The #H2IQ Hour

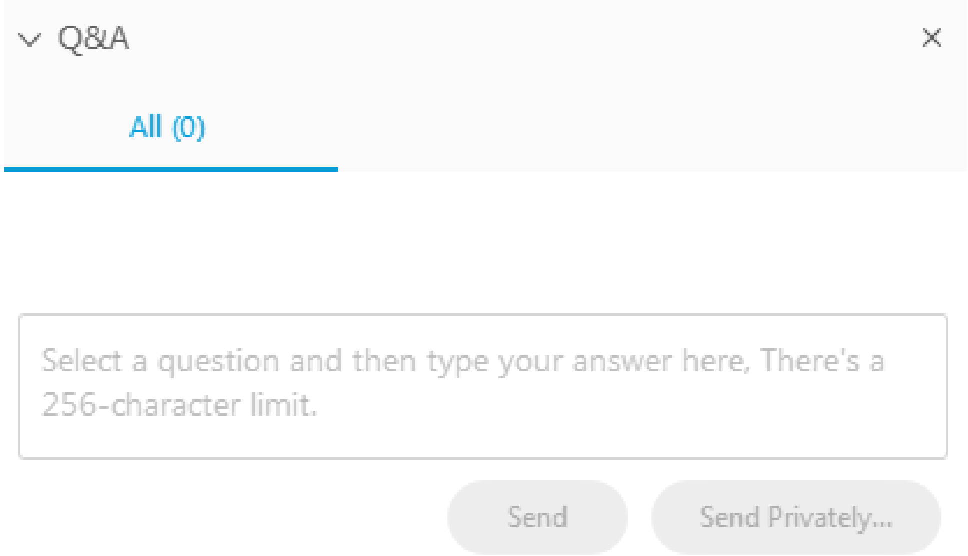
Today's Topic:

The Technical, Demand, and Economic Potential of H2@Scale within the United States

This presentation is part of the monthly H2IQ hour to highlight research and development activities funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



The Technical, Demand, and Economic Potential of H2@Scale within the United States

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H2IQ Hour

January 28, 2021

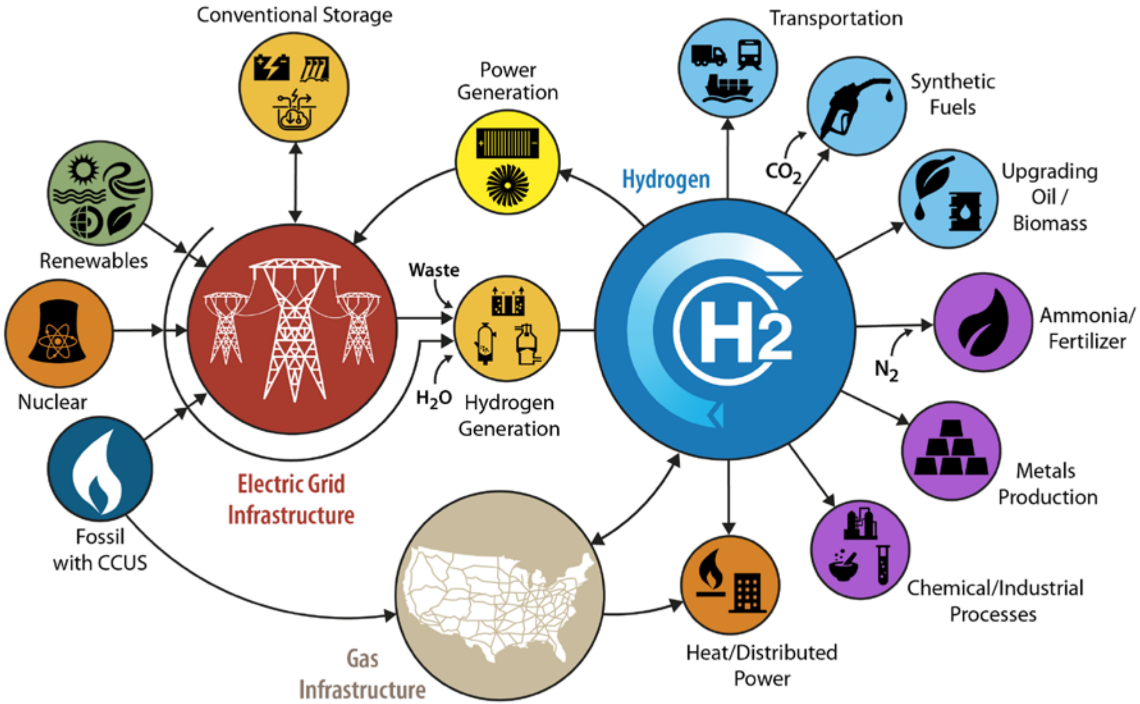
NREL/PR-6A20-78956

Report available at: https://www.nrel.gov/docs/fy21osti/77610.pdf

Detailed demand report available at: https://greet.es.anl.gov/publication-us_future_h2

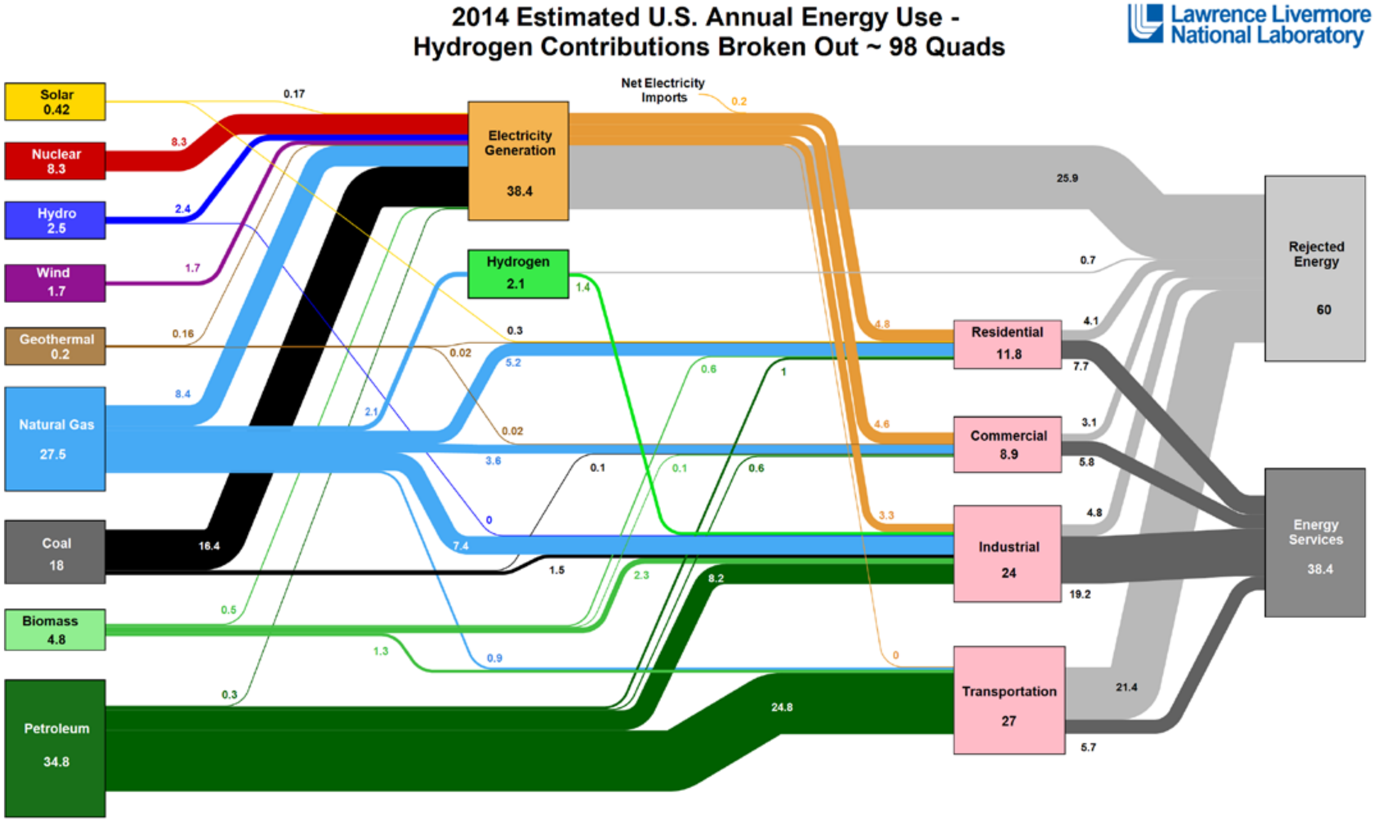
H2@Scale

DOE initiative focusing on hydrogen as an energy intermediate.



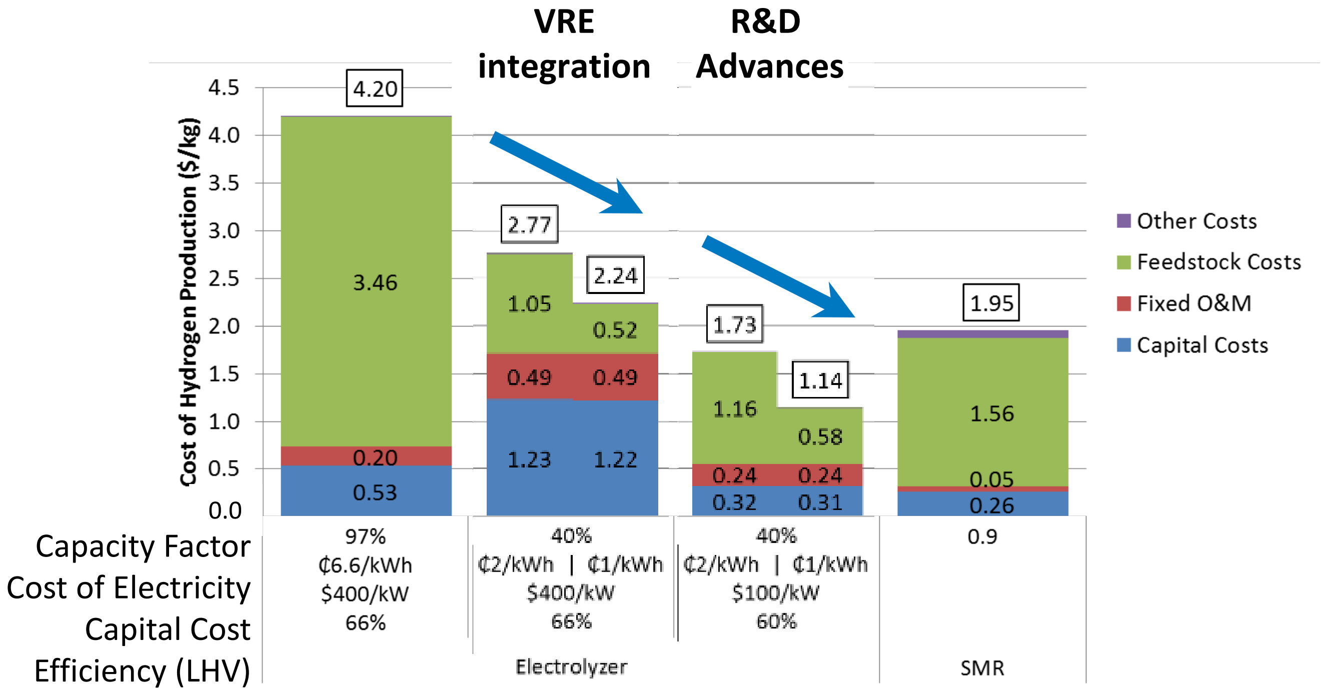
https://www.energy.gov/eere/fuelcells/h2scale

Hydrogen in Today's Energy System: 10 MMT / yr



Source: LLNL September 2015. Data is based on DOE/EIA-0035(2015-03) and Annual Energy Outlook DOE/EIA-0383(2014). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate". The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

Low-Cost, Variable Electricity Could Be Source for Low-Cost Hydrogen



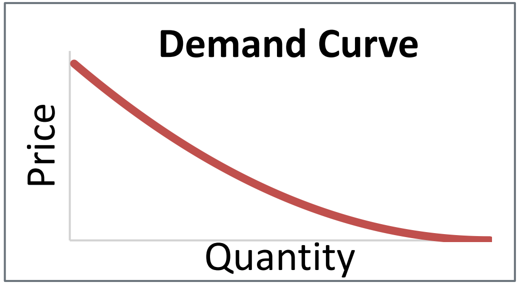
Low-temperature electrolysis could produce hydrogen using low-cost, dispatch-constrained electricity.

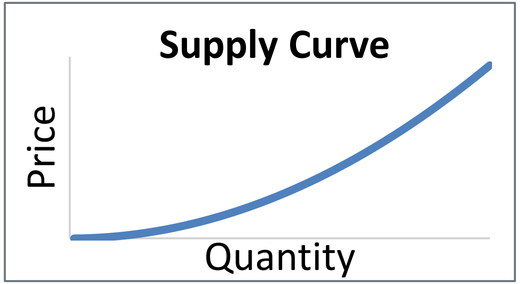
Analysis Objectives

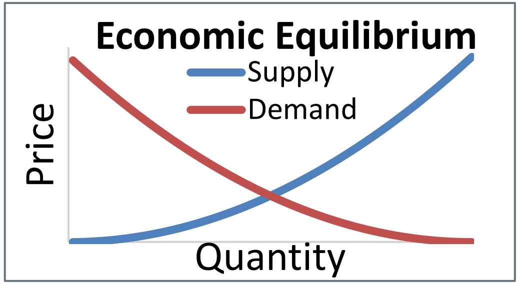
- **Quantify the potential of the H2@Scale vision** for the 48 contiguous states in the U.S.
- **Serviceable consumption potential and resource technical potential**
  - The serviceable consumption potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, and system performance, but not by economics
  - The resource technical potential is the amount of hydrogen that can be produced from a resource constrained by existing technology concepts, real-world geography, and system performance, but not constrained by economics.
- **Economic potential**
  - The quantity and price of hydrogen at which suppliers are willing to sell and consumers are willing to buy, assuming various market and technology-advancement scenarios.

Analysis results will help prioritize early-stage R&D for the initiative

Economic Potential Methodology: Market Equilibrium







Demand Curve: how much are consumers willing and able to pay for a good?

Supply Curve: threshold prices showing how much are producers willing and able to produce at each?

Economic Equilibrium: Quantity where demand price is equal to the supply price.

- No excess supply or demand.
- Market pushes price and quantity to equilibrium.

Methodology described in Schwartz, Robert A. *Micro Markets A Market Structure Approach to Microeconomic Analysis*. Wiley Finance. Chichester: Wiley, 2010.

Economic Potential: Limitations and Caveats

- Market equilibrium methodology and market size estimates in 2050
  - Transition issues such as stock turnover are not considered
- New policy drivers, such as emission policies, are not included either for hydrogen or the grid
- Technology and market performance involve many assumptions about adjacent technologies
  - In all but the non-reference scenario, the assumption is that R&D targets are met
- Demand analysis is limited to sectors that could be forecast for the foreseeable future
  - Hydrogen use to convert biomass based market size equal to 50% of aviation demand
  - Hydrogen for industrial heat is not included
  - Single hydrogen threshold price for fuel cell vehicle market estimates
- Estimates of delivery costs were standardized and without location specificity
- Potential long-term production technologies (e.g., photo-electrochemical) not included
- Economic feedback impacts are not considered
- Competing technologies (both for markets that use hydrogen and for resources to generate hydrogen) are addressed in a simplified manner only

Economic Potential: Five National Scenarios

<table>
<tr><th>Scenario Name</th><th>Reference</th><th>R&D Advances + Infrastructure</th><th>Low NG Resource / High NG Price</th><th>Aggressive Electrolysis R&D</th><th>Lowest-Cost Electrolysis</th></tr>
<tr><td>Natural gas prices</td><td colspan="2">Reference</td><td colspan="3">Higher</td></tr>
<tr><td>HTE costs</td><td>Current</td><td colspan="4">Improvements</td></tr>
<tr><td>LTE capital costs</td><td>Current</td><td colspan="2">Current trajectory</td><td>Improvements</td><td>Optimistic assumptions</td></tr>
<tr><td>LDE market assumption</td><td colspan="3">Available at retail price</td><td>Between retail and wholesale</td><td>Wholesale price</td></tr>
<tr><td>Distribution for FCEVs</td><td>Current</td><td colspan="4">Cost targets met</td></tr>
<tr><td>Metals demand</td><td>Market competition</td><td colspan="4">Premium for hydrogen</td></tr>
</table>

Key differences in scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers' access to grid service markets, and 5) increased threshold price in metals industry

Hydrogen Applications and Threshold Prices

Potential hydrogen demands are based on potential market sizes. Threshold prices are estimates of hydrogen prices necessary to replace incumbent technologies.

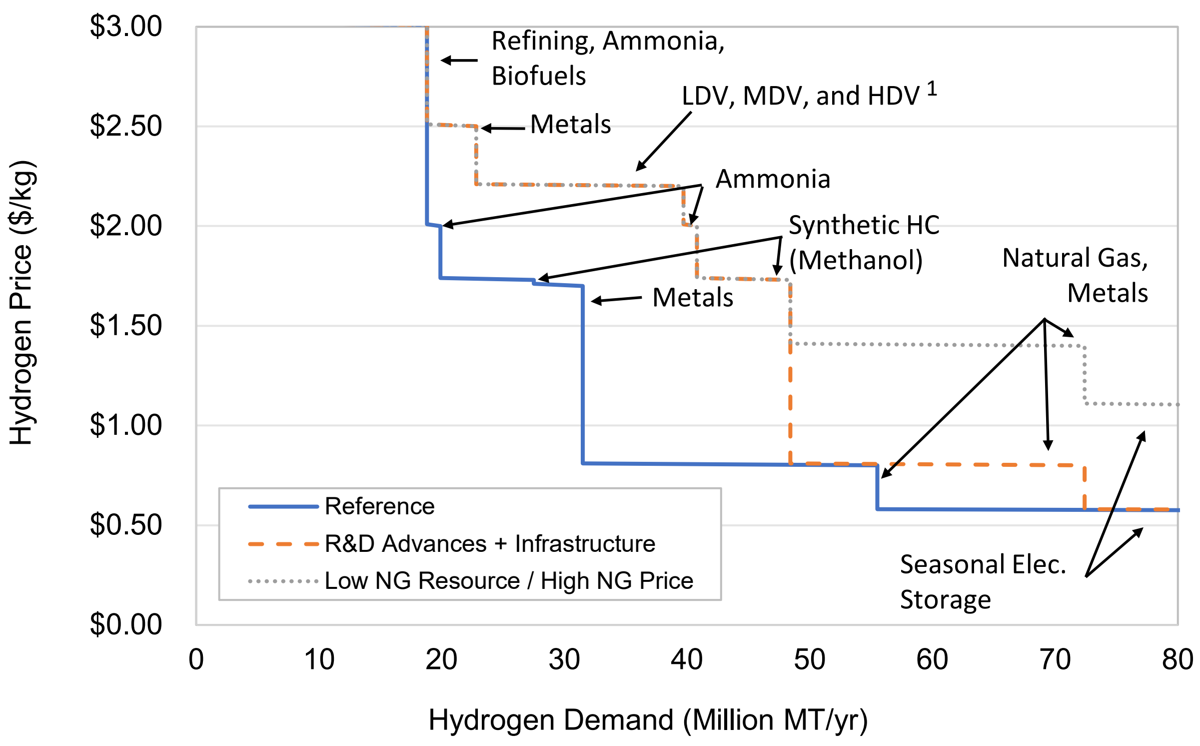
Application	Hydrogen Threshold Price-1 ($/kg)	Demand at Threshold Price-1 (MMT/yr)	Hydrogen Threshold Price-2 ($/kg)	Additional Demand at Threshold Price-2 (MMT/yr)
Refineries and the chemical processing industry (CPI) [a]	High	7.5	----	----
Metals	$1.70	4.0	$1.40	8.0
Ammonia	High	2.5	$2.00	1.1
Biofuels	High	8.7	----	----
Synthetic hydrocarbons	$1.73	6.0	$0.00	8.0
Natural gas supplementation	$1.40	16	----	----
Seasonal energy storage for the electricity grid	$1.10	14	$0.26	0.8
Light-duty fuel cell electric vehicles (FCEVs)	$2.20	12	----	----
Medium- & Heavy-Duty FCEVs	$2.20	5.2	----	----

Hydrogen threshold prices and demands for scenarios using the EIA's Low Oil and Gas Resource Scenario. Other scenarios have different threshold prices and quantities.

Additional Potential Hydrogen Demands – Not Included in this Analysis

- Additional hydrocarbon opportunities
- Rail transport
- Marine transport (shipping, ferries)
- Material handling equipment
- Coal-to-Liquids
- Glassmaking
- Rocket fuel

Aggregated Demand Curves

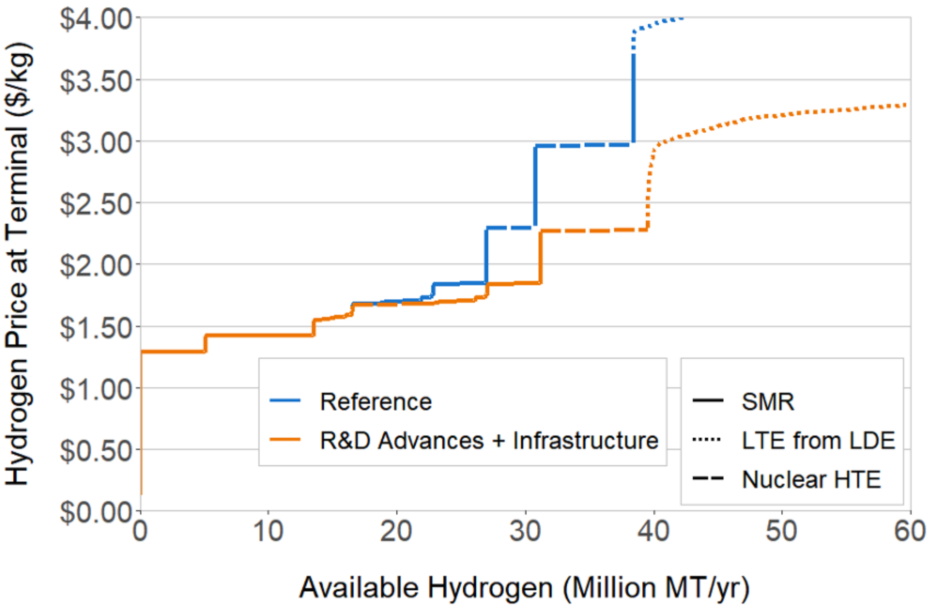


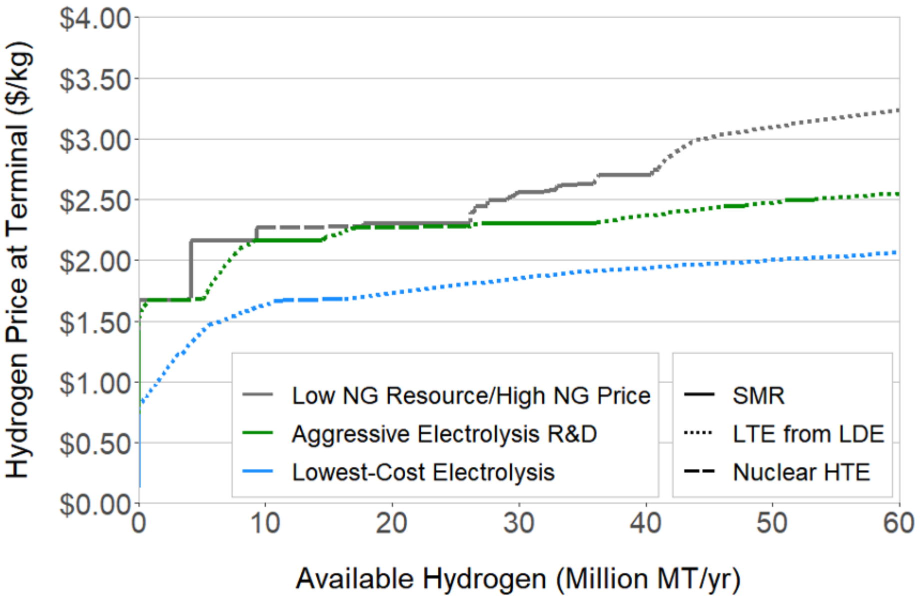
Demand curves represent aggregated threshold prices (at the terminal) for the potential hydrogen applications

1.Does not include cost of fueling station.

Aggregated Supply Curves

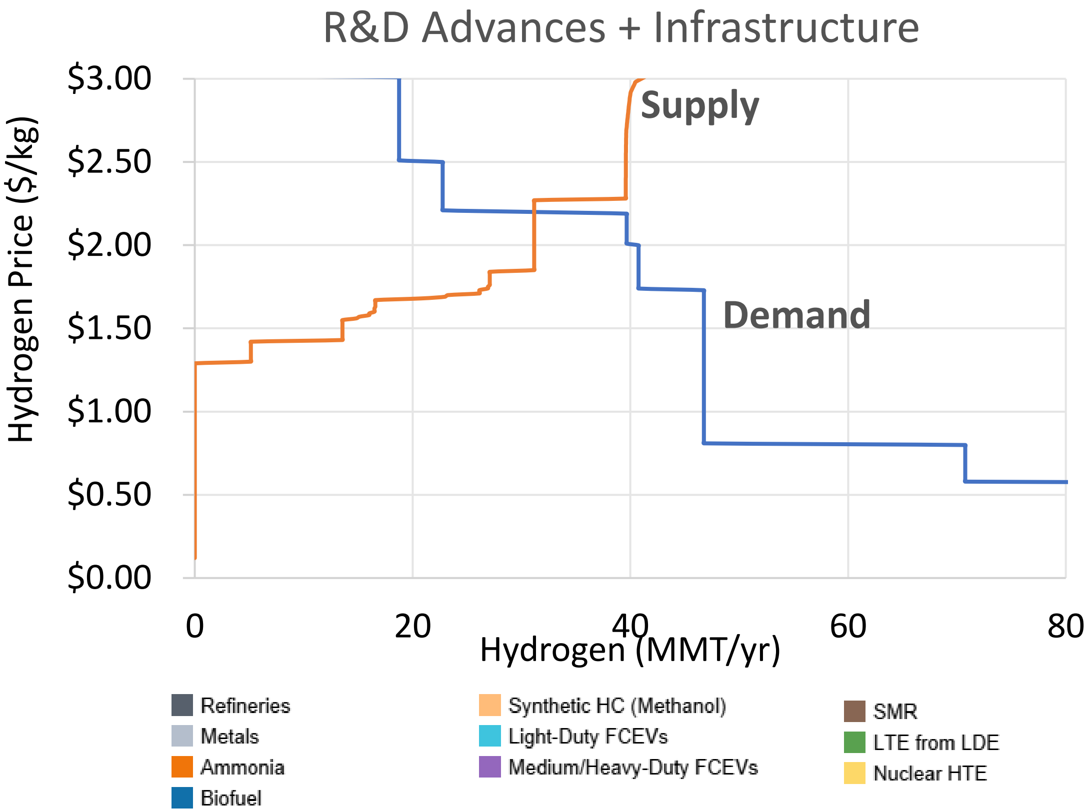
We created aggregated supply curves by aggregating supplies across sources. Supplies are combined from the lowest cost to the highest.





Economic Potential Methodology

- **We develop supply and demand curves by stacking from the highest-to-lowest threshold price and lowest-to-highest supply price points**



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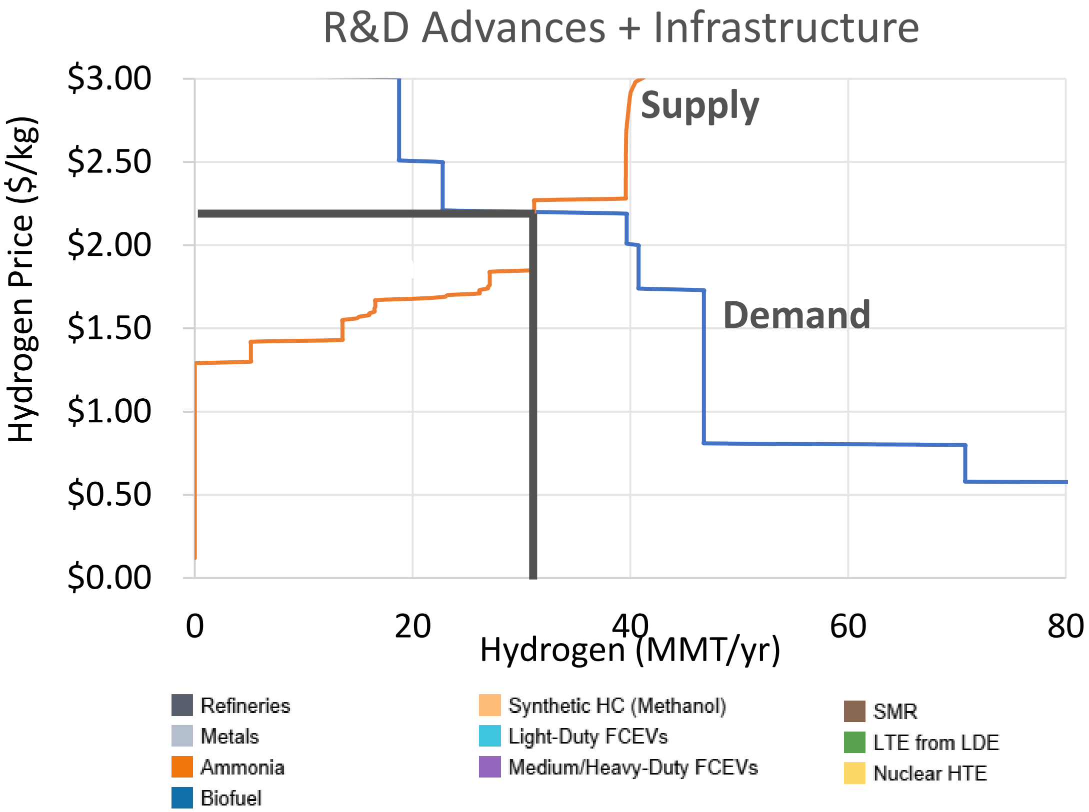
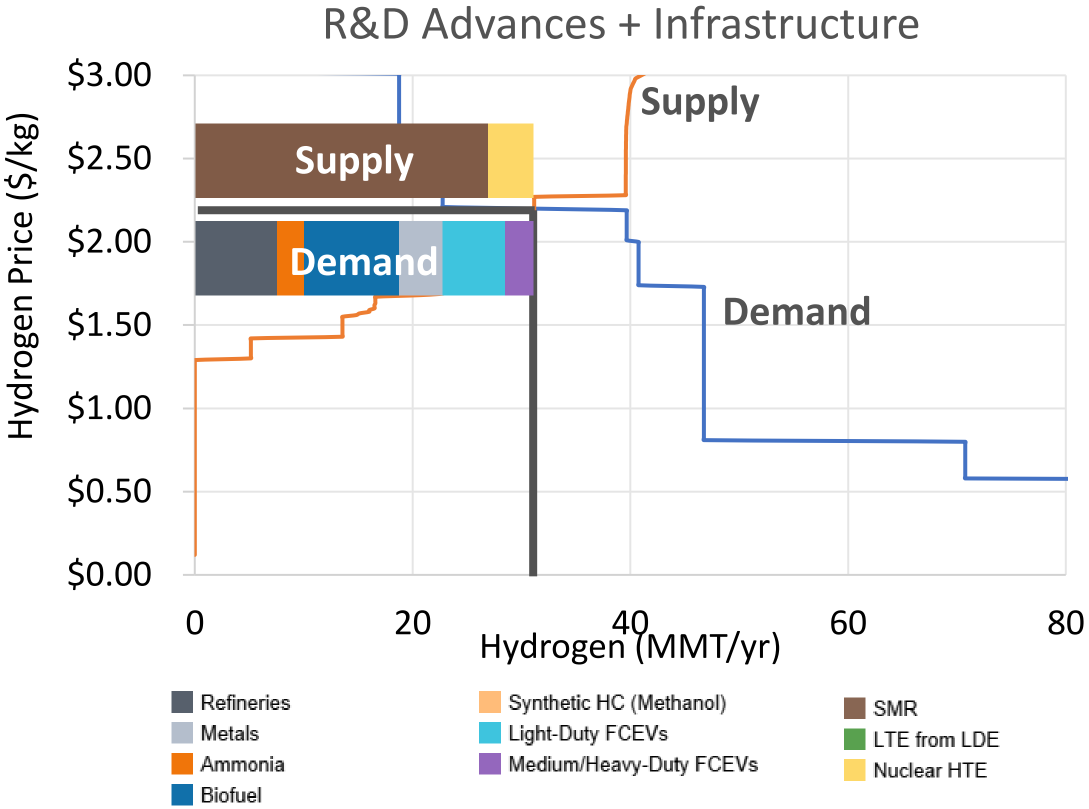
- The intersection provides the market size and price at equilibrium



Economic Potential Methodology

- We develop supply and demand curves by stacking from the highest-to-lowest threshold price and lowest-to-highest supply price point
- The intersection provides the market size and price at equilibrium
- We can then determine the supply and demand portfolios at that point

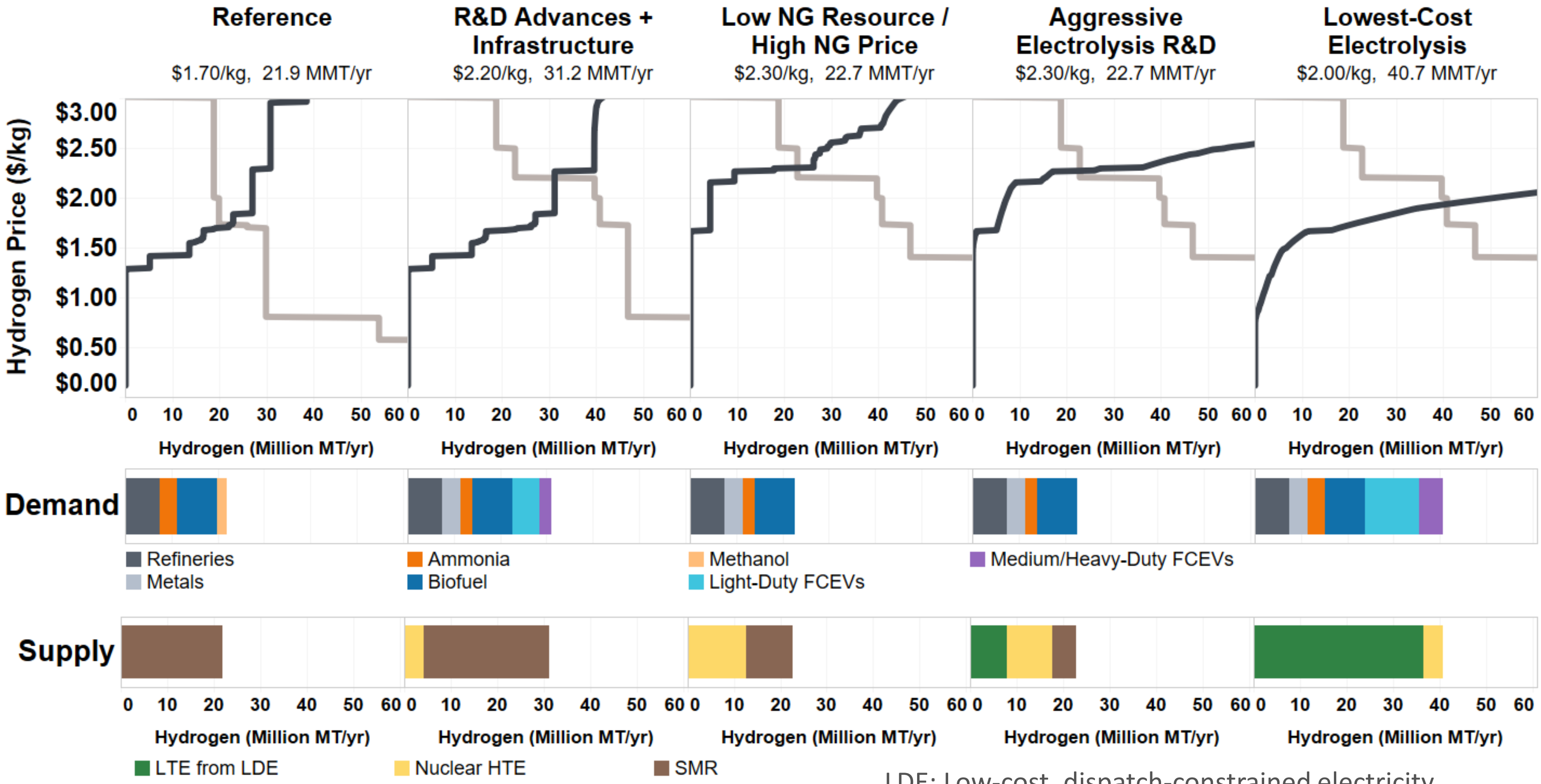


Economic Potential: Five National Scenarios

Scenario Name	Reference	R&D Advances + Infrastructure	Low NG Resource / High NG Price	Aggressive Electrolysis R&D	Lowest-Cost Electrolysis
Natural gas prices	Reference	Reference	Higher	Higher	Higher
HTE costs	**Current**	Improvements	Improvements	Improvements	Improvements
LTE capital costs	Current	Current trajectory	Current trajectory	Improvements	**Optimistic assumptions**
LDE market assumption	Available at retail price	Available at retail price	Available at retail price	Between retail and wholesale	Wholesale price
Distribution for FCEVs	**Current**	Cost targets met	Cost targets met	Cost targets met	Cost targets met
Metals demand	**Market competition**	Premium for hydrogen	Premium for hydrogen	Premium for hydrogen	Premium for hydrogen

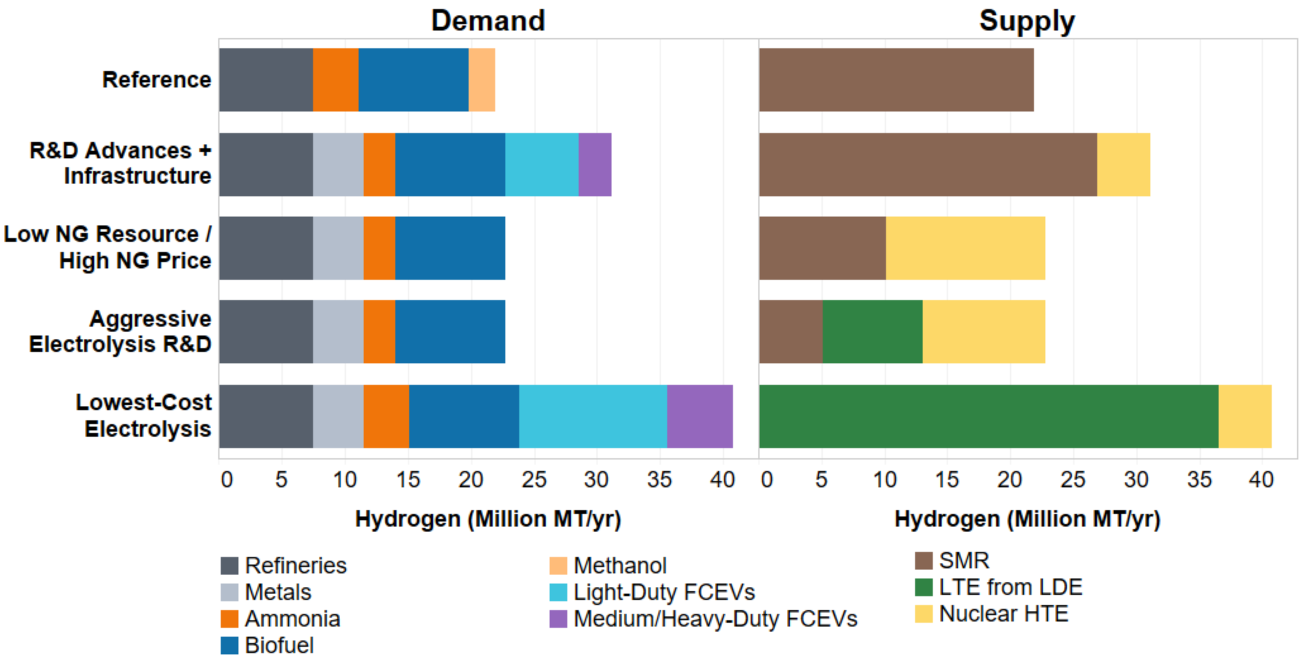
Key differences in scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers' access to grid service markets, and 5) increased threshold price in metals industry

New Economic Potential Results



LDE: Low-cost, dispatch-constrained electricity

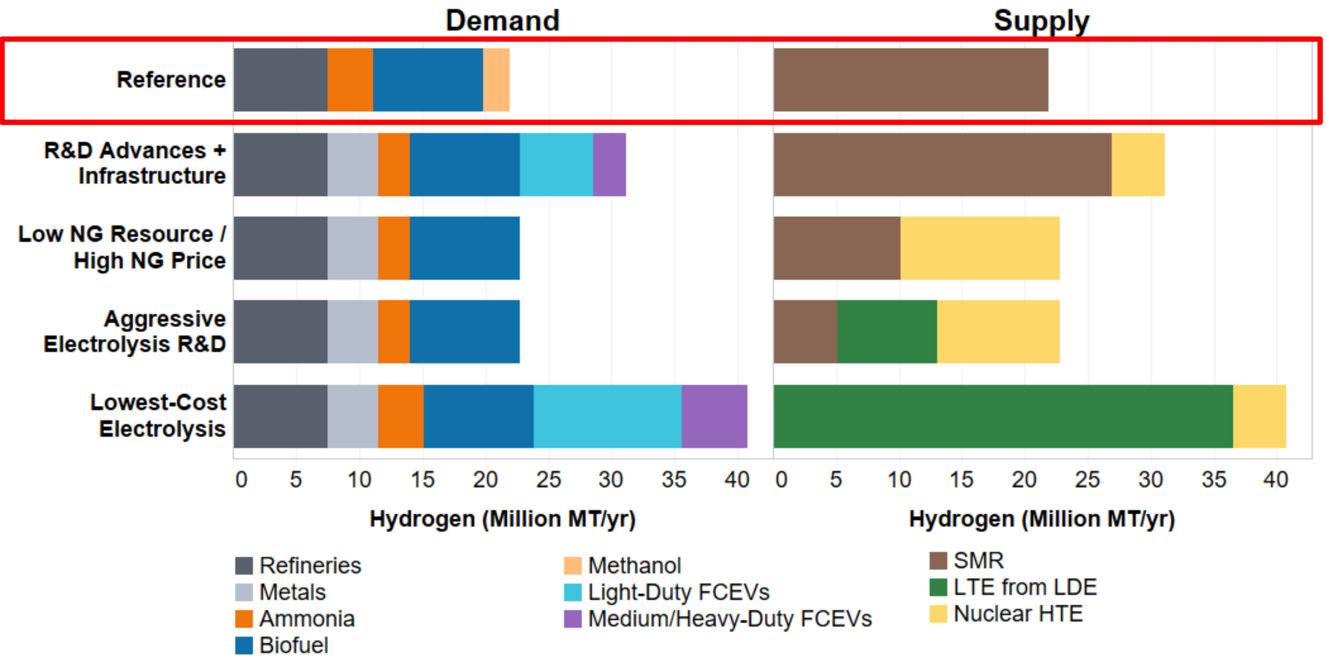
Economic Potential Results



The economic potential of hydrogen demand in the U.S. is 2.2-4.1X current annual consumption.

LDE: Low-cost, dispatch-constrained electricity

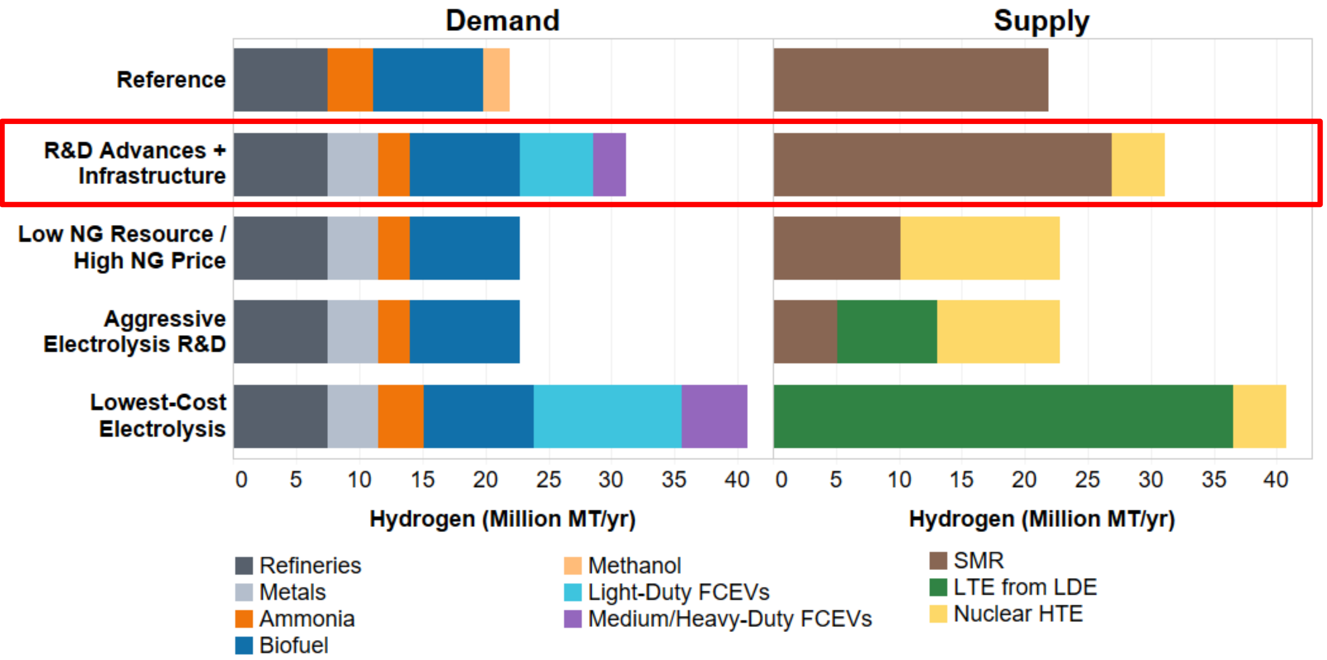
Reference Scenario



- Refineries and ammonia demands based on growing markets
- Biofuels penetrate 50% of jet fuel market
- No advancement in electrolysis, fuel cells, and hydrogen distribution technologies.
- FCEVs do not penetrate markets
- SMR dominates supply.

LDE: Low-cost, dispatch-constrained electricity

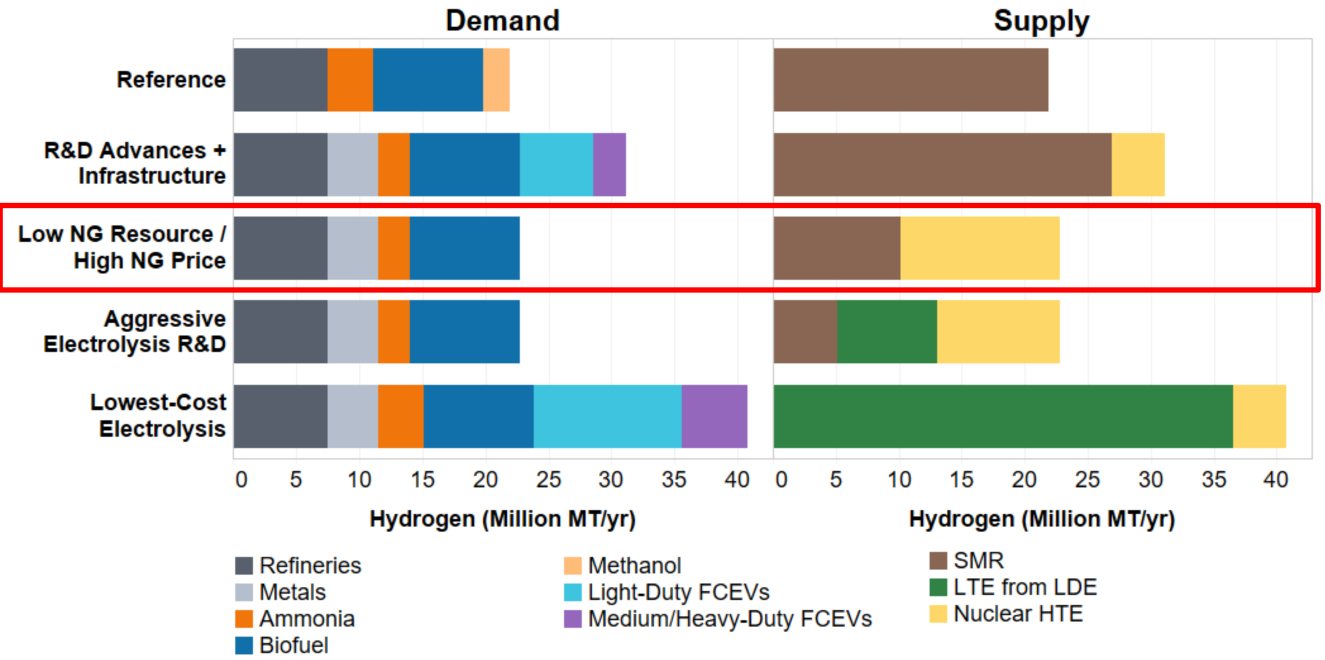
R&D Advances + Infrastructure Scenario



- Low natural gas prices and reduced delivery costs for FCEVs; thus, higher penetrations of FCEVs
- Increased willingness to pay for H_2 for metals refining
- About 20% of U.S. nuclear generation to H_2

LDE: Low-cost, dispatch-constrained electricity

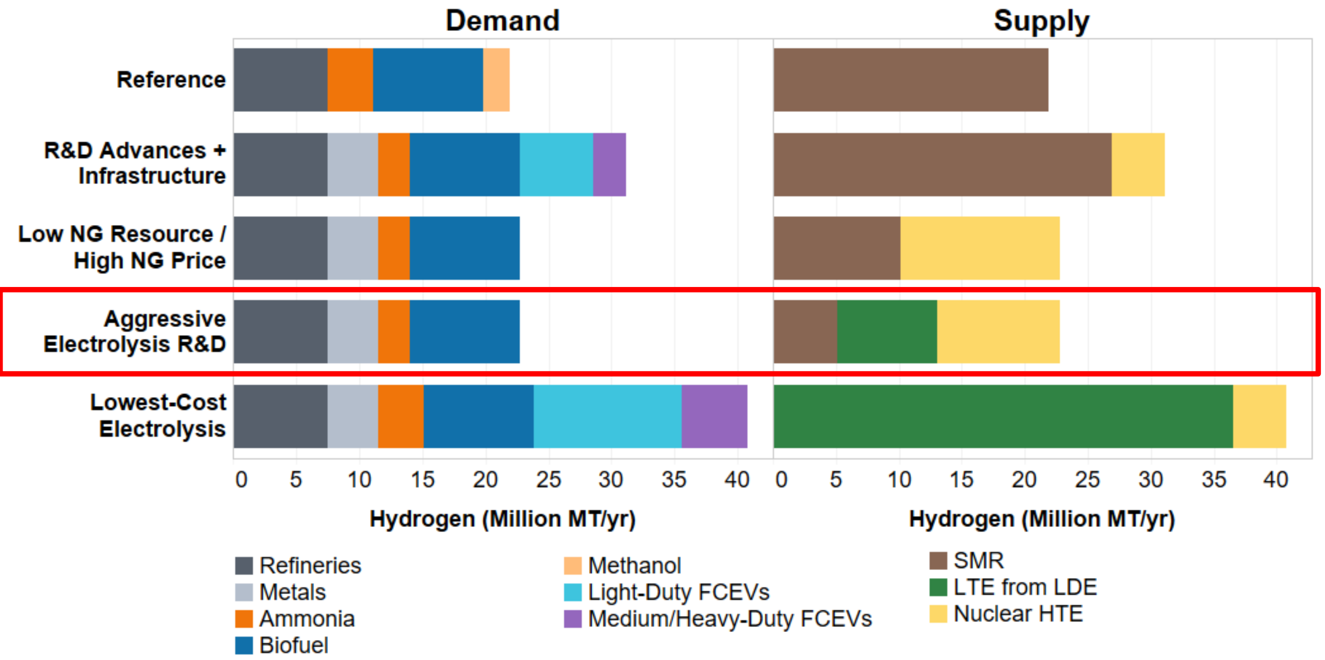
Low Natural Gas Resource / High NG Price Scenario



- Higher natural gas prices than reference scenario
- Thus, only growth in hydrogen demand is due to increased willingness to pay for H_2 for metals refining
- Almost 60% of nuclear generation converted to hydrogen production because it is more competitive

LDE: Low-cost, dispatch-constrained electricity

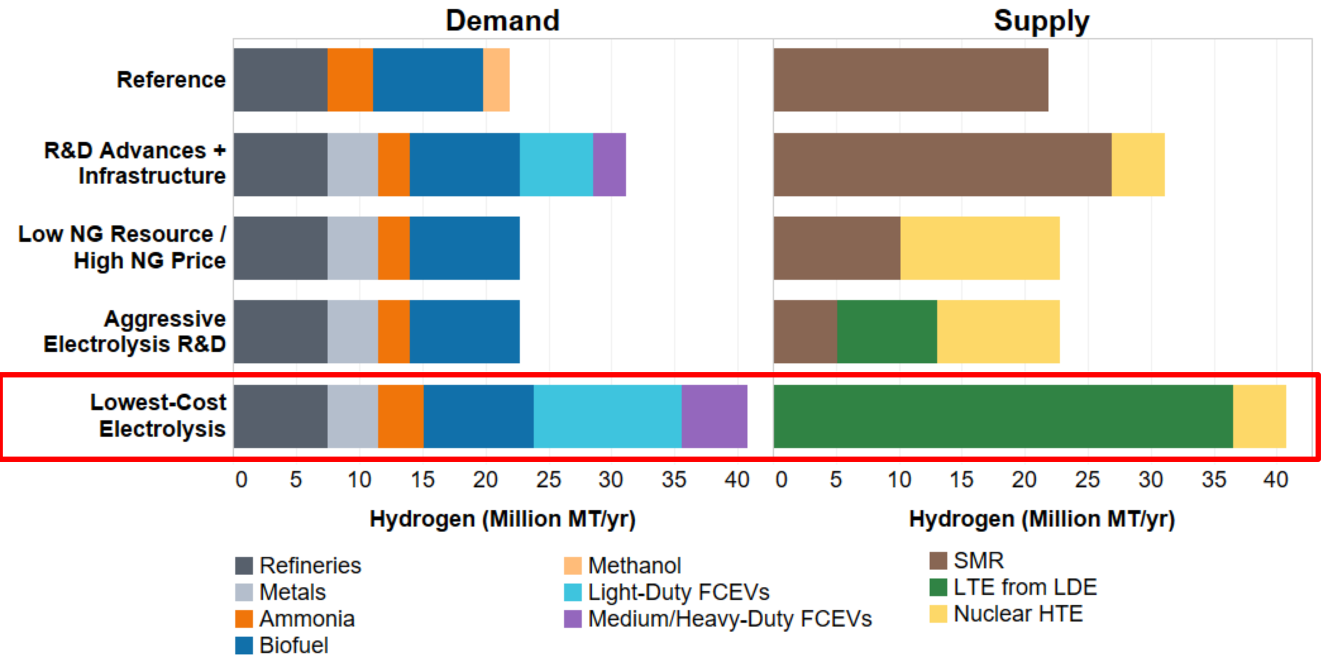
Aggressive Electrolysis R&D Scenario



- Low-Temperature electrolyzer (LTE) purchase cost reduced to $200/kW & reduced electricity price adder
- Share of electrolytic H_2 generated using LTE increases offsetting both SMR and nuclear generated H_2

LDE: Low-cost, dispatch-constrained electricity

Lowest-Cost Electrolysis Scenario

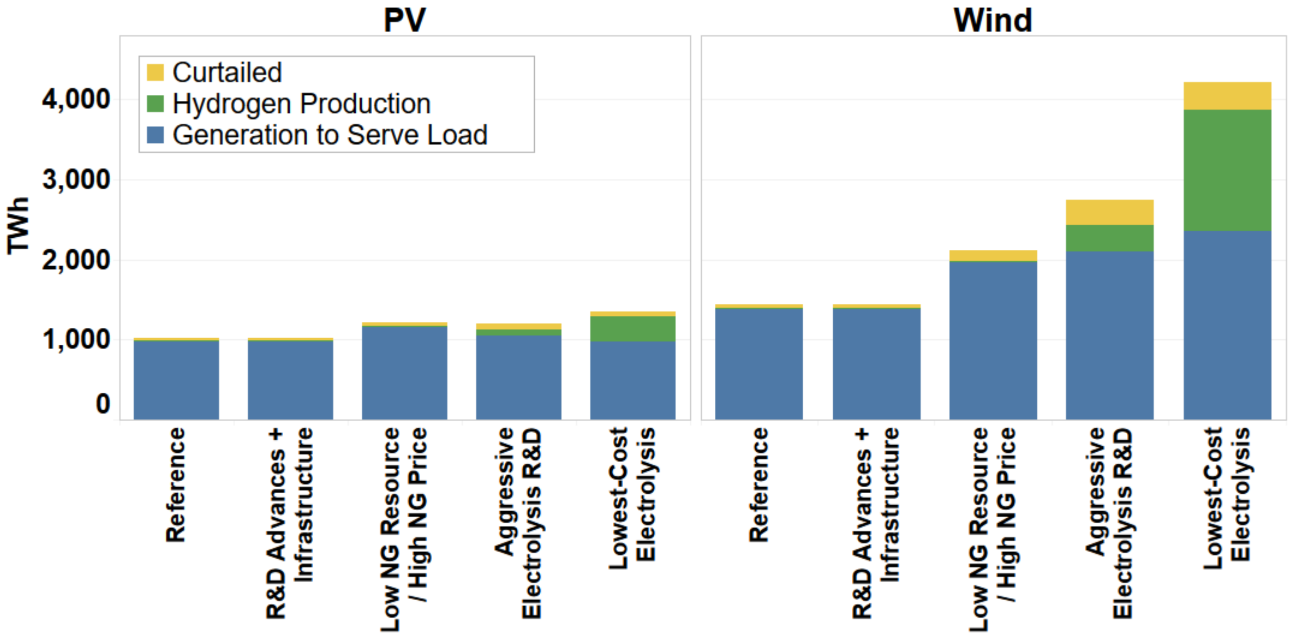


- **Electrolytic hydrogen less costly than steam methane reforming due to aggressive R&D and high NG prices (LTE purchase cost reduced to $100/kW & no price adder on LDE)**
- **LTE dominates the market**
- **Low-cost H_2, enables increased FCEV penetrations and offsets ammonia imports**

LDE: Low-cost, dispatch-constrained electricity

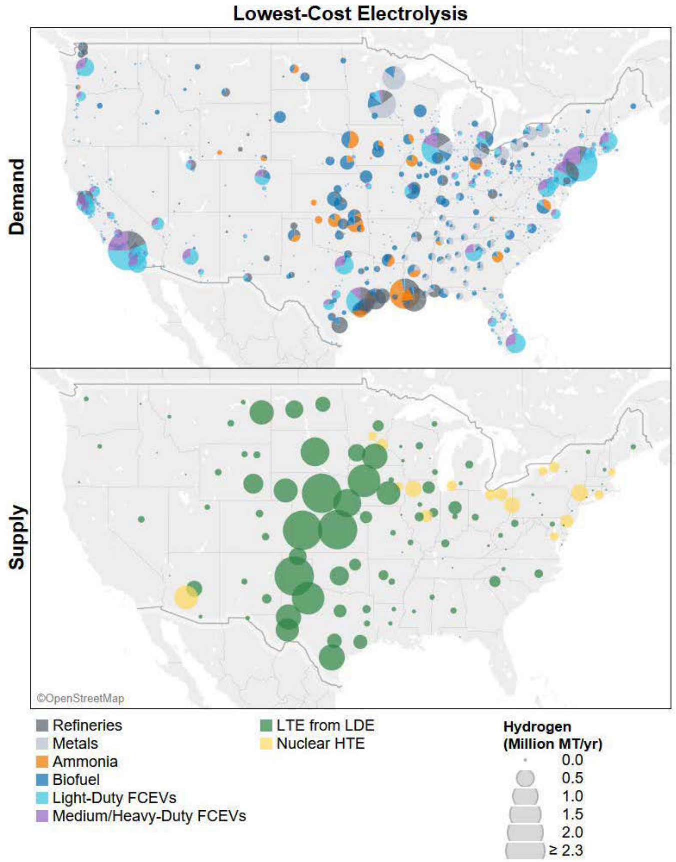
Potential Impact on Wind and Solar PV Markets

H2@Scale 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

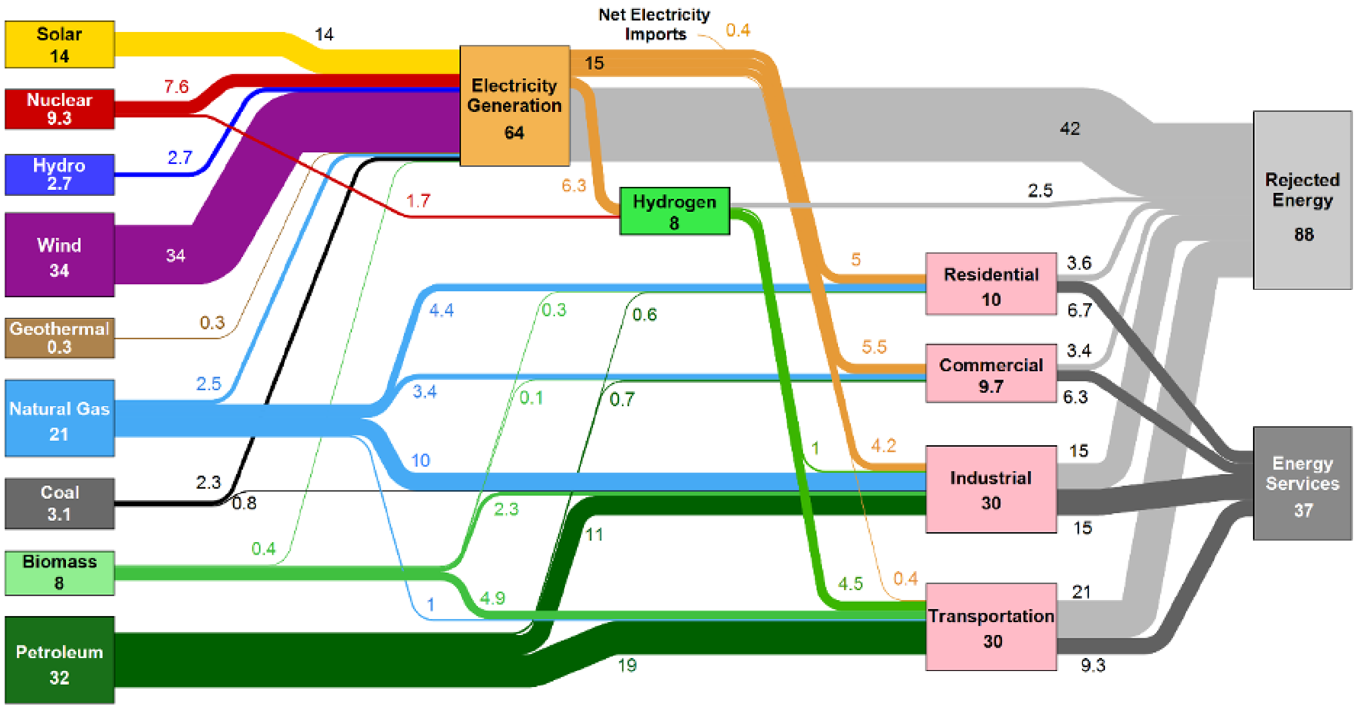
Spatial Aspects of Economic Potential Scenarios



- In the Lowest-Cost Electrolysis Scenario, the majority of the hydrogen is generated in the central U.S.
- Demands are primarily near urban centers
- Indicates that large delivery infrastructure investments could be necessary

Hydrogen in the U.S. Energy Sector: Lowest Cost Electrolysis Scenario

2050 Estimated U.S. Annual Energy Use ~ 125 Quads
Lowest-Cost Electrolysis



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The Lowest-Cost Electrolysis Scenario has about a 20% reduction in greenhouse gas emissions over electricity grid improvements alone

Summary of Key Conclusions

- **The economic potential of hydrogen demand in the U.S. is 2-4X current annual consumption**. **At those market sizes, hydrogen production is 4-17% of primary energy use.**
  - Range across 5 scenarios developed using a variety of economic and R&D success assumptions
  - Total U.S. petroleum use could decline by up to 15% below a scenario with a high renewable penetration on the grid
- **An increased hydrogen market size can be realized even if low-cost LTE is not available as long as other hydrogen production options are available**
- **Grid-integrated electrolysis can increase wind power generation by more than 60%** by monetizing additional low-cost, dispatch-constrained electricity
- Up to 60% of current **nuclear power plants could improve their profitability** by producing hydrogen.
- Scenarios show the potential for up to **20% reduction in U.S. CO_2e emissions over electricity grid improvements alone**. Higher reductions may be feasible given policy drivers and development of additional demand sectors.

Thank You

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www.nrel.gov

The reports with details on this presentation are available at

https://www.nrel.gov/docs/fy21osti/77610.pdf

https://greet.es.anl.gov/publication-us_future_h2

Additional information on H2@Scale can be found at:

https://www.hydrogen.energy.gov/pdfs/review18/h2000_pivovar_2018_o.pdf

http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

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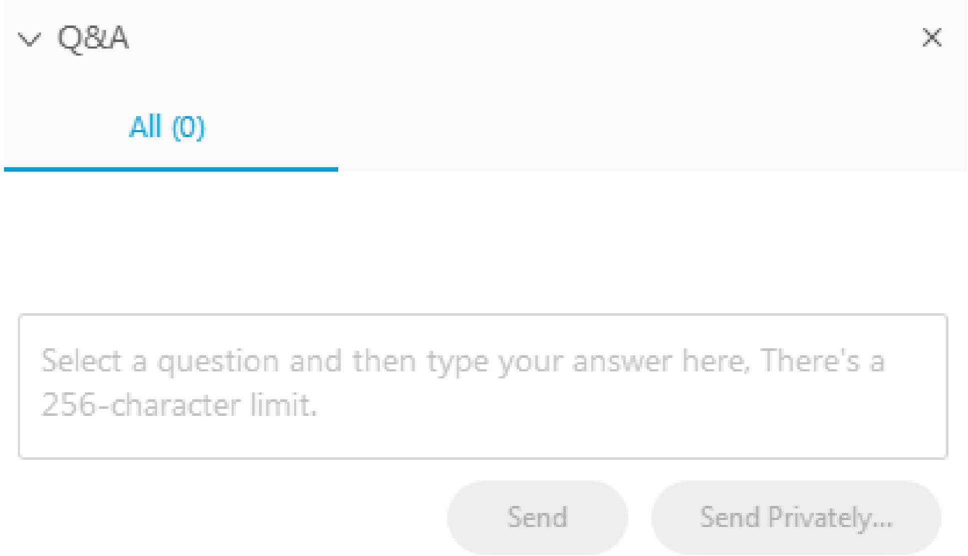

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