Are We Looking at "Green Hydrogen?"

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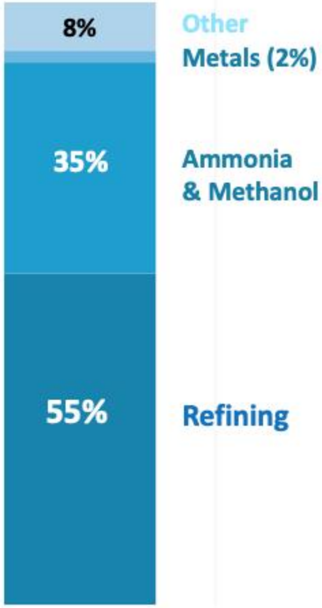
April 12, 2024

Photo by Dennis Schroeder, NREL 46840

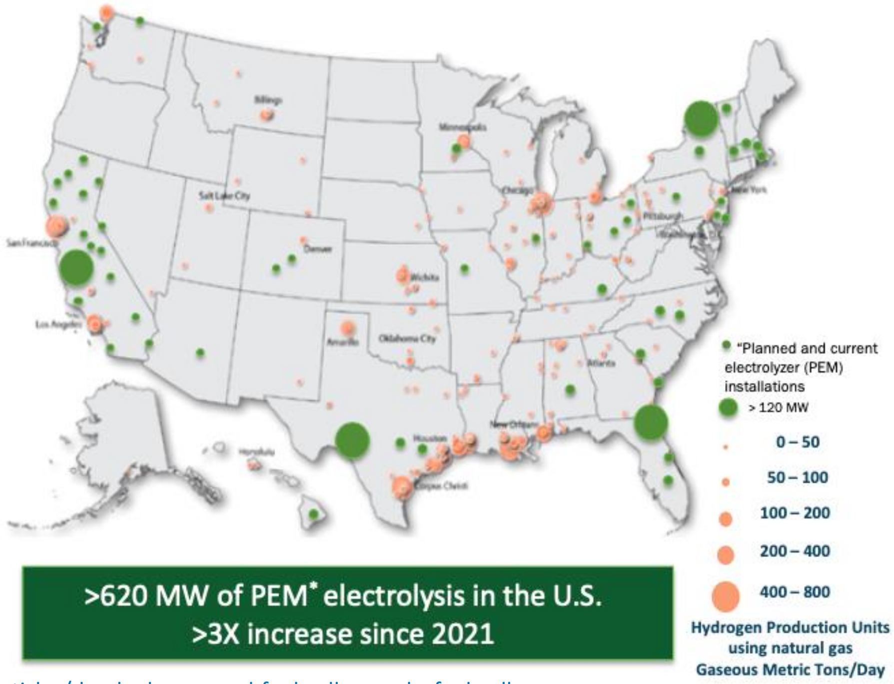
How Does the U.S. Use Hydrogen Today?

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

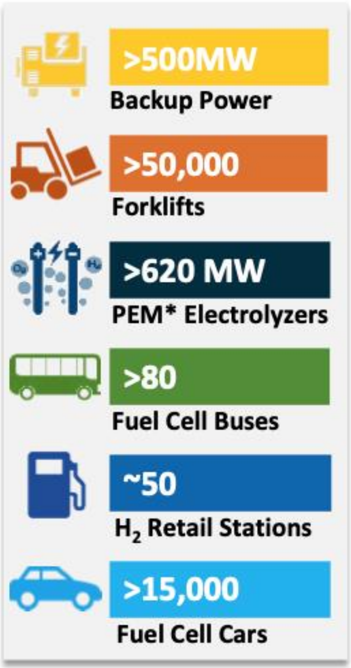
Use of Hydrogen in the U.S. Today



Examples of Hydrogen Production Locations



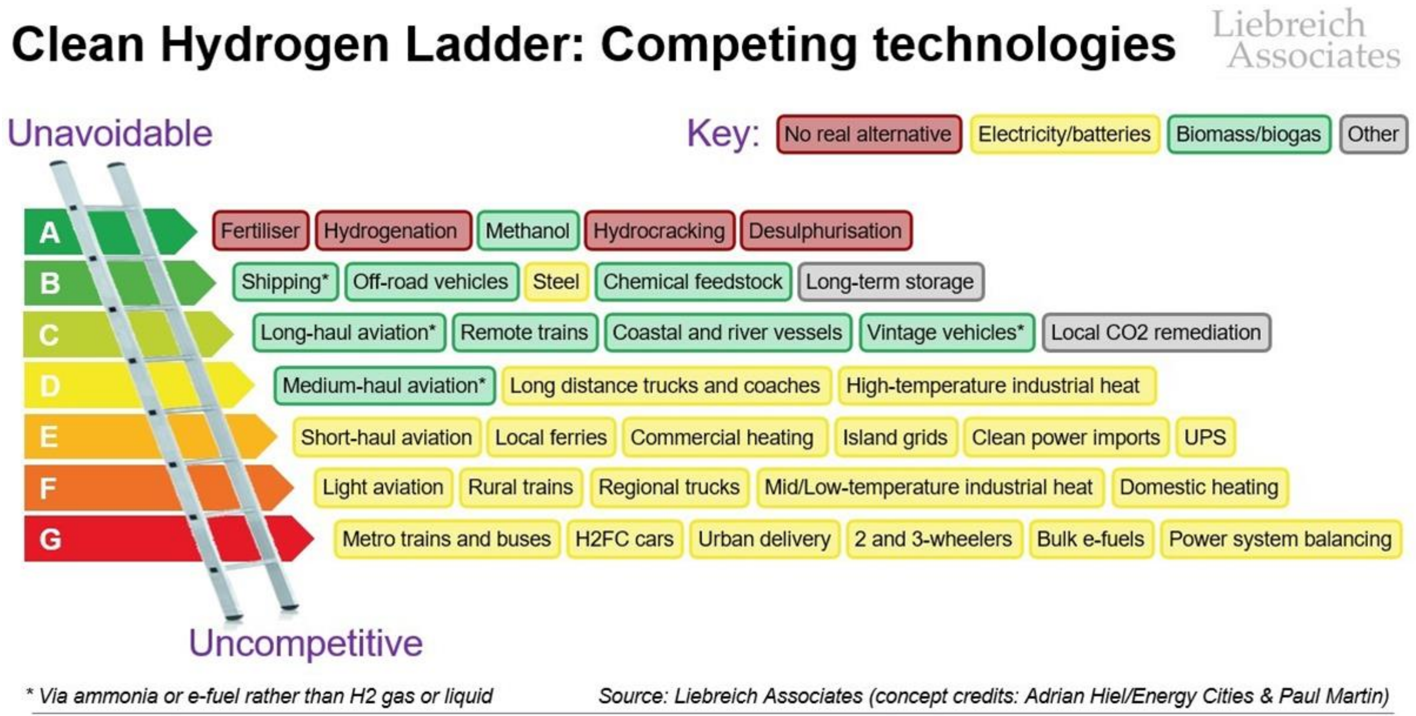
Examples of Deployments



*Proton exchange membrane

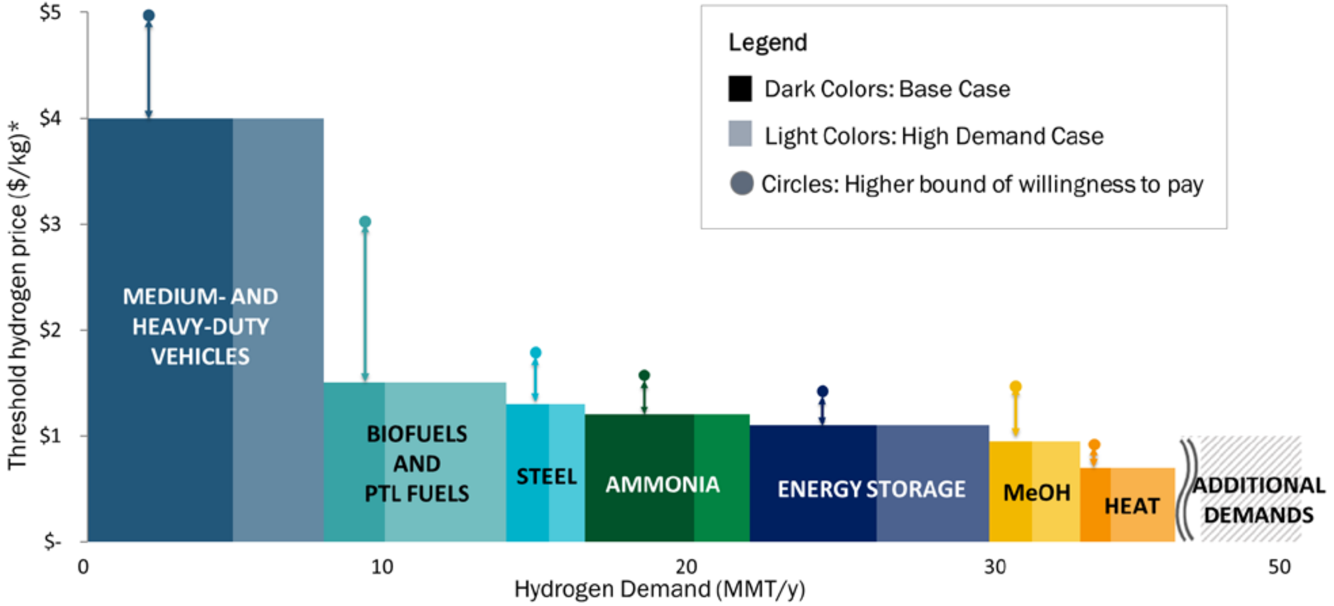
Source: https://www.energy.gov/eere/fuelcells/articles/doe-hydrogen-and-fuel-cell-remarks-fuel-cell-expo

Where Might Hydrogen Benefit Future Energy Systems?



Hydrogen is most appropriate for applications that are impossible or too expensive to electrify – often these are location-specific

Economic Drivers for Hydrogen in Future Energy Systems



*Price at point of use (includes production, delivery, and dispensing)

PTL: Power-to-Liquids
MeOH: Methanol

Estimates & Considerations

Hydrogen volumes dependent upon many variables

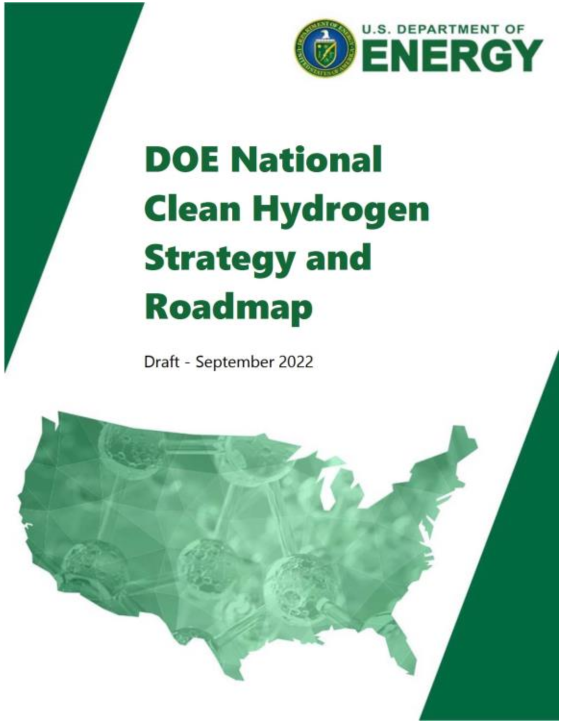
Key estimates

- Trucks: ≃ 10%-15% total energy
- Aviation: 100% sustainable aviation fuel using hydrogen
- Steelmaking: ≃ 10% using H_2
- Ammonia: 100%
- ≃50% of methanol
- Blends with natural gas for high-temperature heat
- Additional applications include stationary power, synfuels, and exports

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

U.S. Clean Hydrogen Strategy and Roadmap

"Snapshot of hydrogen production, transport, storage, and use in the United States today and the opportunity that clean hydrogen could provide in contributing to national goals across sectors."



Identifies strategic opportunities for clean hydrogen

- 10 MMT/yr by 2030
- 20 MMT/yr by 2040
- 50 MMT/yr by 2050

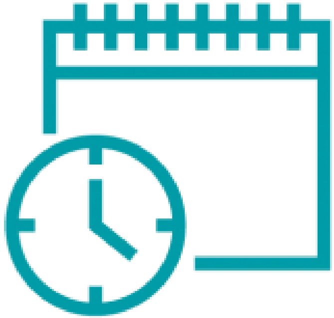
https://www.hydrogen.energy.gov/pdfs/clean-hydrogen-strategy-roadmap.pdf

Can Clean Hydrogen Meet Cost Requirements?

U.S. Department of Energy Hydrogen Shot Cost Target

1 Dollar

1 Kilogram



1 Decade

Launched June 7, 2021

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

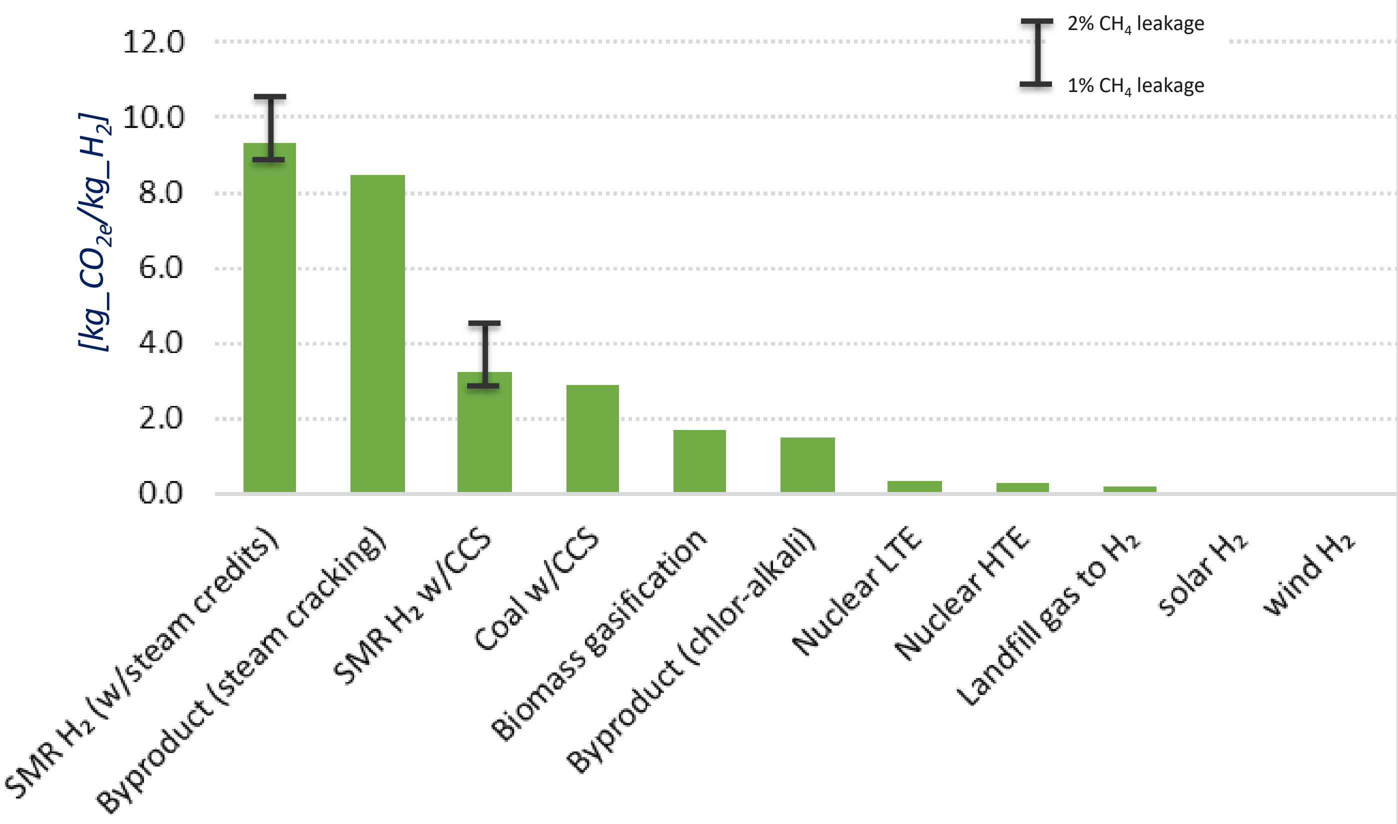
How We Often Identify Hydrogen – Colors

Color	Energy Source	Mode of Production
Green	Renewable energy	Water electrolysis
White	Natural geologic formations	Natural fracking
Yellow	Solar	Water electrolysis
No Color	Biomass	Gasification
Red	Nuclear	Catalytic splitting
Purple/Pink	Nuclear	Water electrolysis
Turquoise	Natural gas	Pyrolysis
Blue	Natural gas	Steam reforming + CCS
Gray	Natural gas	Steam reforming
Black/Brown	Coal (lignite and bituminous coal)	Gasification

Derived from: Parkinson, B., P. Balcombe, J.F. Spiers, A.D. Hawkes, and K. Hellgardt. 2018. "Levelized cost of CO2 mitigation from hydrogen production routes. *Energy & Environmental Science* 12: 19-40. https://pubs.rsc.org/en/content/articlelanding/2019/ee/c8ee02079e and https://www.nrel.gov/docs/fy22osti/82554.pdf.

A Better Option to Identify Hydrogen – Greenhouse Gas (GHG) Emissions of Hydrogen Production

Actual emissions will vary by facility depending on system design and location



https://greet.es.anl.gov/files/hydrogenreport2022

H_2 = Hydrogen
CH_4 = Methane
SMR= Steam Methane Reforming of Natural Gas;
CCS=Carbon Capture and Sequestration;
LTE=Low-Temp Electrolysis;
HTE=High-Temp Electrolysis;
LFG=Landfill Gas

Clean Hydrogen Production Tax Credit (PTC) Provision 45V

- **The clean hydrogen 45V PTC is the first-of-its-kind production-based credit specifically for hydrogen production.**
  - Projects must begin construction by 2033.
  - Credit value duration is for 10 years
  - Projects can select an investment tax credit (ITC) instead, if desired
- **Values.**
  - Emissions-based using 45VH2–GREET (https://www.energy.gov/eere/greet)
  - $0.60 per kg base
  - $3.00 per kg prevailing wage 5 x multiplier
- **The ITC 48/48E in lieu of provision 45V.**

H2 PTC Valuation

Carbon Intensity (kg CO_2e/kg H_2)	Min H_2 PTC ($/kg H2)	Max H_2 PTC ($/kg H2) (prevailing requirements)
0-0.45	$0.60 (100%)	$3.00 (100%)
0.45-1.5	$0.20 (33.4%)	$1.00 (33.4%)
1.5-2.5	$0.15 (25%)	$0.75 (25%)
2.5-4	$0.12 (20%)	$0.60 (20%)

ITC Valuation in lieu of H2 PTC

Carbon Intensity (kg CO_2e/kg H2)	ITC % Value (% of full credit)	ITC % Value (% of full credit) (prevailing requirements)
0-0.45	6% (100%)	30% (100%)
0.45-1.5	2% (33.4%)	10% (33.4%)
1.5-2.5	1.5% (25%)	7.5% (25%)
2.5-4	1.2% (20%)	6% (20%)

Energy Attribute Certificate Requirements for Provision 45V

Deliverability

Electricity generation and electrolysis in the same electrical region.

Temporal Matching

Hourly matching of electricity generation and electrolysis after Jan 1, 2028 – annual before that date.

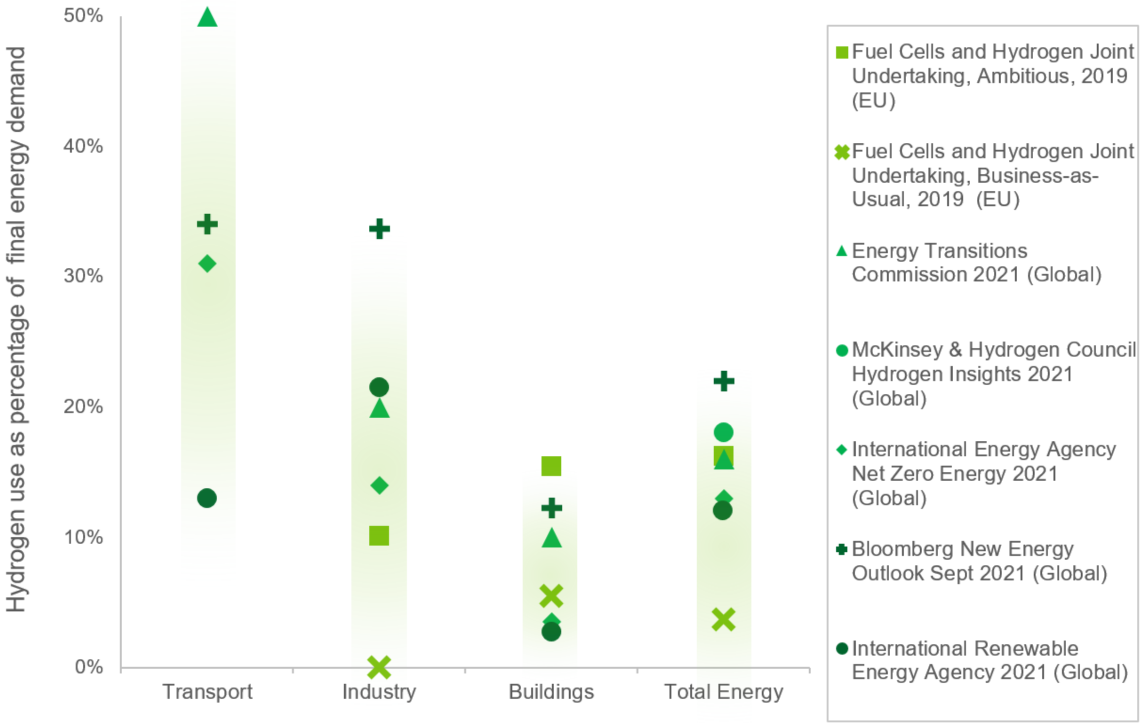
Incrementality

Electricity generation facility goes online no more than 36 months before the hydrogen production facility.

Hydrogen Has the Potential to be a Key Energy Intermediate in a Decarbonized Energy System

Multiple enablers will likely be involved in meeting that potential:

- Application technology development and scaling
- Production technology development and scaling
- Initial economic opportunities that can network and scale



Total Energy includes transport, industry, buildings, and power sector uses

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

Thank You

www.nrel.gov

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NREL Transforming ENERGY

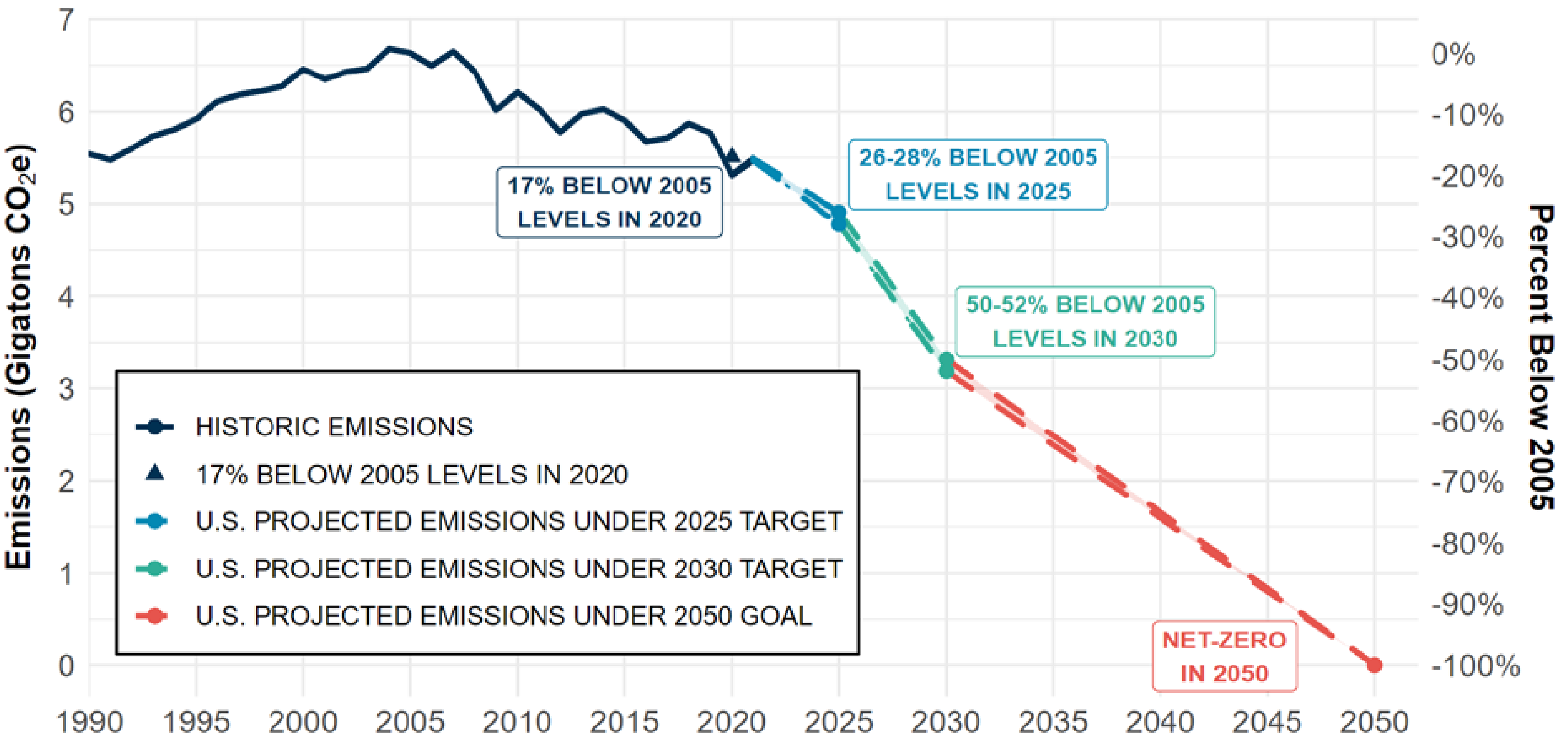
Previous Hydrogen Initiative in the U.S.

"Tonight I am proposing $1.2 billion in research funding so that America can lead the world in developing clean, hydrogen-powered automobiles."
President George W. Bush
2003 State of the Union Address

Focus on meeting consumers' range requirements and reducing oil imports

Image Source: https://en.wikipedia.org/wiki/2003_State_of_the_Union_Address

United States' Decarbonization Objective



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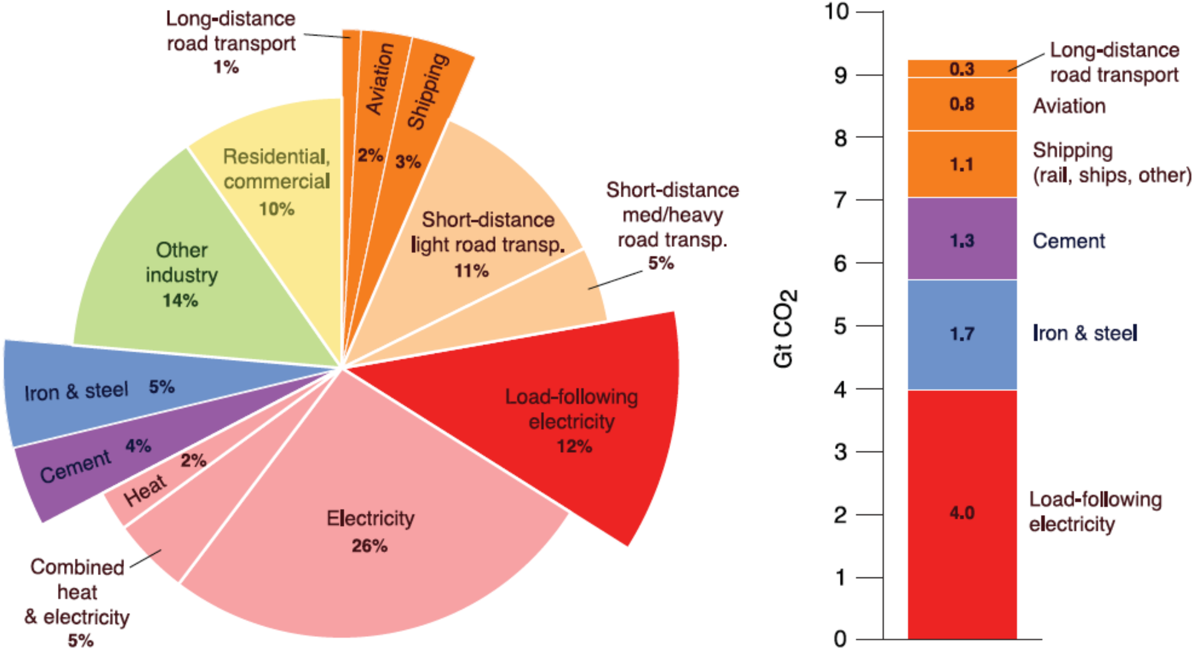
Sectors that are Difficult to Decarbonize



A **Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)**

B **Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)**

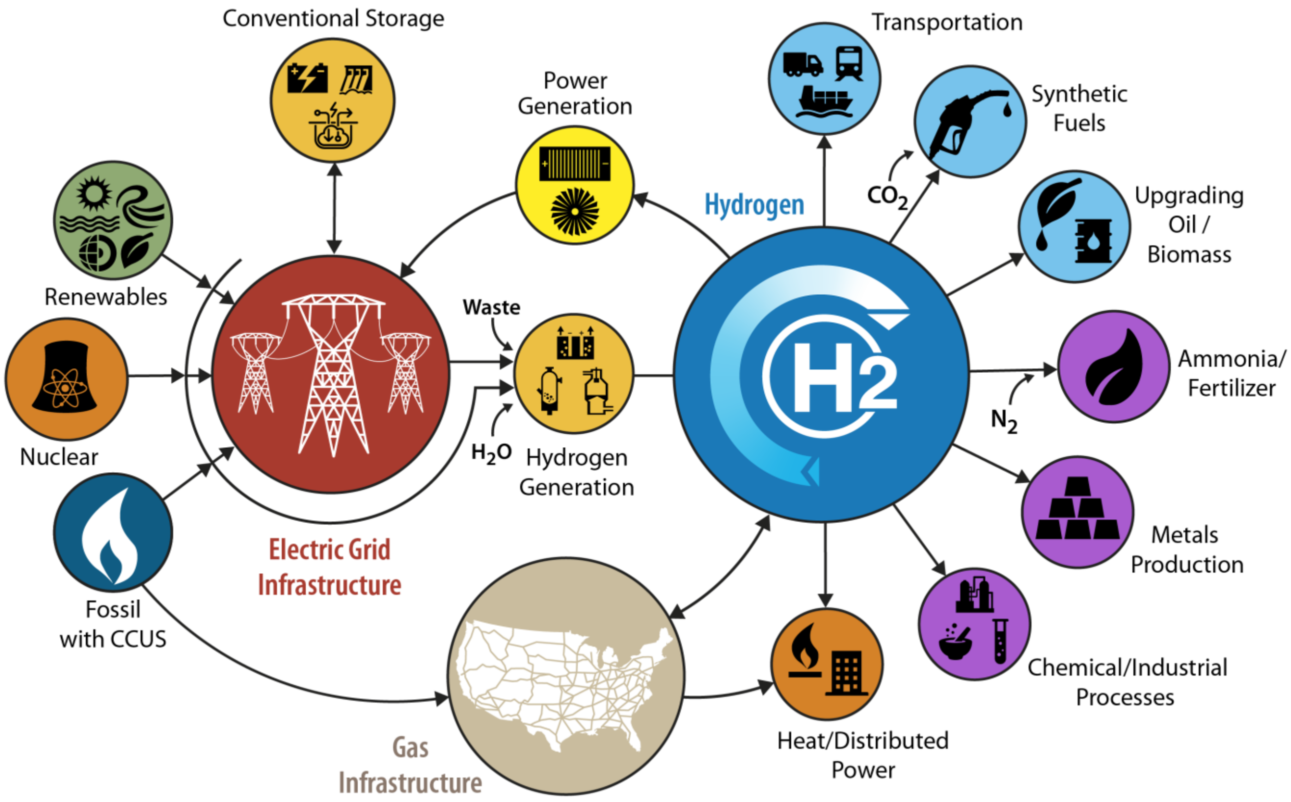
Key challenge areas

- Electricity resource adequacy
- Iron & Steel
- Cement
- Long-distance transport

Source: Adapted from S. J. Davis et al., *Science* **360**, eaas9793 (2018). DOI: 10.1126/science.aas9793

Opportunity: H2@Scale

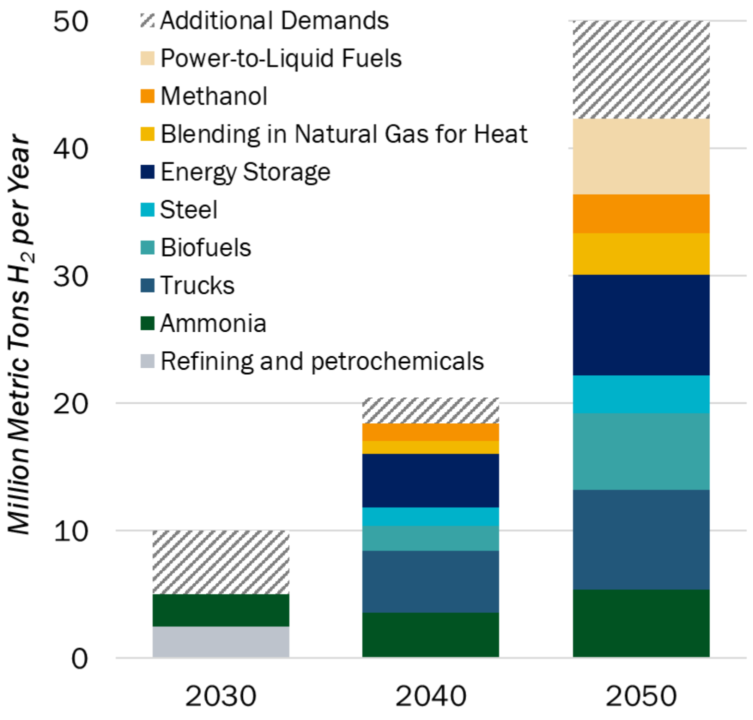
Objective:
Enable clean-energy pathways across applications and sectors by developing the full hydrogen value chain



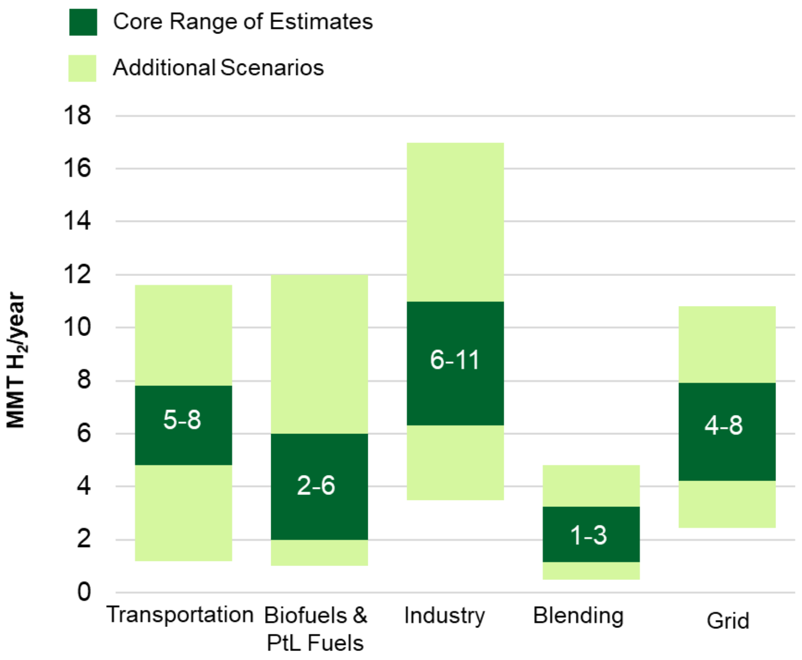
https://www.energy.gov/eere/fuelcells/h2scale

Strategy #1: Strategic, High-Impact End Uses Deployment Opportunities

Deployment Estimates across Applications



Deployment Estimate Ranges for 2050



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What is Green Hydrogen?

How many currently refer to hydrogen:

Color	Energy Source	Mode of Production
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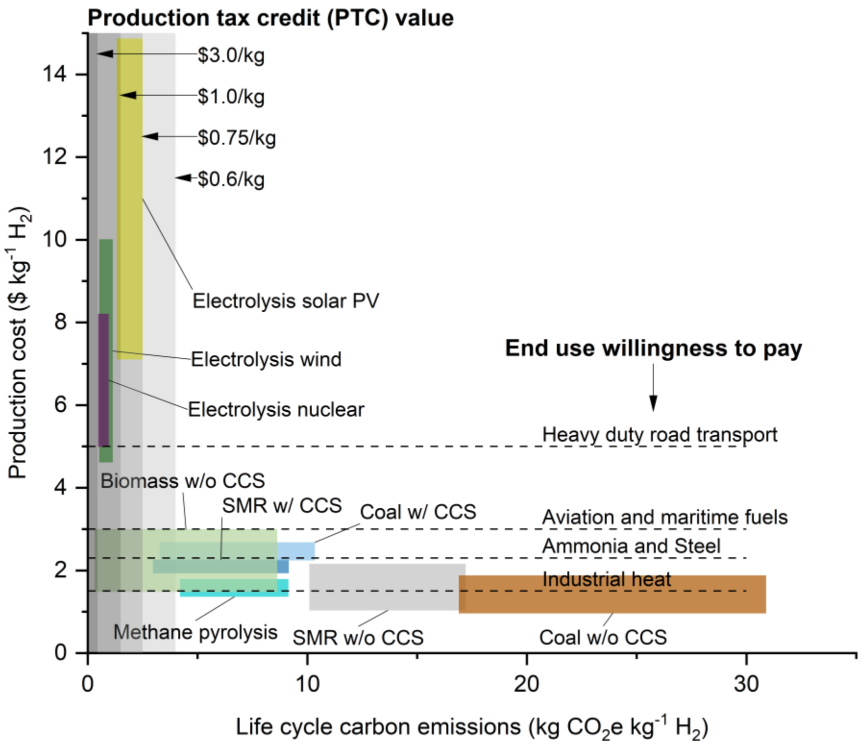
White	Natural geologic formations	Natural fracking
Yellow	Solar	Water electrolysis
No Color	Biomass	Gasification
Red	Nuclear	Catalytic splitting
Purple/Pink	Nuclear	Water electrolysis
Turquoise	Natural gas	Pyrolysis
Blue	Natural gas	Steam reforming + CCS
Gray	Natural gas	Steam reforming
Black/Brown	Coal (lignite and bituminous coal)	Gasification

How we should be discussing hydrogen:



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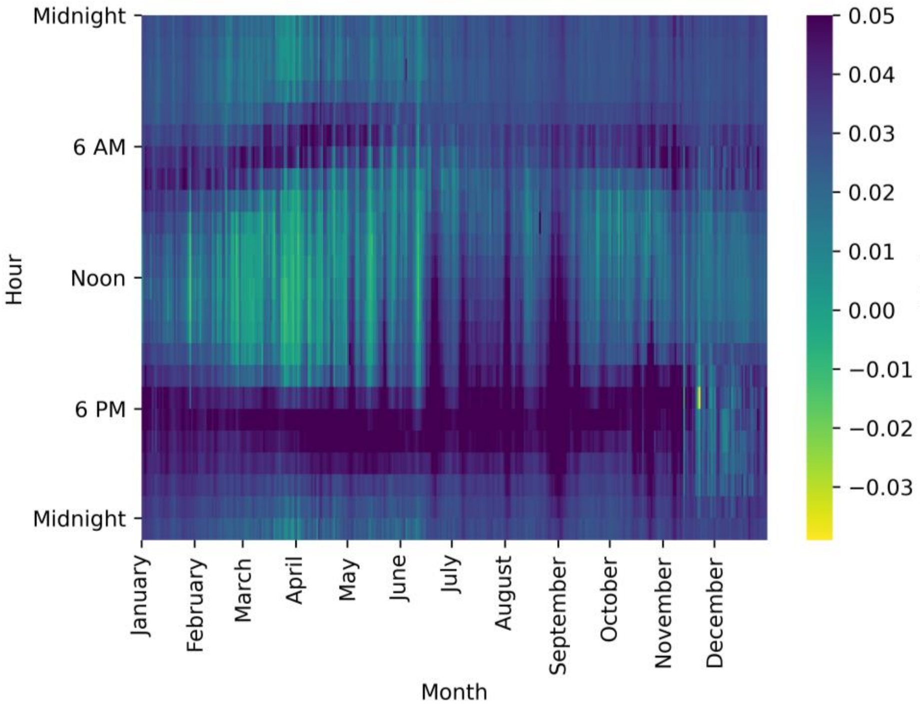
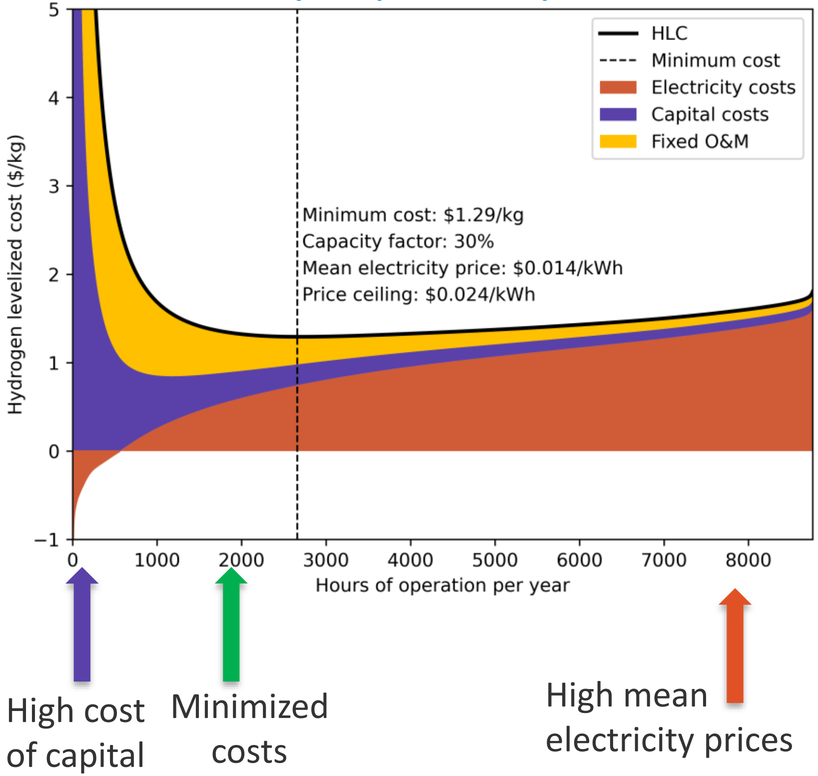
Opportunity to Reduce the Cost of Electrolytic Hydrogen Using Low-Cost Electricity

LMPs for California ISO Palo Verde Node in 2017



Electrolyzer Operational Optimization



Badgett, A., Ruth, M. and Pivovar, B. (2022) 'Chapter 10 - Economic considerations for hydrogen production with a focus on polymer electrolyte membrane electrolysis', in Smolinka, T. and Garche, J. (eds) *Electrochemical Power Sources: Fundamentals, Systems, and Applications*. Elsevier, pp. 327–364.

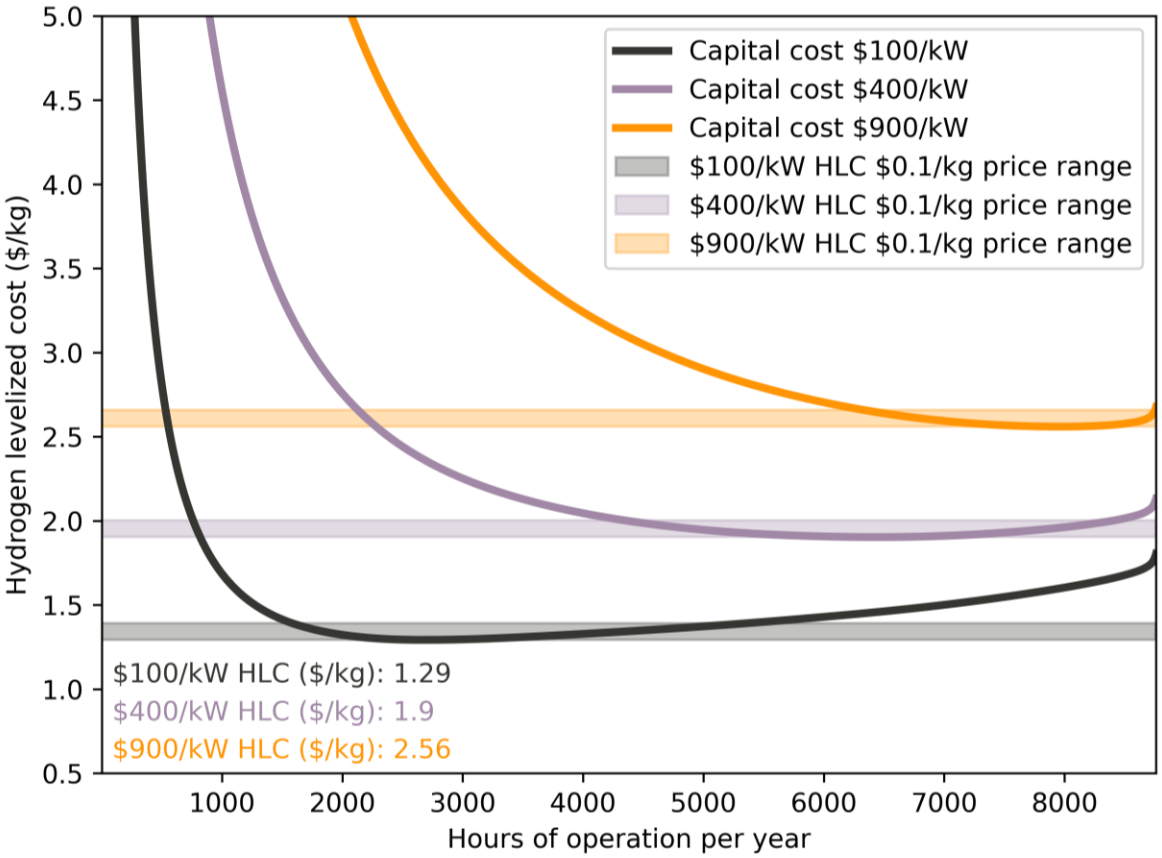
H2A Future Central case. 51.3 kWh/kg system efficiency. $100/kW total system purchase cost. Palo Verde LMPs.

Capital Costs Influence Shape and Minima of Hydrogen Levelized Cost Curves

Curves at low capital costs are:

- Lower cost
- Flatter
- Optimum at lower capacity factor

Impacts of Electrolyzer Cost on Hydrogen Levelized Cost



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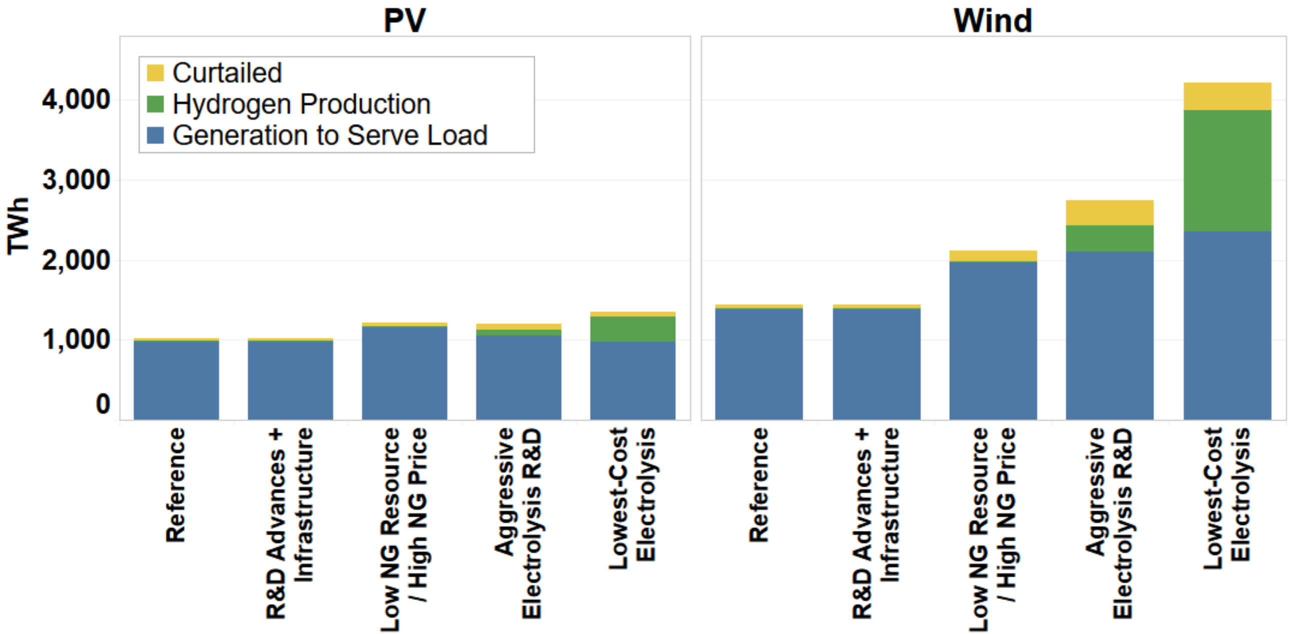
Hydrogen Production has the Potential to Support Wind and Solar Generation

In the U.S., hydrogen production has the potential to increase the total market size of wind and solar photovoltaic (PV) generation

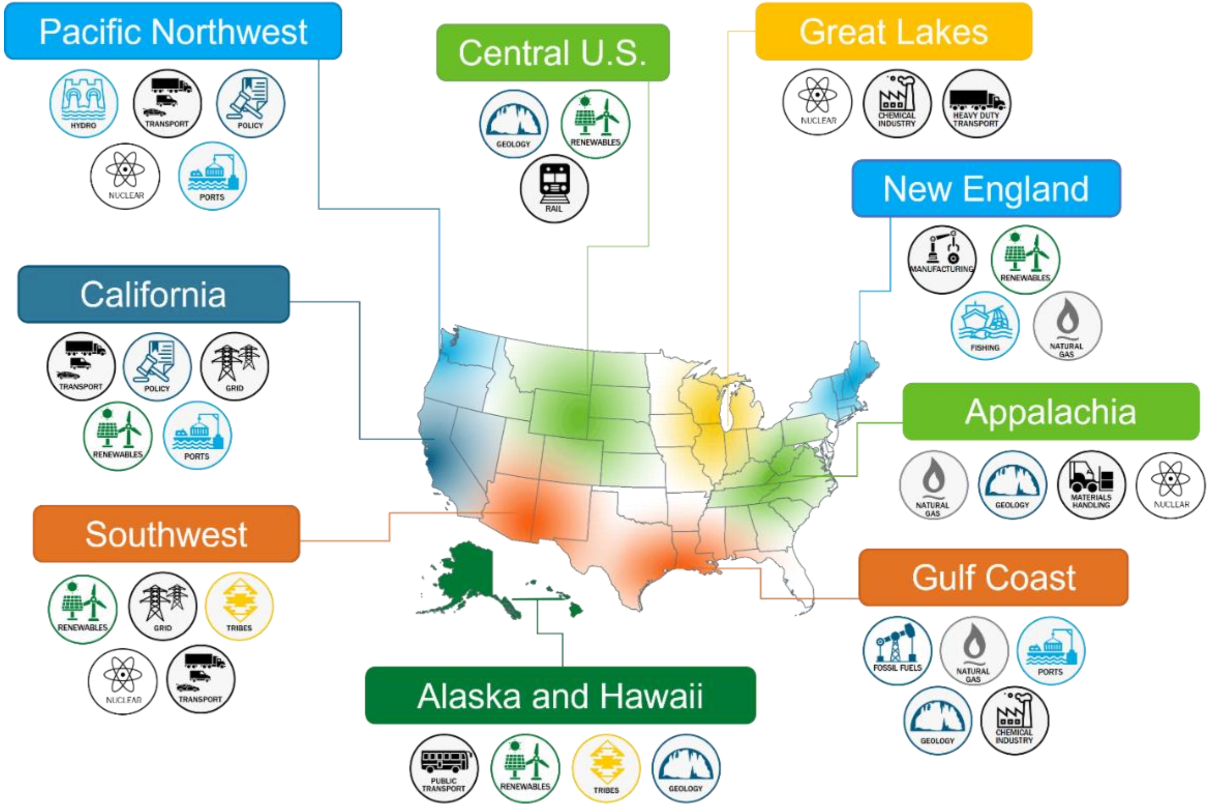


Estimates are based on national scenarios with minimal resolution into regional constraints. Increased resolution will likely impact the most competitive source of energy supply

Ruth, Mark, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. The Technical and Economic Potential of the H2@Scale Concept within the United States. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf.

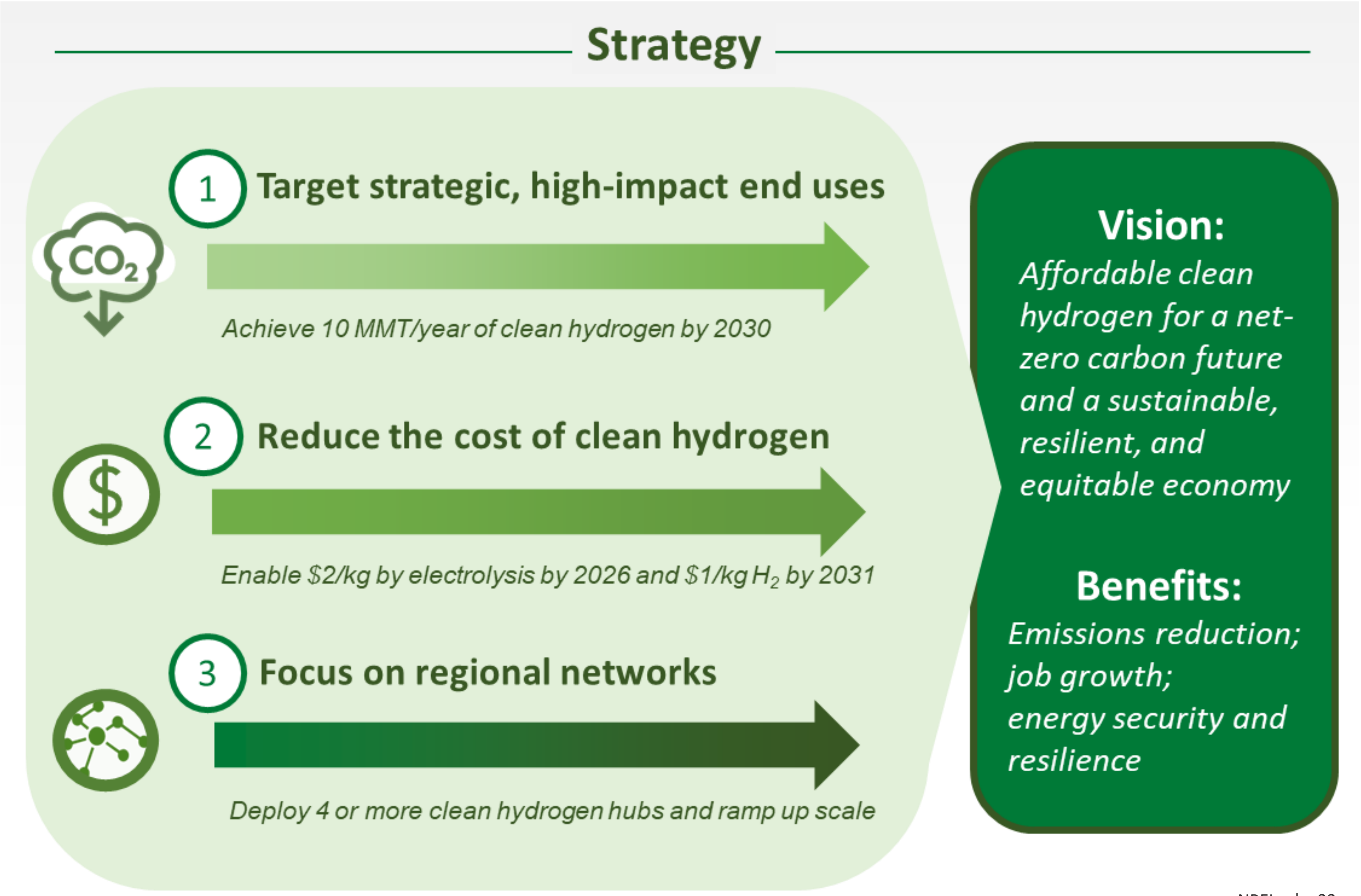
Strategy #3: Focus on Regional Networks Initially

Hubs allow each region to focus on their production and utilization opportunities



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

Priority Strategies to Achieve the Hydrogen Vision



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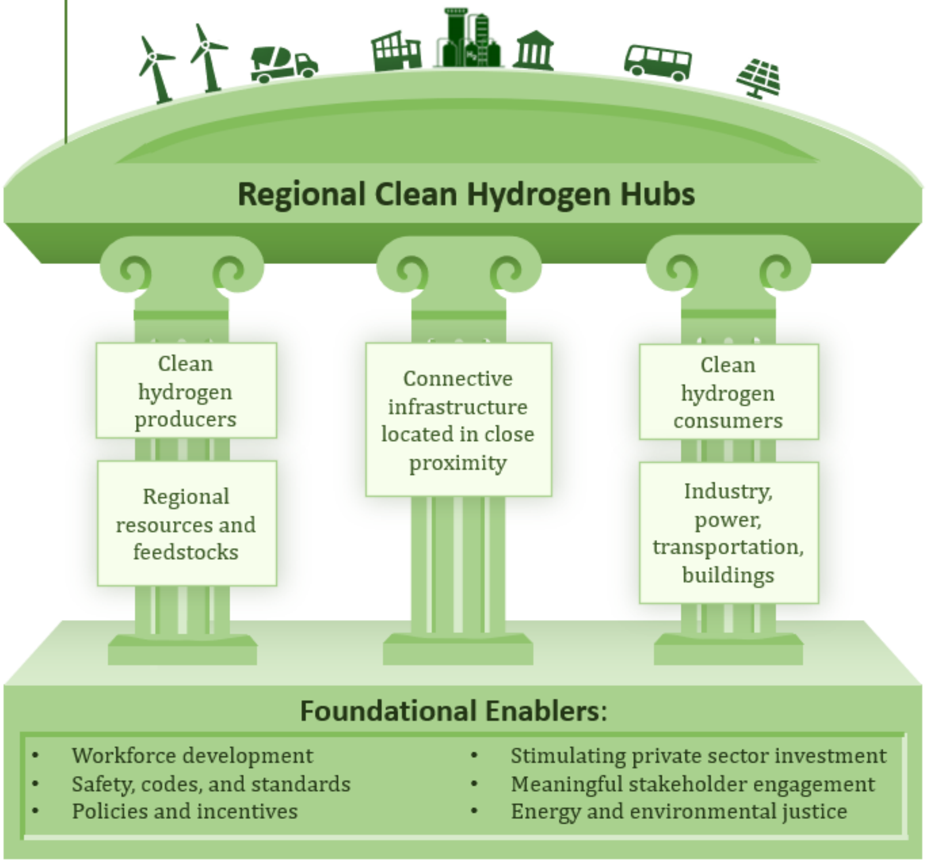
Focus on Regional Networks Initially

One challenge for hydrogen is that it involves production, delivery, often storage, and utilization. Economics improve with more connections. However, initial connections are challenging to develop.



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The U.S. Department of Energy is Funding Seven Hydrogen Hubs

https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations

U.S. Legislation Supporting Hydrogen

Bipartisan Infrastructure Law (BIL)

Includes $9.5B for clean hydrogen:

- $1B for electrolysis
- $0.5B for manufacturing and recycling
- $8B for at least four regional clean hydrogen hubs

Inflation Reduction Act (IRA)

Includes several tax credits:

- Clean hydrogen production (45V)

Carbon Intensity (kg CO_2e/kg H_2)*	Max Tax Credit ($ / kg H_2)
4 – 2.5	$0.60
2.5 – 1.5	$0.75
1.5 – 0.45	$1.00
0.45 – 0	$3.00

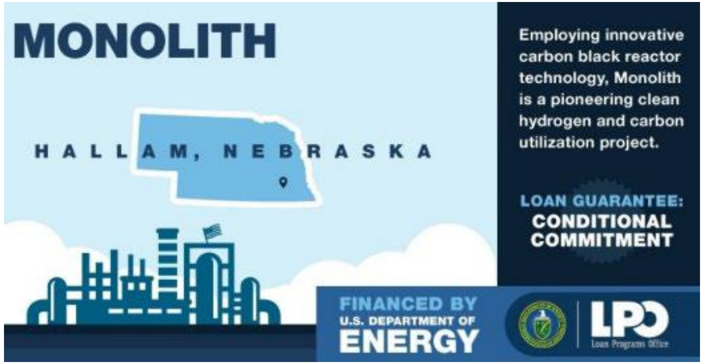
- Commercial Clean Vehicles Credit (45W)
- Alternative Fuel Refueling Property Credit (30C)

Source: https://www.energy.gov/eere/fuelcells/articles/doe-hydrogen-and-fuel-cell-remarks-fuel-cell-expo

* Well-to-gate

Loan Guarantees Provided by U.S. Government

The U.S. Department of Energy Loan Program Office provides loan guarantees for hydrogen technologies.



$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)

Source: https://www.energy.gov/eere/fuelcells/articles/doe-hydrogen-and-fuel-cell-remarks-fuel-cell-expo