The Potential of Hydrogen in a Decarbonized Future

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WEI IRP Forum

November 16, 2021

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

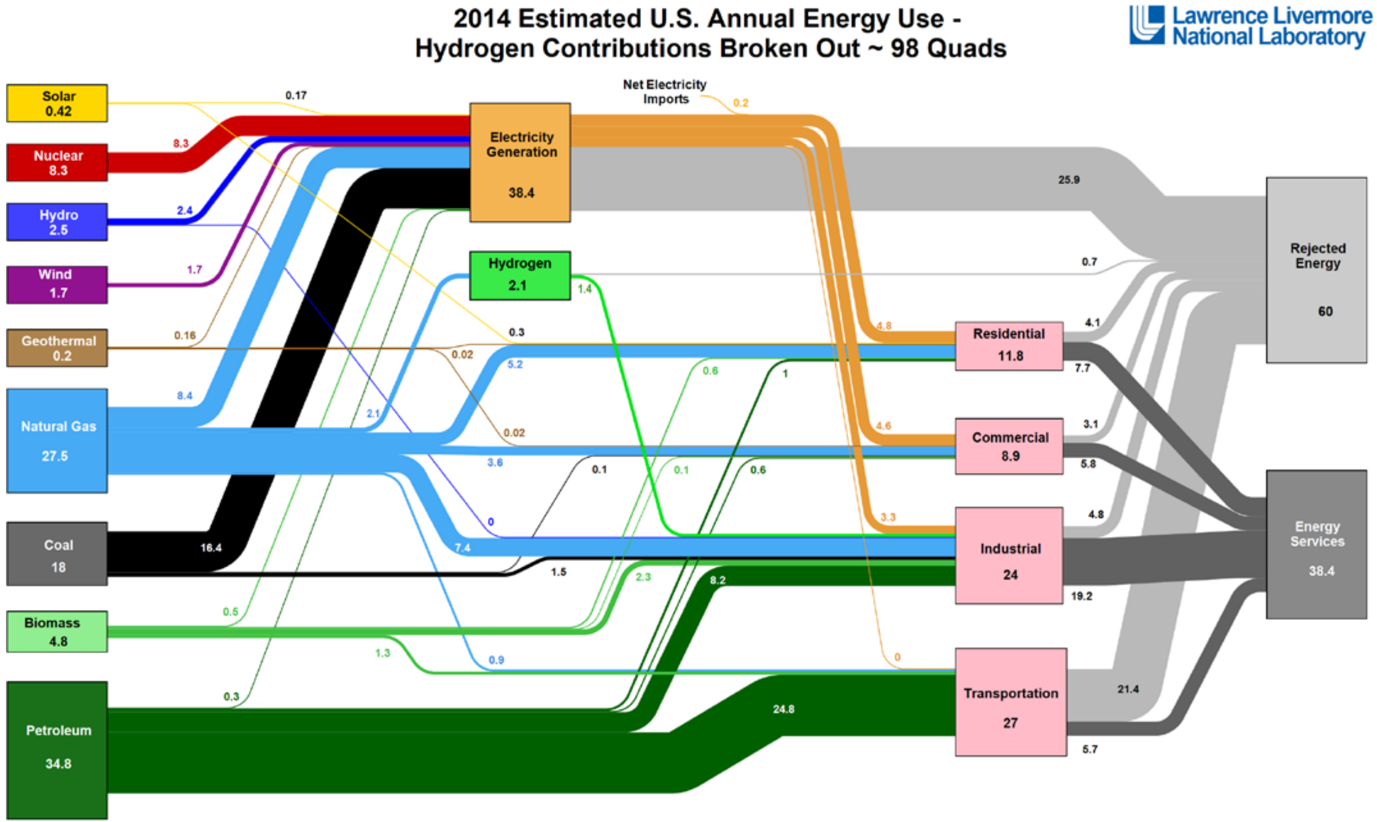
Detailed demand report available at: https://greet.es.anl.gov/publication-us_future_h2

Presentation Outline

- Hydrogen today
- Reasons why interest in hydrogen is growing
- Hydrogen production options and challenges
- Potential hydrogen applications and market opportunities
- Resource requirements
- Economic potential for hydrogen

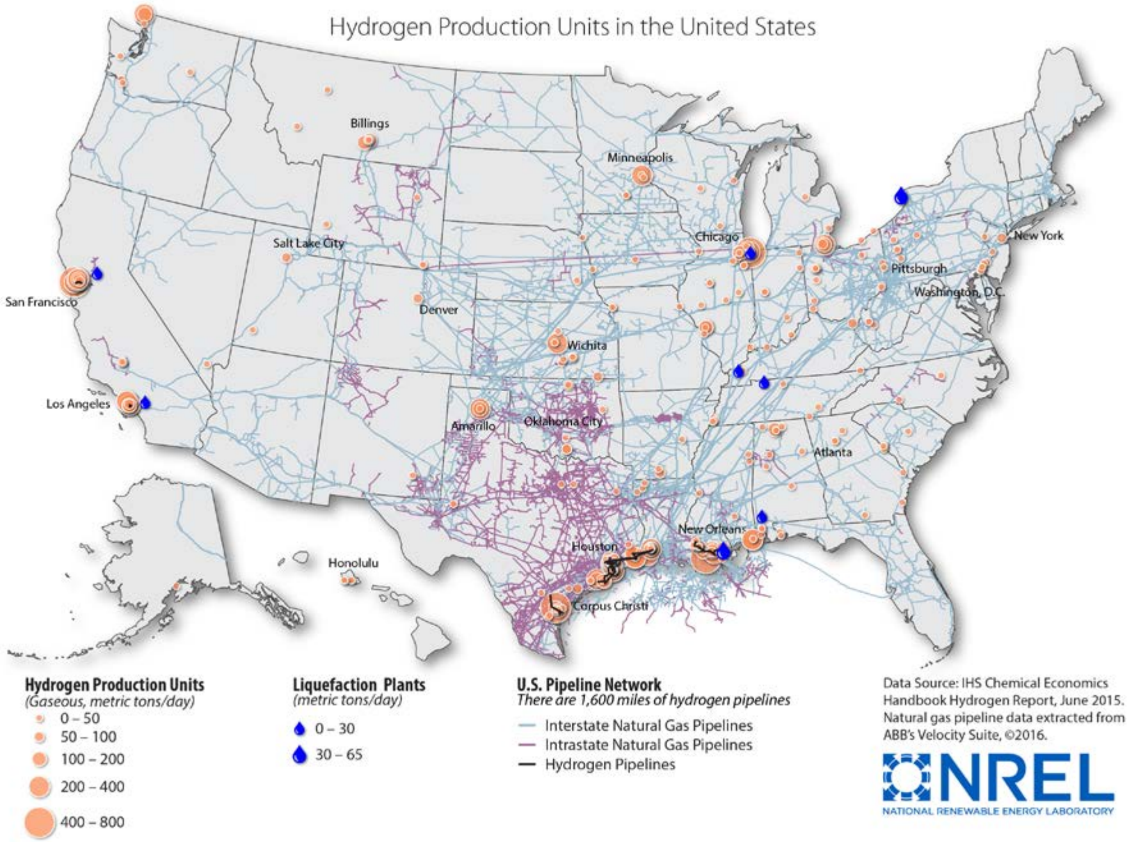
Hydrogen in Today's Energy System

Today's U.S. energy system includes about 10 MMT/yr hydrogen which requires about 2% of primary energy



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

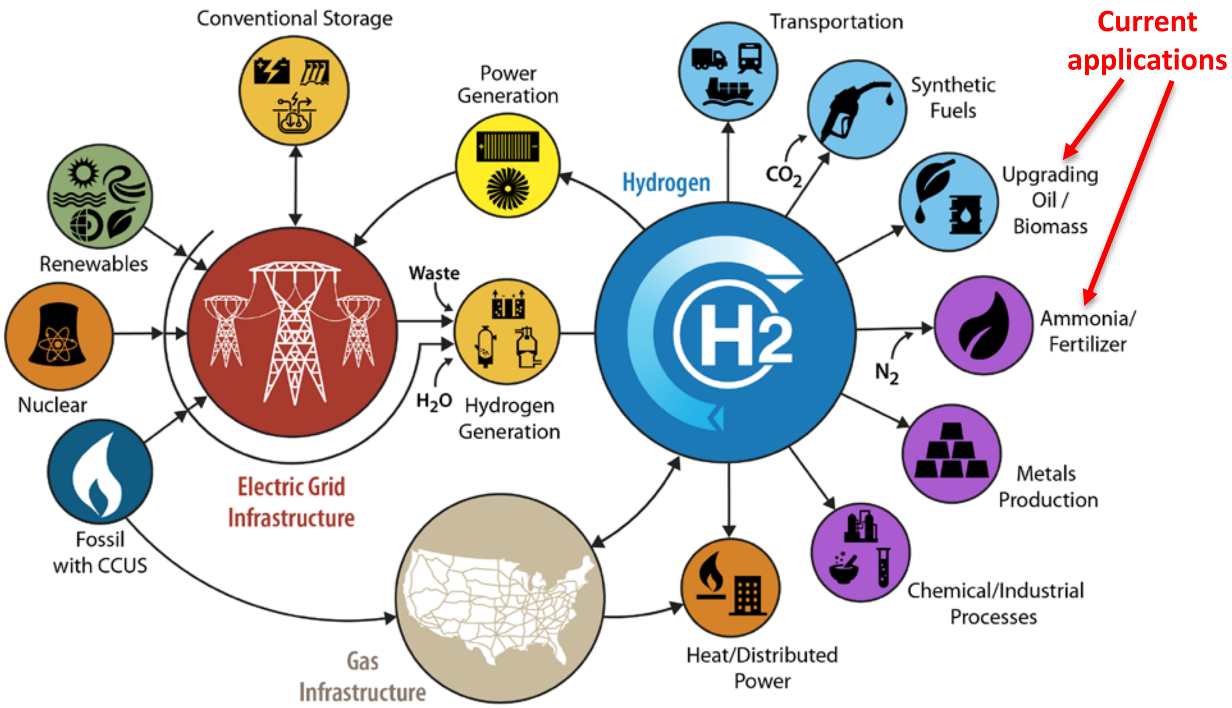
Hydrogen Production is Distributed Throughout the U.S.



Why has Interest in Hydrogen Grown Recently?

The H2@Scale Initiative focuses on opportunities for hydrogen to act as an energy intermediate

Can address difficult-to-decarbonize sectors and support higher penetrations of non-dispatchable generation



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

Hydrogen Production Opportunities

Colors are commonly used to describe hydrogen production options

BUT they do not necessarily correlate with emission levels

GREEN
Hydrogen produced by electrolysis of water, using electricity from renewable sources like hydropower, wind, and solar. Zero carbon emissions are produced.

TURQUOISE
Hydrogen produced by the thermal splitting of methane (methane pyrolysis). Instead of CO_2, solid carbon is produced.

YELLOW
Hydrogen produced by electrolysis using grid electricity.

BLUE
Grey or brown hydrogen with its CO_2 sequestered or repurposed.

PINK/PURPLE/RED
Hydrogen produced by electrolysis using nuclear power.

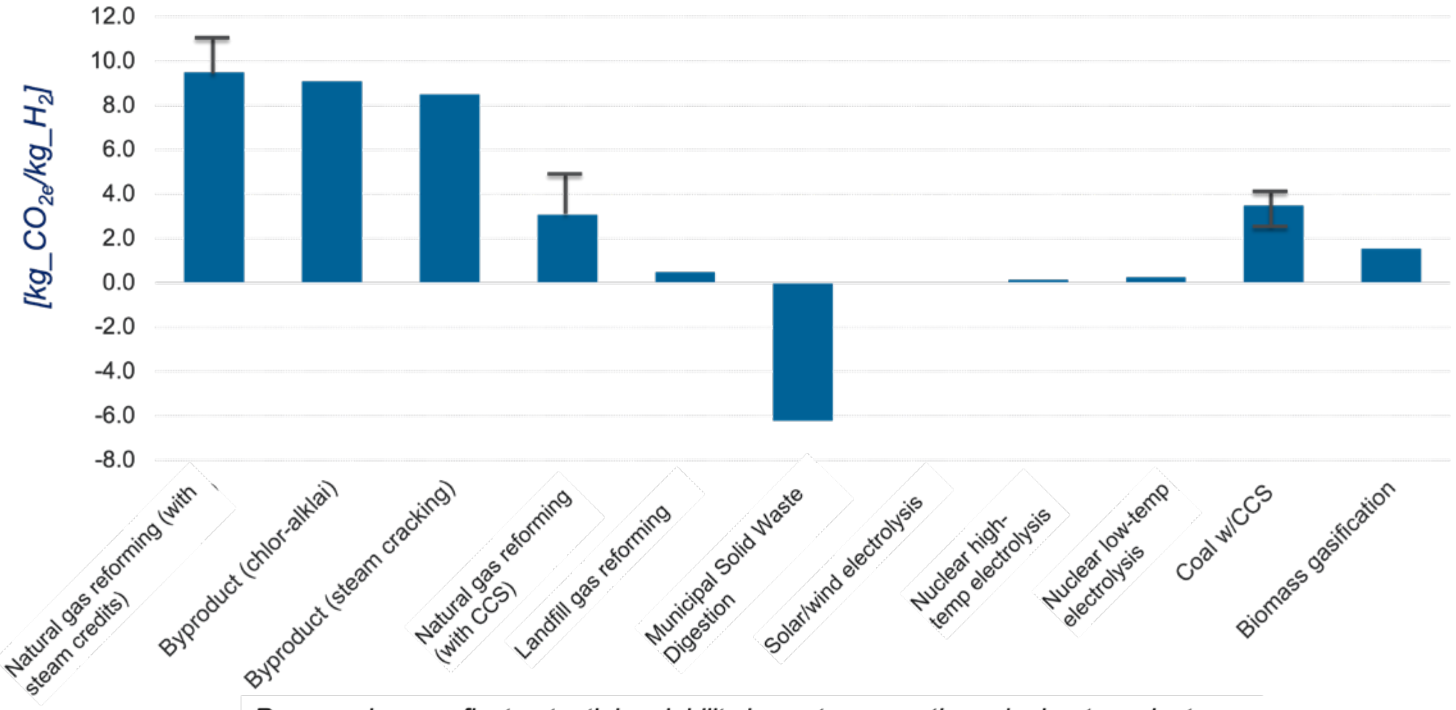
BLACK/GRAY
Hydrogen extracted from natural gas using steam-methane reforming.

WHITE
Hydrogen produced as a byproduct of industrial processes.

BROWN
Hydrogen extracted from fossil fuels, usually coal, using gasification.

Color definitions and descriptions from NACFE
https://nacfe.org/emerging-technology/electric-trucks-2/making-sense-of-heavy-duty-hydrogen-fuel-cell-tractors/

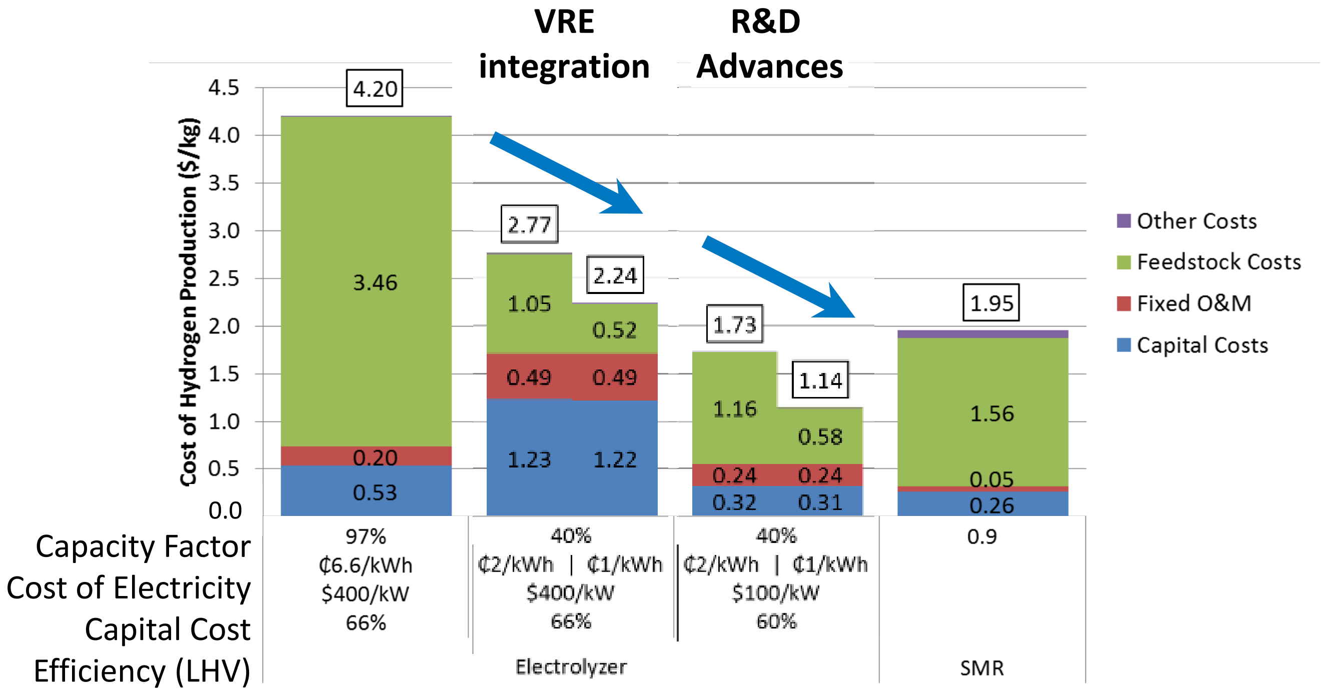
Emission Levels are a More Accurate Description



Ranges shown reflect potential variability in upstream methane leak rates, plant energy efficiency, and CO_2 capture rates. Baseline assumes 90% capture rate

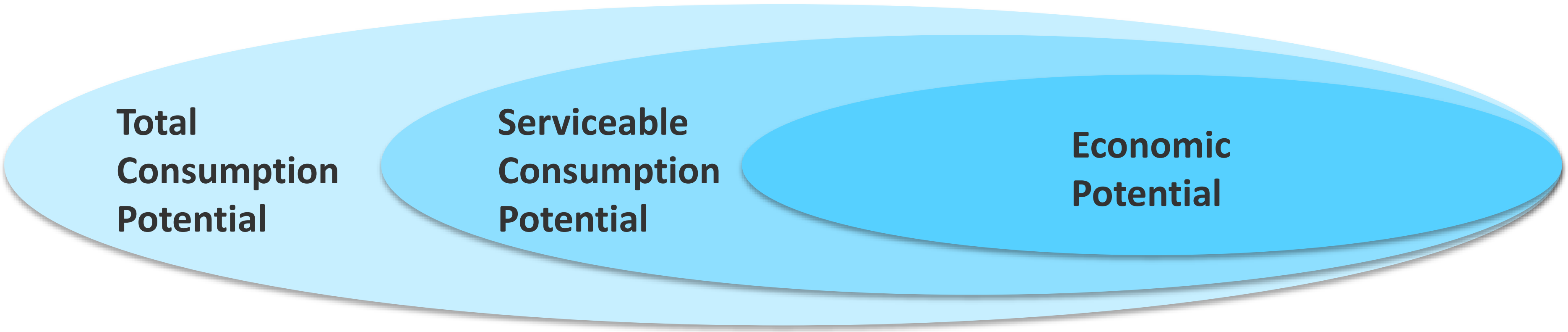
Figure courtesy of Amgad Elgowainy (ANL) – Presented at the H2IQ hour on October 28, 2021

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



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

Demand Categories



- ***Total Consumption Potential:*** the amount of hydrogen that would be consumed if all consumers in a given industry utilized hydrogen without considering costs or economic competition. It is analogous to the maximum possible theoretical consumption.
- ***Serviceable Consumption Potential:*** the amount of hydrogen that would be consumed to serve the portion of the market that could be captured without considering economics (i.e., if the price of hydrogen were $0/kg over an extended period)
- ***Economic Potential*****:** the amount of hydrogen that would be consumed by a sector when its price and the price for competing alternatives are considered.

Serviceable Consumption Potential

Serviceable Consumption Potential of hydrogen market by 2050 is >10X.

Other applications are possible based on technology and policy growth as well as smaller applications

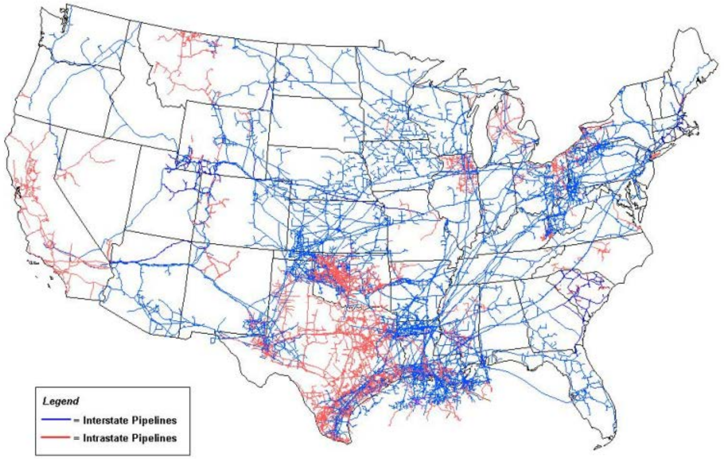
Application	Serviceable Consumption Potential (MMT/yr)	2015 Market for On-Purpose H2 (MMT/yr)
Refineries and the chemical processing industry (CPI) [a]	7	6
Metals	12	0
Ammonia	4	3
Biofuels	9	0
Synthetic hydrocarbons	14	1
Natural gas supplementation	16	0
Seasonal energy storage for the grid	15	0
Industry and Storage Subtotal	**77**	**10**
Light-duty fuel cell electric vehicles (FCEVs)	21	0
Medium- & Heavy-Duty FCEVs	8	0
Transportation Fuel Subtotal	**29**	**0**
Total	**106**	**10**

Definition: The Serviceable Consumption Potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, system performance, and by optimistic market shares but not by economic calculations.

Potential Hydrogen Markets: Natural Gas Supplementation

- Serviceable Consumption Potential:
  - 20% (volume) assumed to not have significant impact on technologies that utilize natural gas
  - 16 MMT_{H2}/yr
- Threshold Price:
  - Energy value on a higher heating value (HHV) basis
  - \$0.80/kg_{H2} for AEO reference case (\$5.88/MMBtu)
  - \$1.40/kg_{H2} for AEO Low Oil & Gas Resource case (\$10.23/MMBtu)

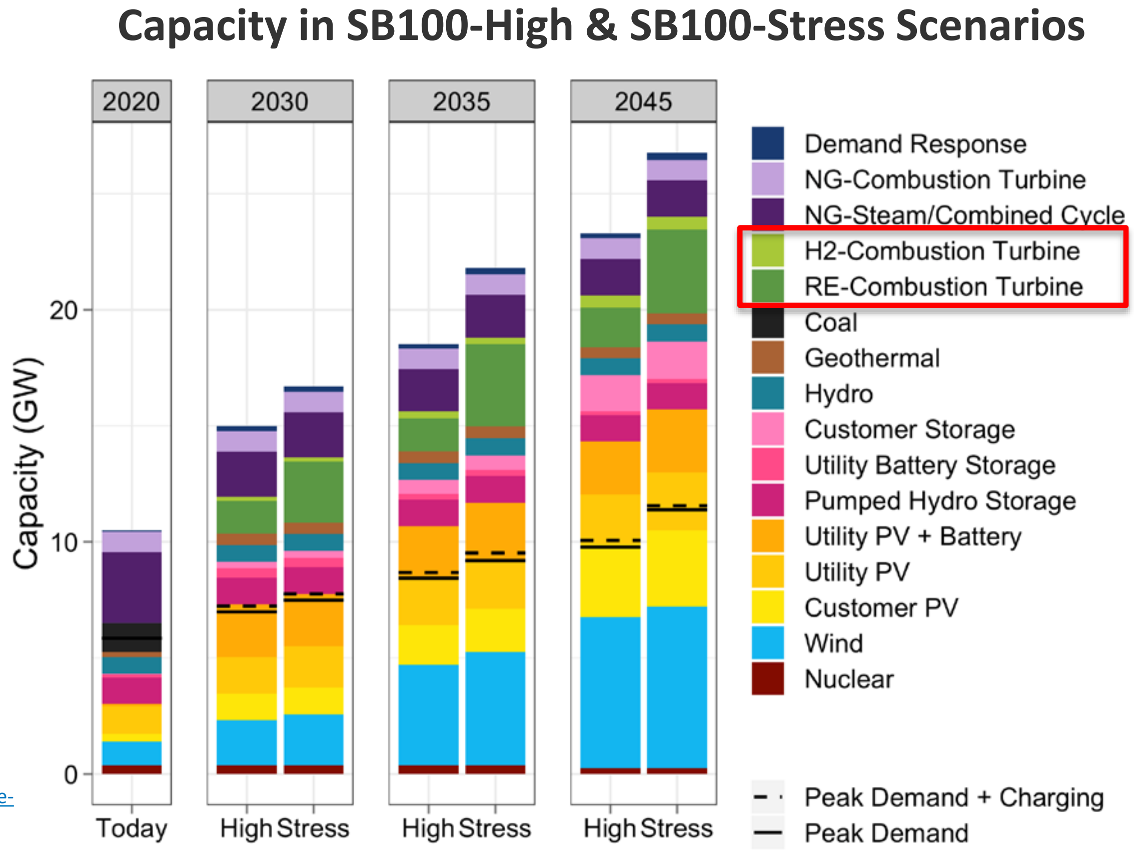
U.S. Natural Gas Pipeline Network



Source: M. W. Melaina, O. Antonia, M. Penev. 2013. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. NREL/TP-5600-51995. https://www.nrel.gov/docs/fy13osti/51995.pdf

Hydrogen is Often Identified as a Carbon-Free Energy Source for Dispatchable Power Generation

The LA100 study identified options to achieve 100% renewable energy by 2045. Findings include hydrogen to provide electricity when other storage options are depleted.



More available at: https://maps-dev.nrel.gov/la100/key-findings/topics/renewable-energy-pathways#renewable-energy-pathways-assumptions

Potential Hydrogen Markets: Seasonal Electricity Storage

- Opportunity
  - Hydrogen can decouple storage power (W) from energy (Wh) making it a key candidate for seasonal storage
- Potential demand & threshold price:
  - Based on natural gas loads in ReEDS high penetration scenarios
  - 15 MMT/yr potential demand in the ReEDS High Curtailment Scenario
  - Prices to produce electricity competitively with natural gas source

Hydrogen Demand and Required Threshold Prices for Seasonal Electricity Storage under the ReEDS High Curtailment Grid Scenario (Using the AEO LOGR Costs)

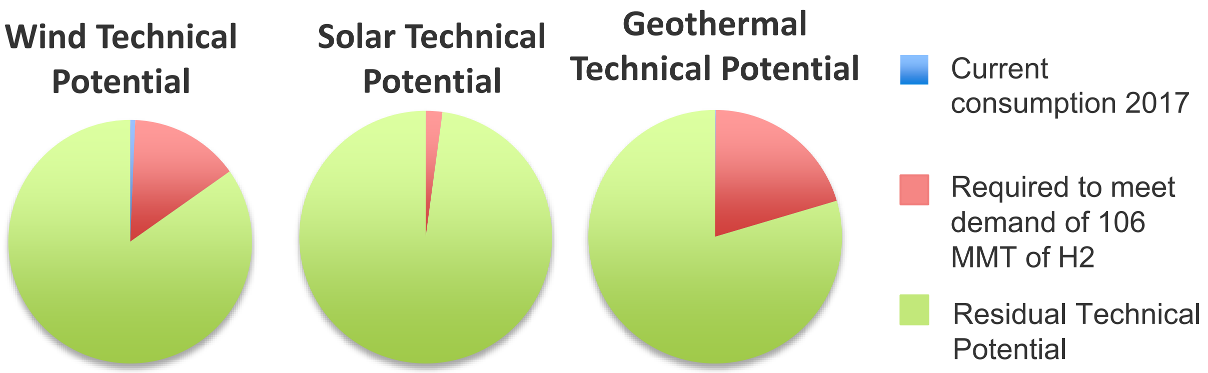
	Annual Electricity Generation to Serve Load (TWh)	Hydrogen Price ($/kg)	Annual Hydrogen Demand (MMT)
NGCC generation	252	1.10	14
NGCT generation	14	0.26	0.8
Cumulative	266	N/A	15

Technical Potential Supply from Renewable Resources

	2017 consumption (quad/yr)	Quantity required to produce 106 MMT/yr (quad/yr)	Total technical potential (quad/yr)
Solar electricity	0.31	18.2	890
Wind electricity	0.87	18.2	130
Conv. Hydropower electricity	1.0	18.2	2.4
Adv. hydropower electricity	0.0	18.2	6.2
Geothermal electricity	0.07	18.2	85
Solid biomass	5.0	25.8	19

Total demand including hydrogen serviceable consumption potential is satisfied by:

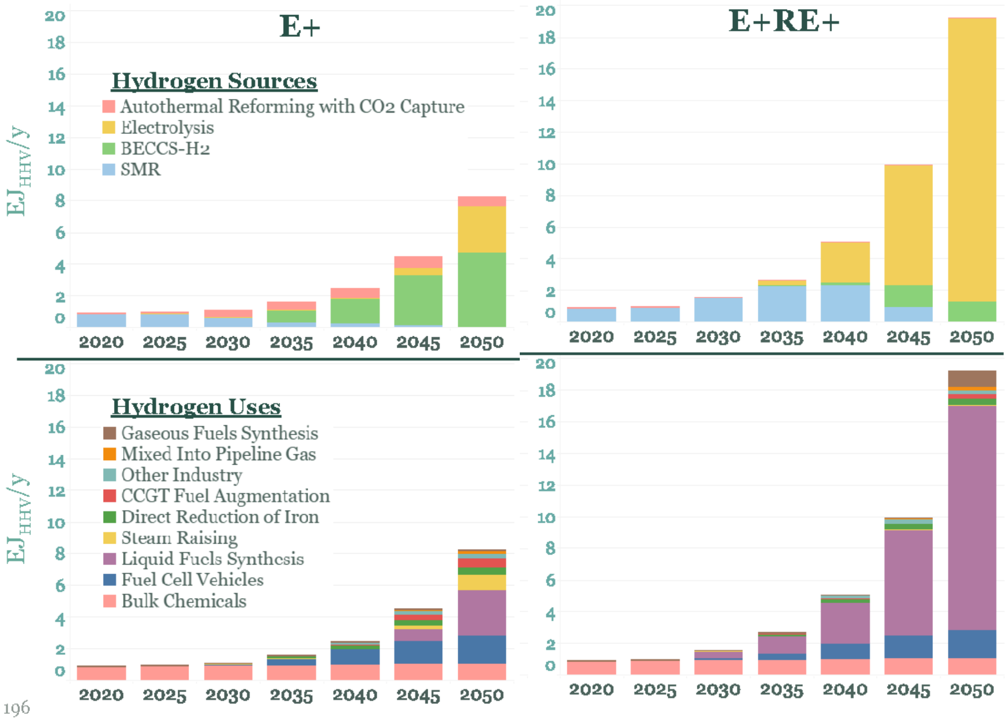
- **15% of wind**
- **2.1% of solar**
- **820% of conventional hydropower**
- **300% of advanced hydropower**
- **22% of geothermal**
- **160% of biomass technical potential**



Others Have Estimated Similar Hydrogen Markets

Princeton Net Zero America

1 EJ ≈ 7 MMT

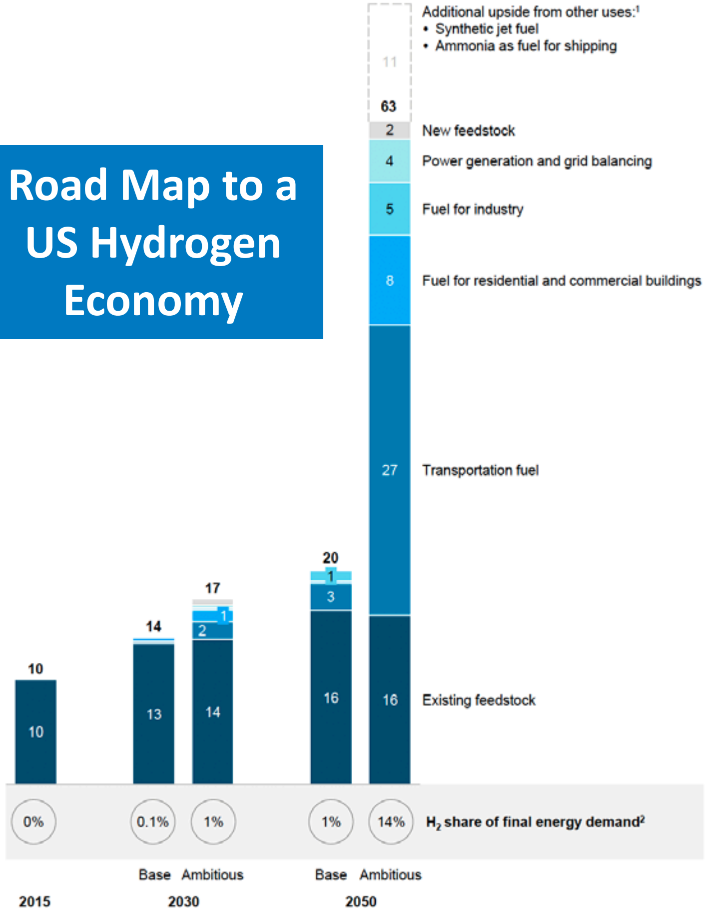


Road Map to a US Hydrogen Economy

Exhibit 2

Hydrogen demand potential across sectors – 2030 and 2050 vision

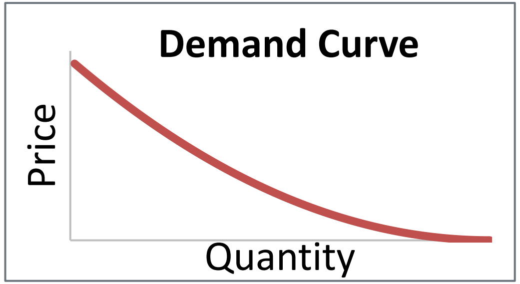
Million metric tons per year



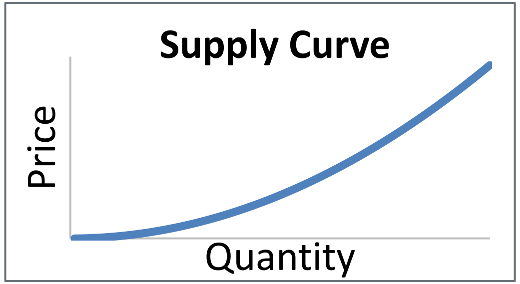
[1] Assuming that 20% of jet fuel demand would be met by synthetic fuel and 20% of marine bunker fuel by ammonia
[2] Demand excluding feedstock, based on IEA final energy demand for the US
Note: Some numbers may not add up due to rounding

Sources: Princeton Net Zero America Report (https://netzeroamerica.princeton.edu/the-report).
Road Map to a US Hydrogen Economy Reducing emissions and driving growth across the nation. www.ushydrogenstudy.org

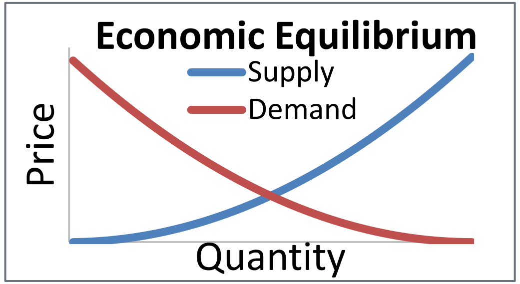
Economic Potential Methodology: Market Equilibrium



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

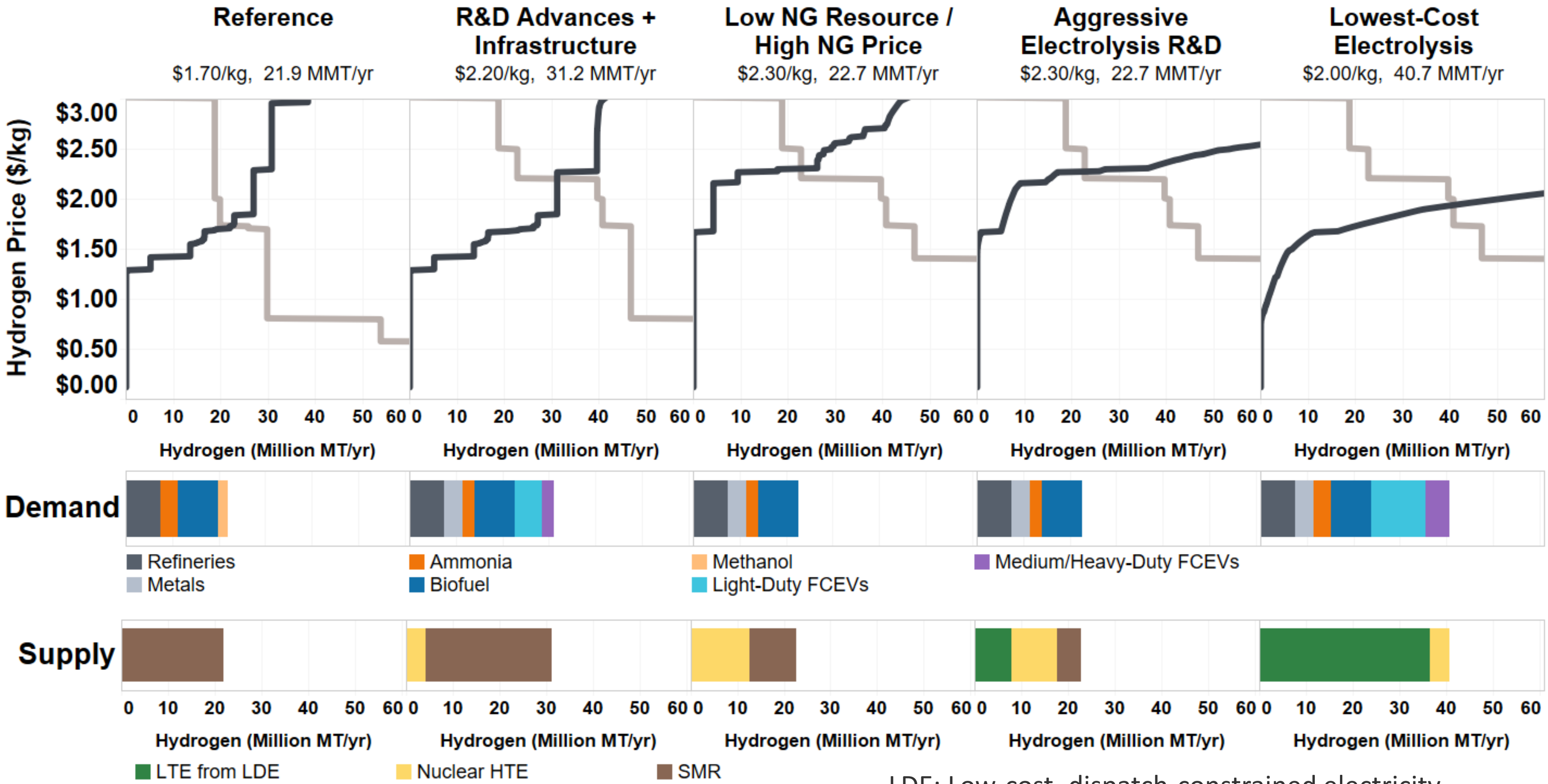
- Market equilibrium methodology and market size estimates in 2050
  - Transition issues such as stock turnover are not considered
- New policy drivers, such as emission policies, are not included either for hydrogen or the grid
- Technology and market performance involve many assumptions about adjacent 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>

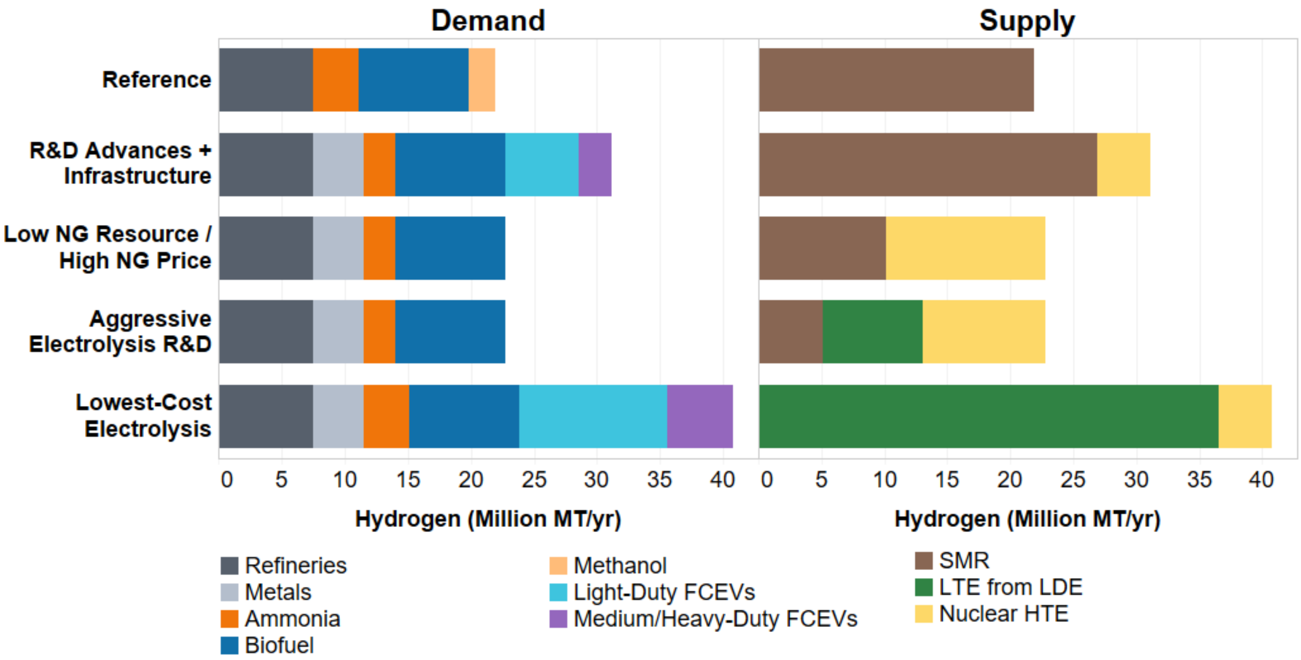
Key differences in scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers' access to grid service markets, and 5) increased threshold price in metals industry

New Economic Potential Results



LDE: Low-cost, dispatch-constrained electricity

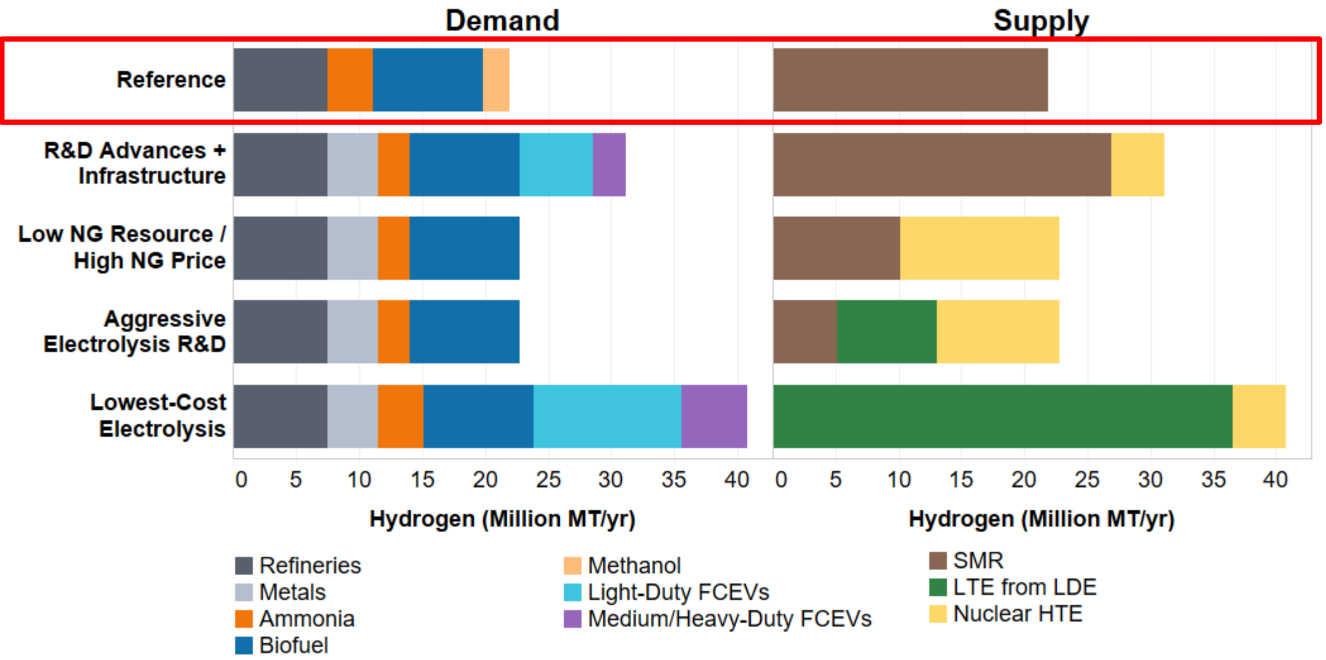
Economic Potential Results



The economic potential of hydrogen demand in the U.S. is 2-4X current annual consumption.

LDE: Low-cost, dispatch-constrained electricity

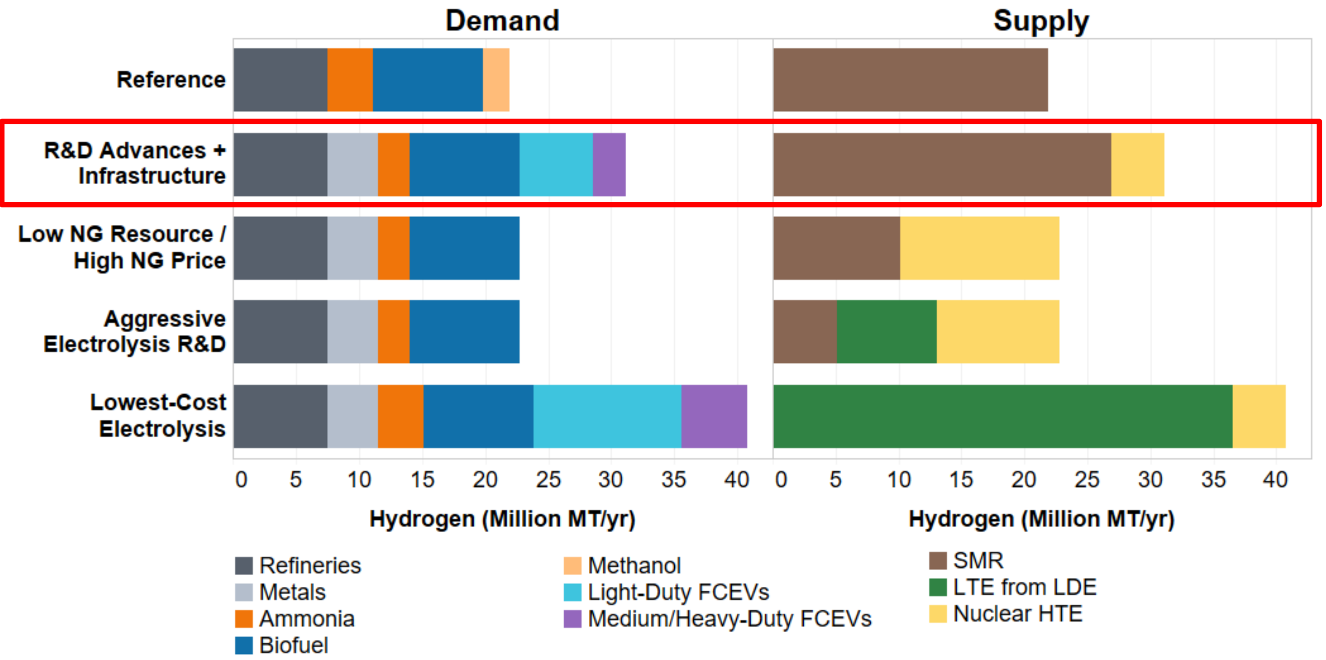
Reference Scenario



- **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

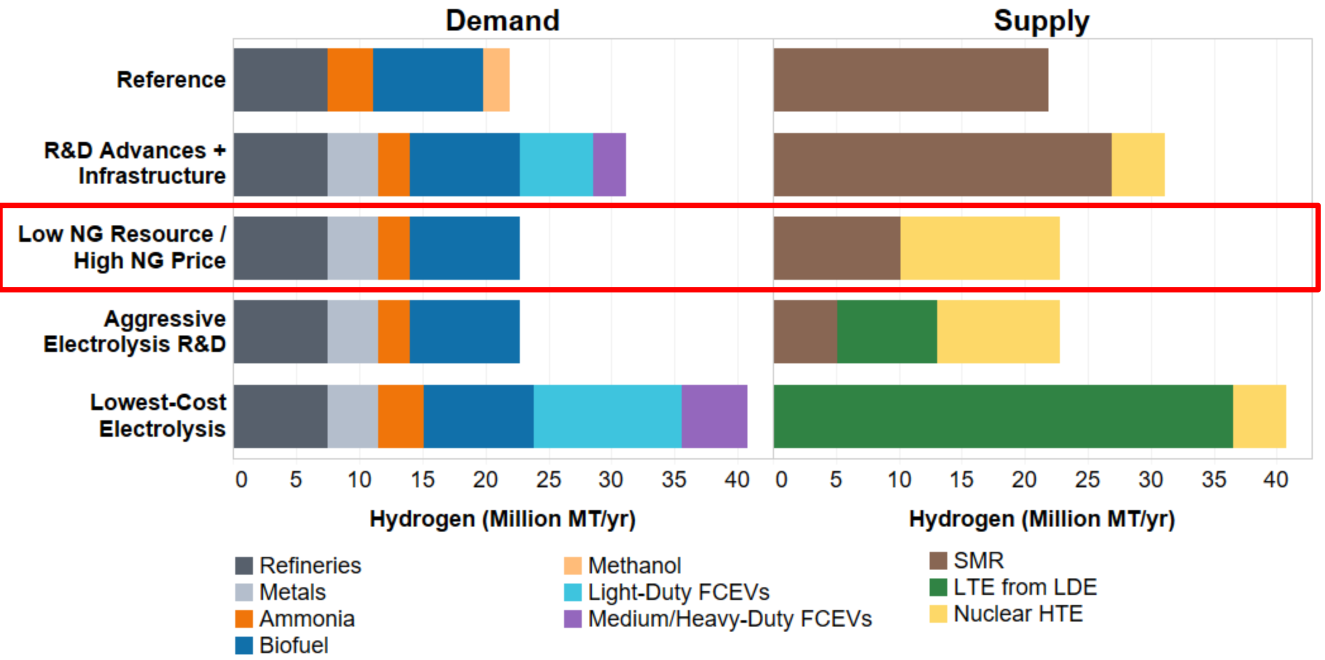
R&D Advances + Infrastructure Scenario



- **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

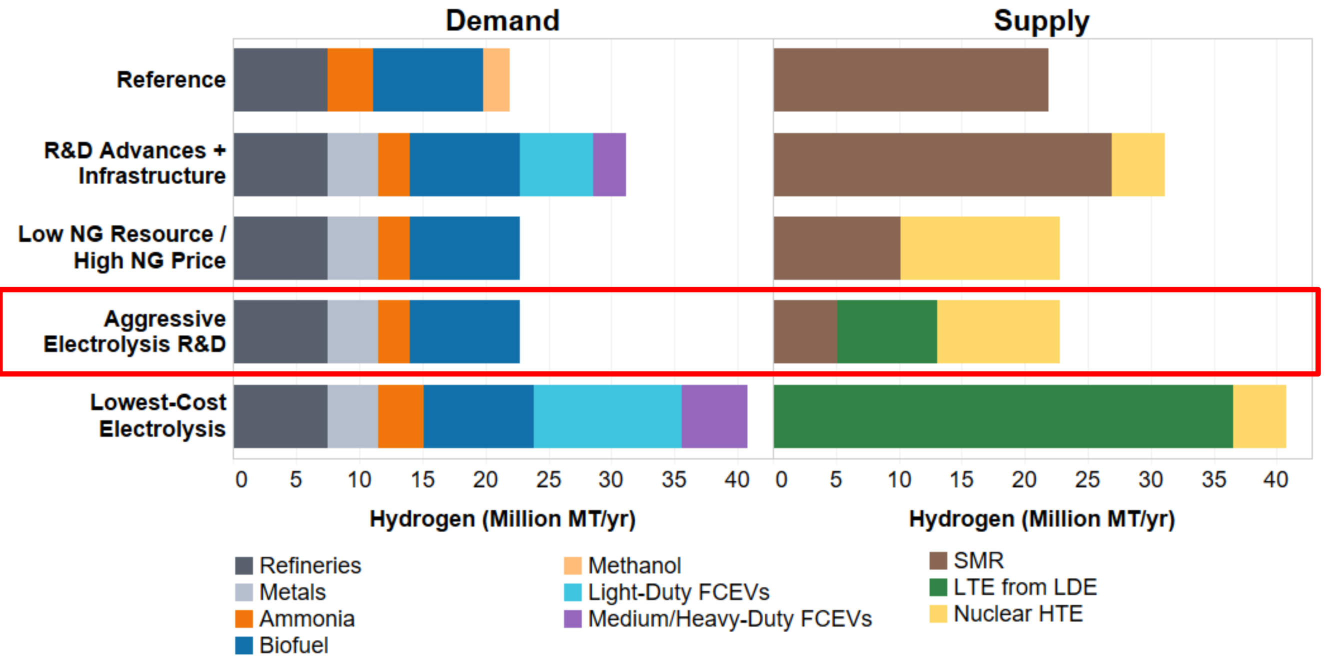
Low Natural Gas Resource / High NG Price Scenario



- 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

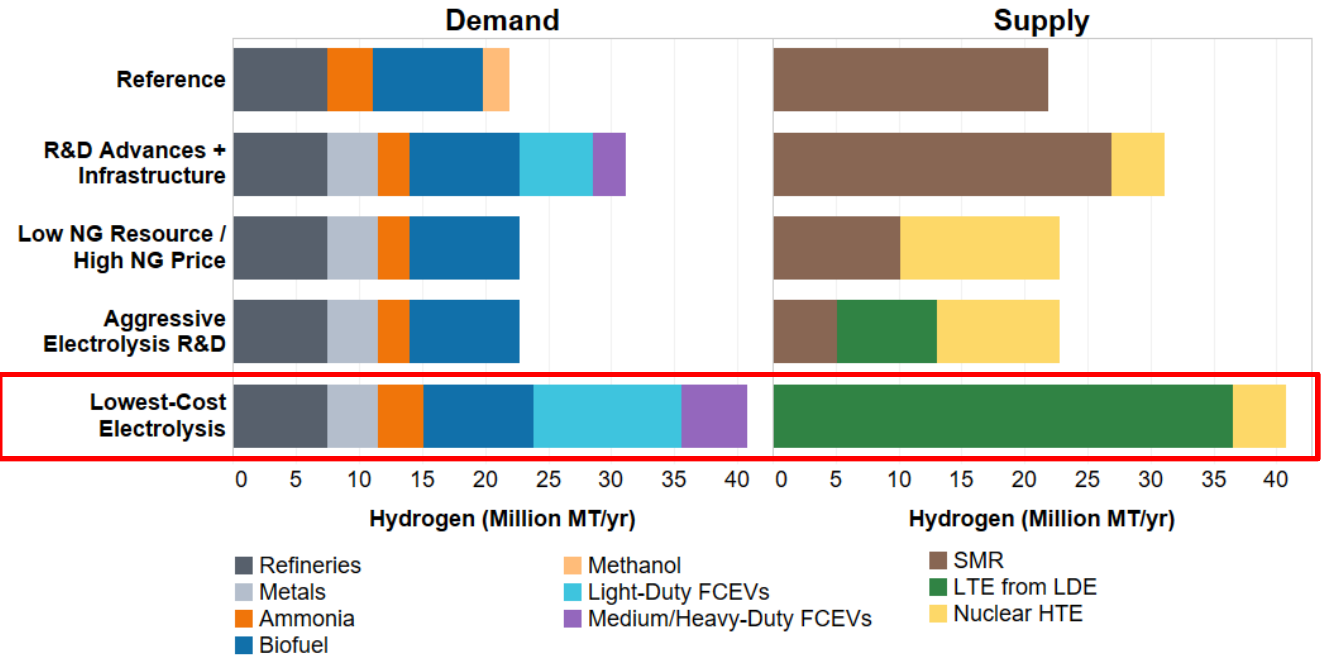
Aggressive Electrolysis R&D Scenario



- 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

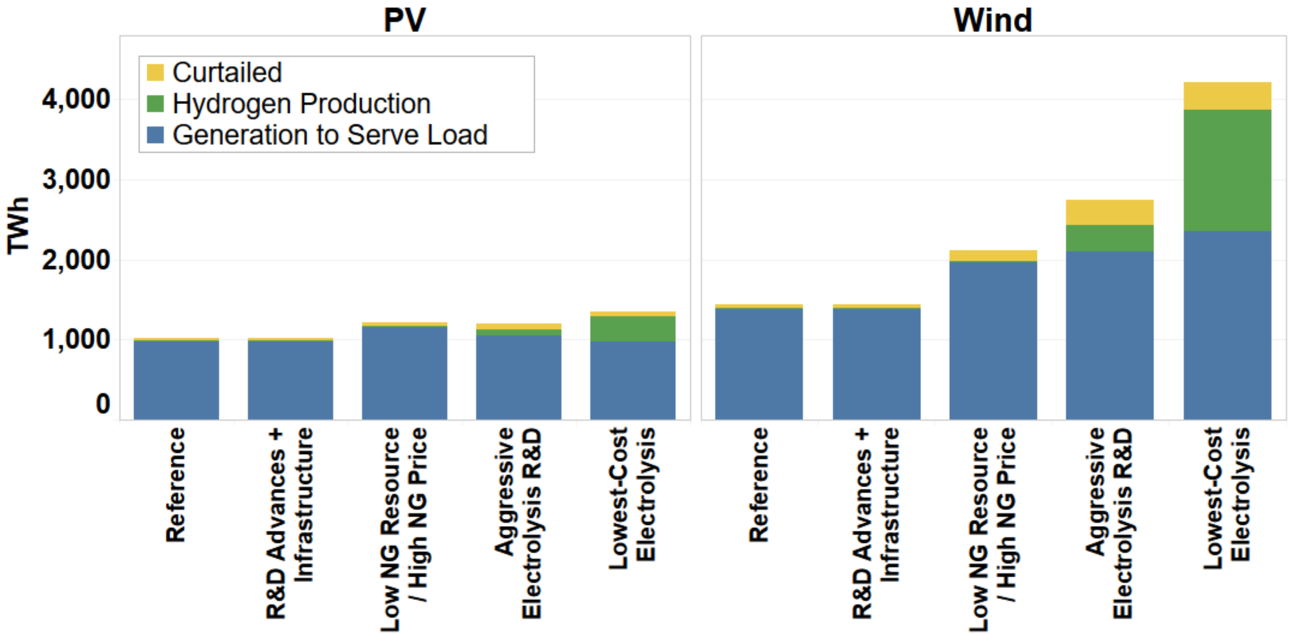


- Electrolytic hydrogen less costly than steam methane reforming due to aggressive R&D and high NG prices (LTE purchase cost reduced to \$100/kW & no price adder on LDE)
- LTE dominates the market
- Low-cost H_2, enables increased FCEV penetrations and offsets ammonia imports

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

Impacts on U.S. Electricity Grid

In the Lowest-Cost Electrolysis scenario, an additional 2,300 TWh/yr of electricity generation is economic. It exceeds load (not including hydrogen) by 45%.

Scenario Name	Reference	R&D Advances + Infrastructure	Low NG Resource / High NG Price	Aggressive Electrolysis R&D	Lowest-Cost Electrolysis
Hydrogen from LTE (MMT/yr)	-	-	-	8	37
Electricity generation that exceeds load (TWh / yr)	80	80	200	790	2,300
Percentage of Electricity Generation that Exceeds Load (annual basis)	2%	2%	4%	16%	45%
LDE used to produce hydrogen (TWh / yr)	-	-	-	400	1,800
LDE Wholesale Average Price* [Range] ($/MWh)	NA	NA	NA	$17 [$0-$21]	$25 [$0-$26]
Average capacity factor of LDE used to produce hydrogen* [Range]	NA	NA	NA	50% [10%-80%]	54% [10%-75%]

* Weighted by hydrogen production

Summary of Key Conclusions

- **The economic potential of hydrogen demand in the U.S. is 2.2-4.1X 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 renewable energy 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.
- **The impacts of an integrated hydrogen system could be larger.** Hydrogen's serviceable consumption potential in the U.S. is >10X current annual consumption. Transportation is the largest new hydrogen market opportunity.

Thank You!

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NREL/PR-6A20-81406

www.nrel.gov

Reports with details on the Technical and Economic Potential of H2@Scale:

https://www.nrel.gov/docs/fy21osti/77610.pdf
https://greet.es.anl.gov/publication-us_future_h2

Additional information on H2@Scale:

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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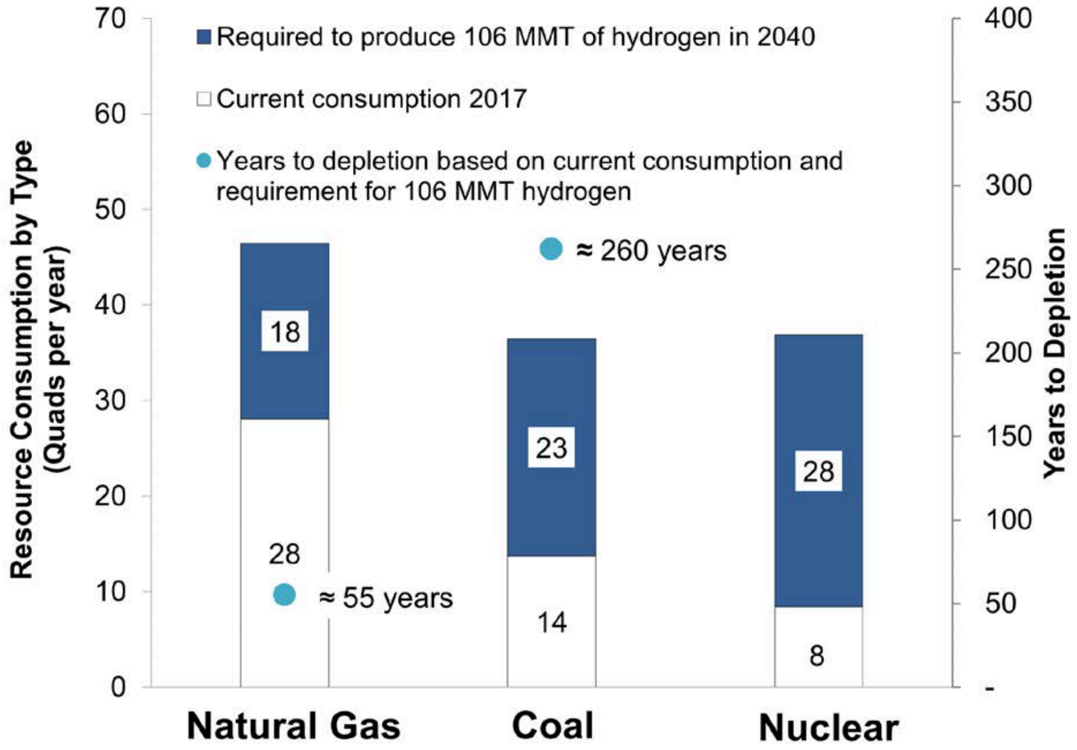
NREL Transforming ENERGY

Backup

Technical Potential of Fossil and Nuclear Resources



Hydrogen can be produced from diverse domestic resources to meet aggressive growth in demand

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.

Economic Potential: Five National Scenarios

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<tr><td>Description</td><td>Current status of hydrogen technologies; low natural gas (NG) prices</td><td>Expected cross-sector hydrogen technology improvement and demand growth; robust hydrogen demand for metals; no grid support; low natural gas (NG) prices</td><td>Expected cross-sector hydrogen demand growth; robust hydrogen demand for metals; no electrolysis for grid support; high NG prices</td><td>Robust metals hydrogen demand growth; limited electrolysis for grid support; high NG prices</td><td>Robust metals hydrogen demand growth; electrolysis providing grid support; high NG prices</td></tr>
<tr><td>Natural gas prices</td><td colspan="2">AEO 2017 Reference scenario</td><td colspan="3">AEO 2017 Low Oil and Gas Resource and Technology scenario</td></tr>
<tr><td>Availability of SMR facilities</td><td colspan="5">Hydrogen generation from SMRs for non-ammonia production is capped at three times current levels (23 MMT/yr)

Hydrogen generation from SMRs estimated for future ammonia production is capped at 5 MMT hydrogen/yr</td></tr>
<tr><td>Nuclear costs</td><td colspan="5">20% of current nuclear fleet available at $\$25/\text{MWh}_e$ opportunity cost & additional 40% at $\$40/\text{MWh}_e$</td></tr>
<tr><td>HTE costs</td><td>$820/kW</td><td colspan="4">$423/kW</td></tr>
<tr><td>LTE capital costs</td><td>$900/kW</td><td colspan="2">$400/kW</td><td>$200/kW</td><td>$100/kW</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 costs</td><td colspan="4">HFTO cost targets met</td></tr>
<tr><td>Metals demand</td><td>Must compete with existing technologies</td><td colspan="4">Markets are willing to pay a premium for metals refined using 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, & 5) increased threshold price in metals industry

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