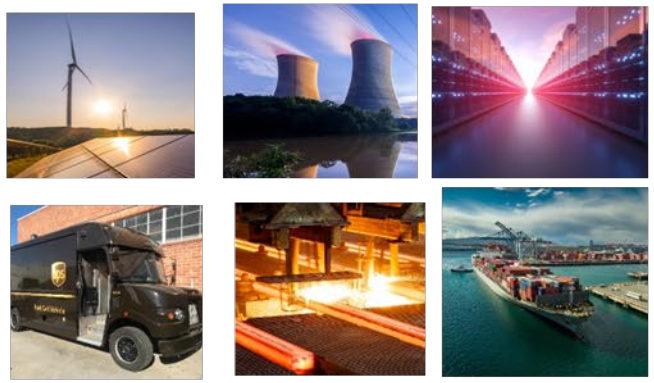
SHASTA Subsurface Hydrogen Assessment, Storage, and Technology Acceleration

Basic science user facilities, theory, modeling

Technology Integration, Validation, Demos

1st of a kind demonstrations and systems integration to de-risk deployments

Examples:



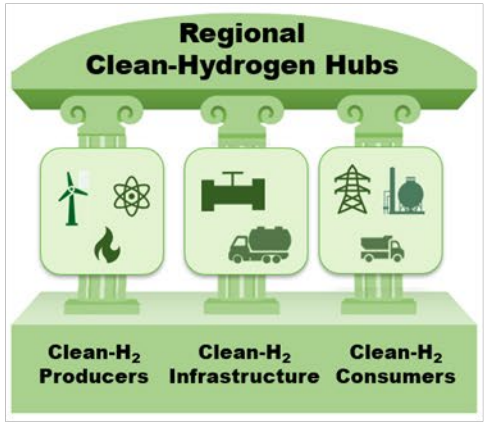
Renewables and nuclear to H_2, 15 delivery trucks in disadvantaged area, 3 Super Truck projects, data center, fueling for passenger ferry, energy storage, H_2 for steel

Deployment and Financing

H2 Hubs, loan guarantee program, workforce development

Example:

$8 billion for at least 4 hubs: Renewables, fossil w/CCS, nuclear; multiple end-uses



2 new loan guarantee projects ($1.5B total) on pyrolysis and large-scale electrolysis, H_2 energy storage and power generation

Enabling Activities

- Analysis and tools
- Safety, codes & standards
- Manufacturing
- Workforce development

H2EDGE Hydrogen Education for a Decarbonized Global Economy

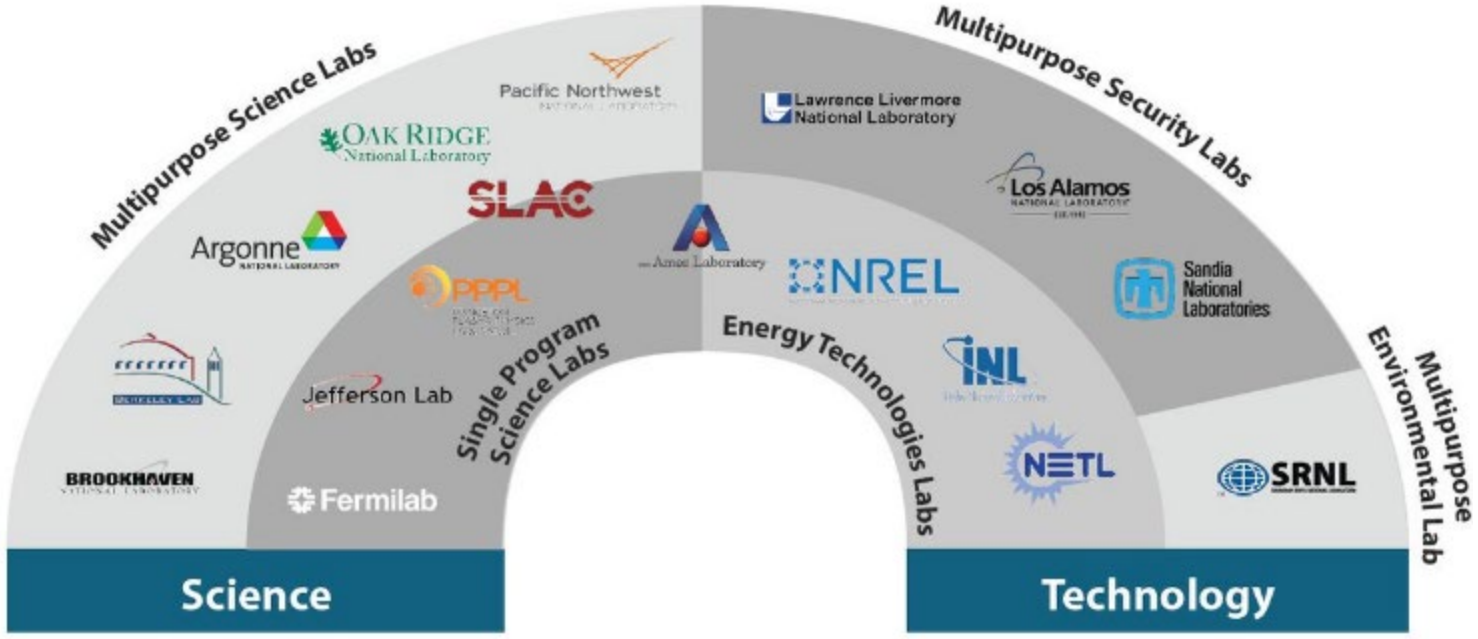
CENTER FOR Hydrogen SAFETY Connecting a Global Community

HyBlend U.S. DEPARTMENT OF ENERGY

H2 Matchmaker

DOE National Laboratories

Strategy leverages DOE National Laboratories, partnering with industry and academia



DOE National Laboratories across energy, science, and security:

- Support RD&D
- Offer User Facilities and science resources
- Help to de-risk technology adoption, accelerating progress

HyBlend and H-Mat Consortia

To assess and enhance compatibility of key materials with hydrogen, and to accelerate the use of hydrogen in multiple applications (including in natural gas blending)

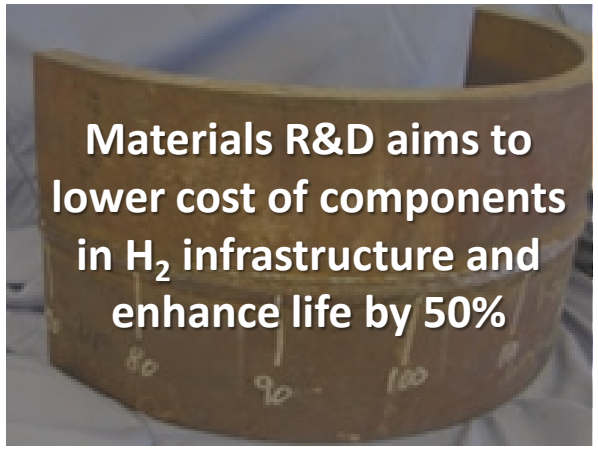
H-Mat Hydrogen Materials Compatibility Consortium

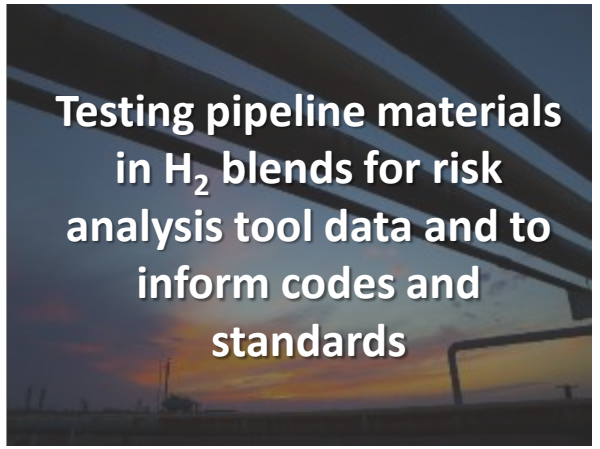
National lab consortium to assess and improve performance and reliability of materials in hydrogen, reduce costs, and inform codes and standards

HyBlend U.S. Department of Energy

Pipeline materials compatibility R&D, technoeconomic analysis, and life-cycle analysis to assess the feasibility of hydrogen blending in the U.S. natural gas pipeline infrastructure

Over 30 partners





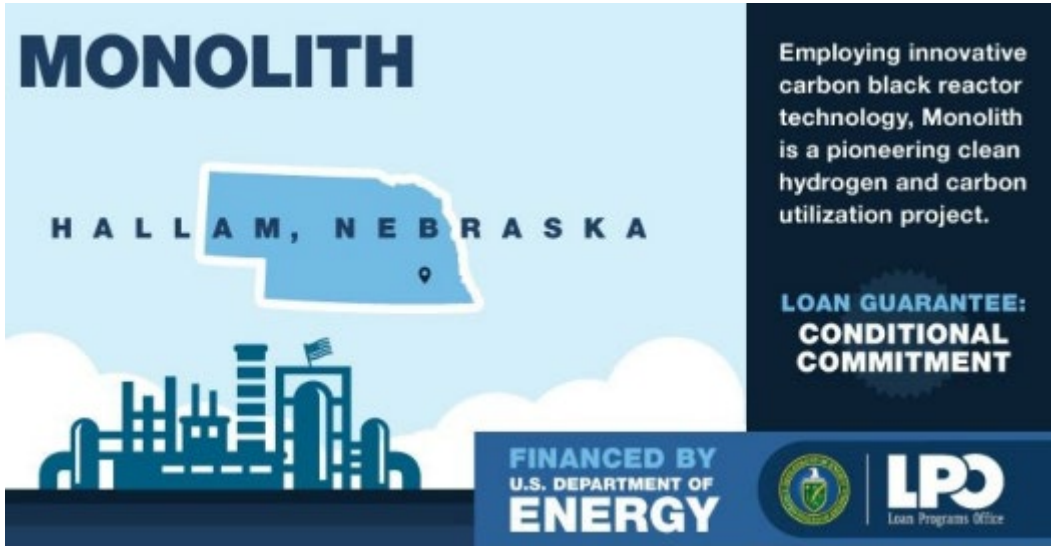
Labs Sandia National Laboratories | PNNL | SRNL | Oak Ridge National Laboratory | Argonne National Laboratory

Labs NREL | Sandia National Laboratories | PNNL | Oak Ridge National Laboratory | Argonne National Laboratory | NETL

Financing to Enable Deployment at Scale

Loan Programs Office (LPO) has $40 Billion in Available Debt Capital

LPO announces loan guarantees for two clean hydrogen projects
(one guarantee pending, as "conditional commitment")



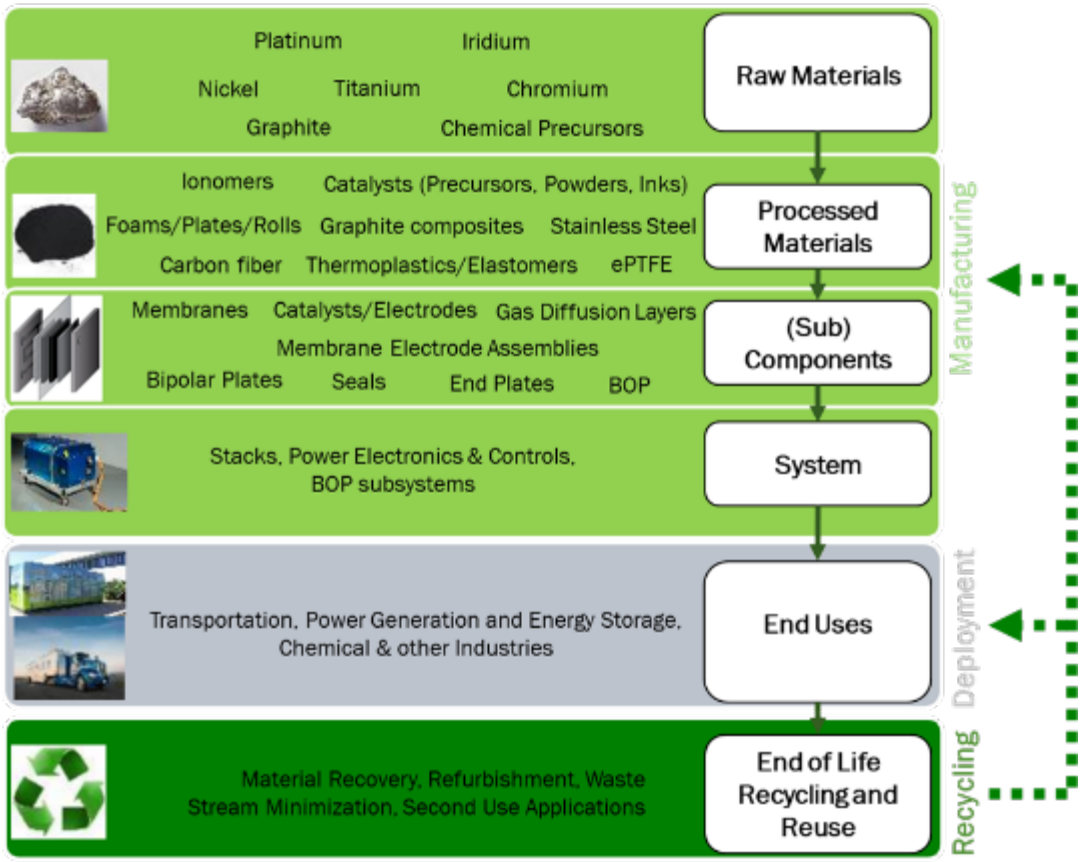
$1.04B for the first-ever commercial-scale project to deploy methane pyrolysis technology. Will enable 1,000 construction jobs and 75 operations jobs. (Conditional commitment for loan guarantee announced December 2021)

$504.4M for large-scale hydrogen energy storage, 220 MW electrolysis and turbine. Will enable up to 400 construction jobs and 25 operations jobs. (Loan guarantee closed in June 2022)

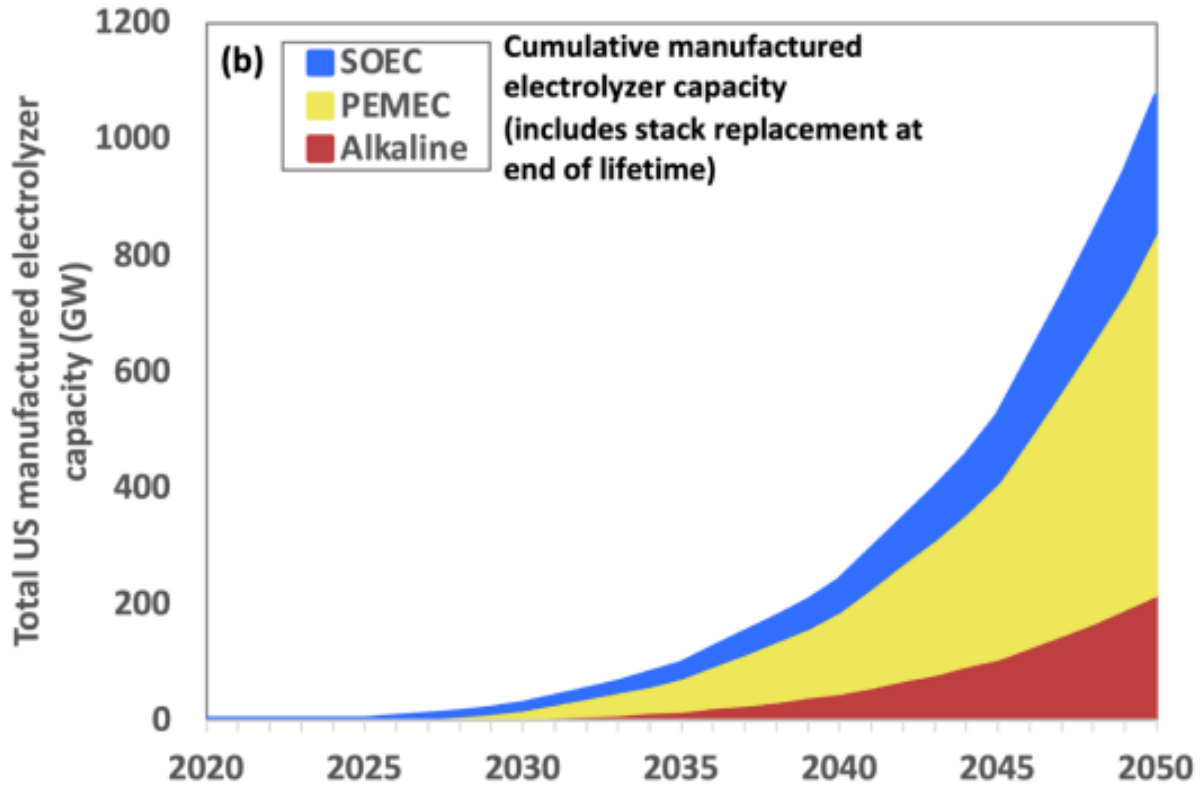
Supply Chain Report

Investigated key U.S. opportunities to enable the growth of electrolytic hydrogen and fuel cell markets

Example: PEM fuel cell & electrolyzer supply chain



Example: Scenario for U.S. electrolyzer capacity



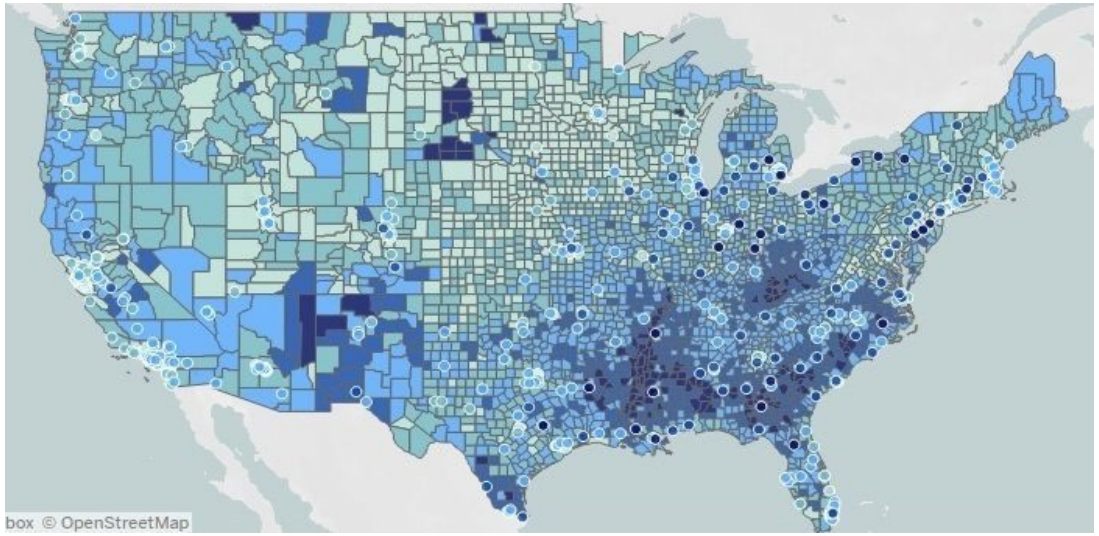
More information: www.energy.gov/eere/fuelcells/water-electrolyzers-and-fuel-cells-supply-chain-deep-dive-assessment


Collaboration
Diversity, Equity, Inclusion

The redwoods are the tallest trees on earth—growing tall and enduring long dry spells—on harsh terrain and despite shallow roots.

They are able to do this through the collective strength of their roots which are an interwoven system, where each tree supports—and is supported by—the trees around it.

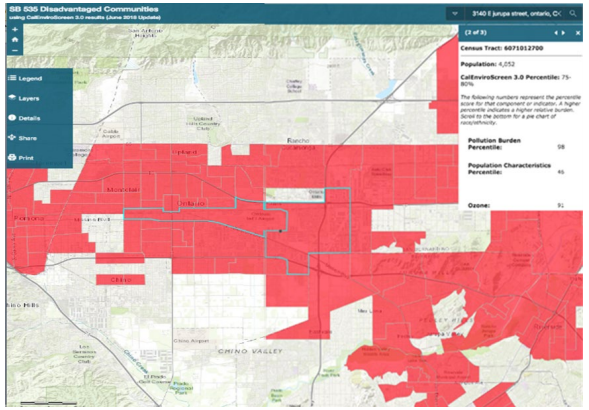
Focus on Benefits in Underserved & Disadvantaged Communities



[New index ranks America's 100 most disadvantaged communities | University of Michigan News (umich.edu)]

Funding Opportunities will encourage broader engagement, demonstrating benefits, including DEI (minorities, gender equity, etc.)

Example: DOE project with CTE for UPS Fuel Cell Delivery Vans



Trucks will be demonstrated in Ontario, CA- disadvantaged community

Goal: Demonstrate 15 fuel cell trucks (up to 125-mile range)

Project impact per year: Savings of

- **285 metric tons of CO_2-eq**
- **280,000 grams of criteria pollutants**
- **56,000 gallons of diesel**

Call to Action: Join the Center for Hydrogen Safety!

IPHE

AIChE
The Global Home of Chemical Engineers

Hydrogen Council

Pacific Northwest NATIONAL LABORATORY

hySafe
INTERNATIONAL ASSOCIATION FOR HYDROGEN SAFETY

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

www.aiche.org/CHS

Over 90 members from industry, government, and academia—and growing!

New Hydrogen Safety Credential!

Composed of 7 fundamental hydrogen safety e-courses, including:

- Properties & Hazards
- Safety Planning
- System Operation
- Inspection & Maintenance

Examples of International Collaboration

Collaborating through multiple global and bilateral partnerships—key priority is creating coordinated framework to leverage activities, identify gaps, and avoid duplication to accelerate progress

CEM Global Ports Coalition with EC
Numerous Bilaterals on Hydrogen
Hydrogen Council, IRENA, and more

The International Partnership for Hydrogen and Fuel Cells in the Economy

Enabling the global adoption of hydrogen and fuel cells in the economy

H_2 Production Analysis (H2PA)
To facilitate international trade
Common analytical framework for GHG emissions footprint

Regulations, Codes, Standards, Safety and Education & Outreach Working Groups

www.iphe.net

Breakthrough Agenda in collaboration with other partnerships is mapping activities across global H_2 initiatives to identify gaps, focus areas, and prioritized workstreams

IPHE Early Career Network

Calling all hydrogen-enthusiast **STUDENTS** (undergraduate & graduate), **POST-DOCS**, and **EARLY CAREER PROFESSIONALS** worldwide!

Connect with peers, mentors, scientific researchers, industry professionals, and policymakers!

Networking ● Career Development ● Webinars
Research ● Policy ● Leadership ● Science

230+ members from 37 countries

www.iphe.net/early-career-chapter

2022-2023 Leadership Team

Handoff from Current Chair and Vice-Chairs for New Term

Chair
Christine Watson (USA)

Vice-Chair
Gaurav Shukla (India)

Vice-Chair
Kendall Parker (USA)

Chair: Gaurav Shukla (India)

Vice-Chair

Sookyung Kang
(France/Korea)

Vice-Chair

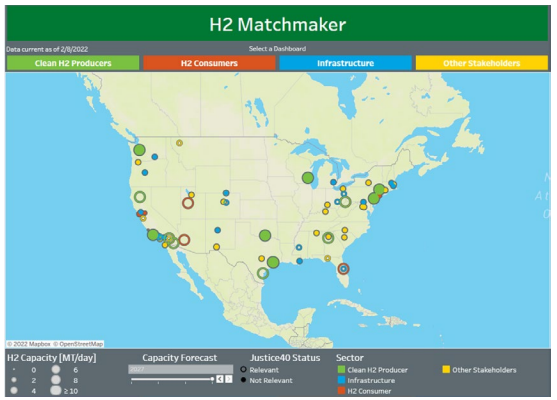
Tomas Green
(USA)

Vice-Chair

Manan Prathak
(India)

Resources and Opportunities for Engagement

ENERGY earthshots | Hydrogen
U.S. DEPARTMENT OF ENERGY

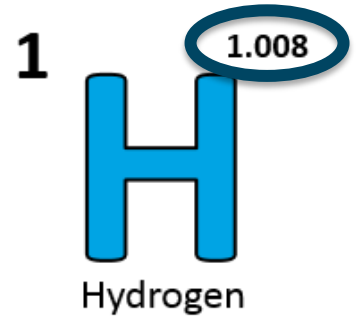


Save the date!

2023 DOE Annual Merit Review and Peer Evaluation Meeting
June 5-8, 2023

Hydrogen and Fuel Cells Day
October 8

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



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Sign up to receive hydrogen and fuel cell updates

www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-newsletter

Learn more at: energy.gov/eere/fuelcells AND www.hydrogen.energy.gov

Thank you

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U.S. Department of Energy

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