The Technical and Economic Potential of Hydrogen within the United States

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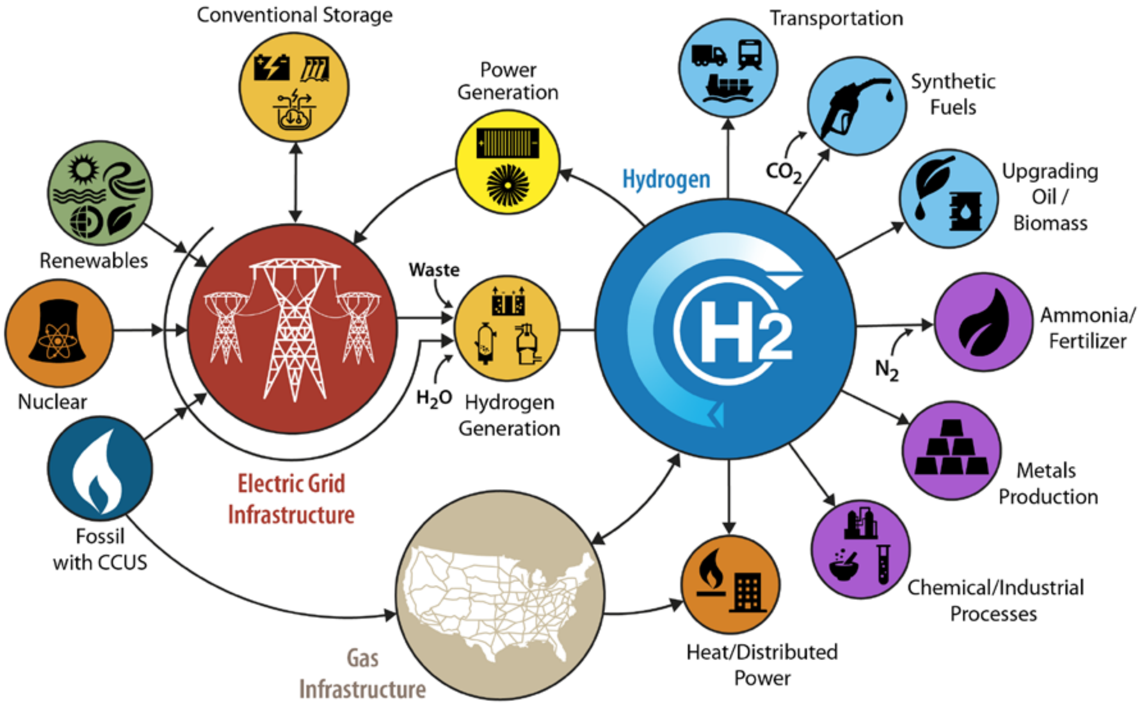
HyPT-2 Meeting
14 September 2021

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

H2@Scale

DOE initiative focusing on hydrogen as an energy intermediate.



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

Analysis Objectives

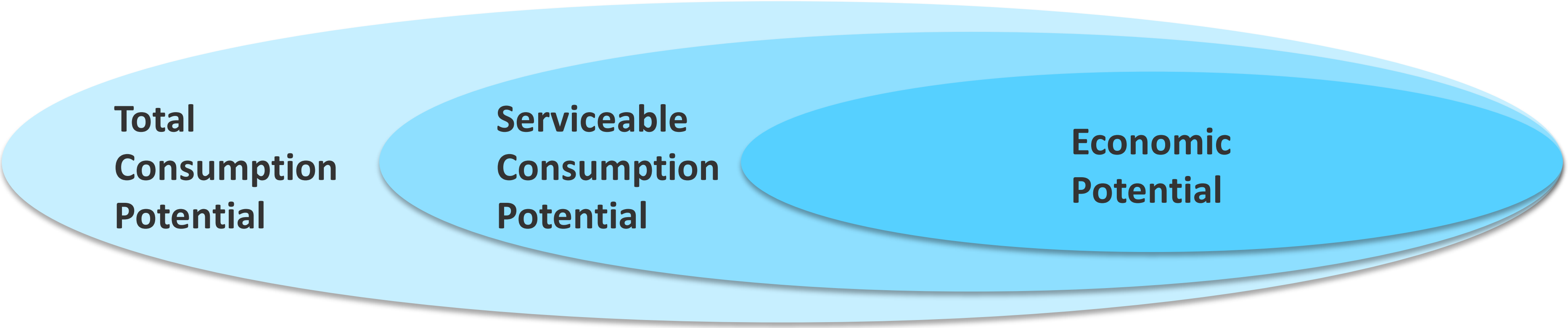
- **Quantify the potential of the H2@Scale vision** for the 48 contiguous states in the U.S.

- **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

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 electricity 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**

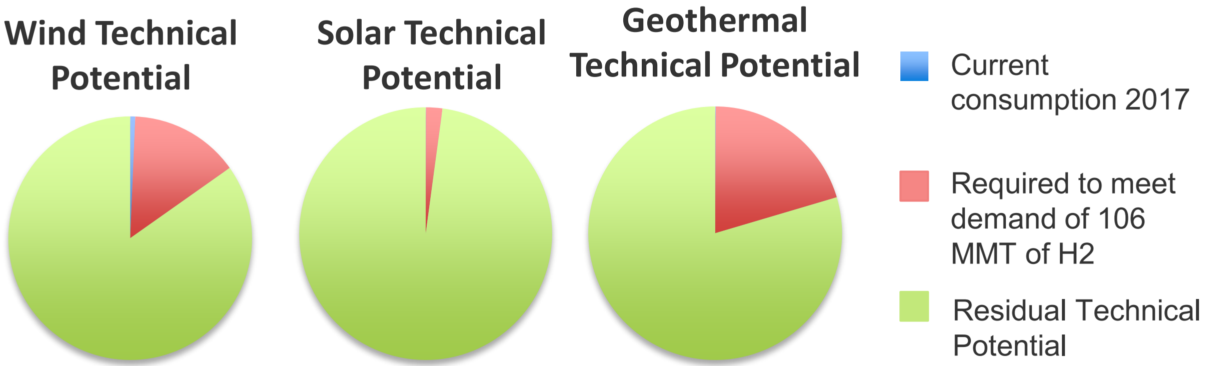
Definition: The Serviceable Consumption Potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, system performance, and by optimistic market shares but not by economic calculations.

Technical Potential Supply from Renewable Resources

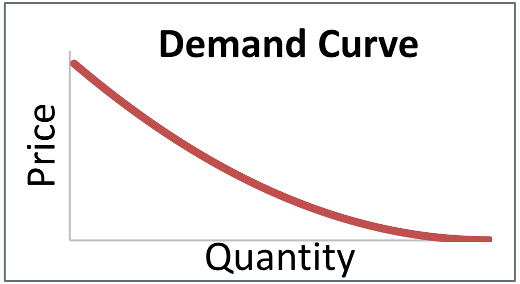
	2017 consumption (quad/yr)	Quantity required to produce 106 MMT/yr (quad/yr)	Total technical potential (quad/yr)
Solar electricity	0.31	18.2	890
Wind electricity	0.87	18.2	130
Conv. Hydropower electricity	1.0	18.2	2.4
Adv. hydropower electricity	0.0	18.2	6.2
Geothermal electricity	0.07	18.2	85
Solid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

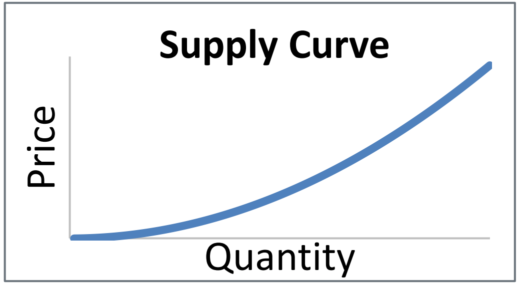
Total demand including hydrogen serviceable consumption potential is satisfied by:

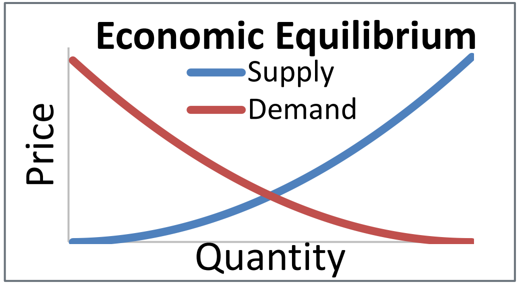
- **15% of wind**
- **2.1% of solar**
- **820% of conventional hydropower**
- **300% of advanced hydropower**
- **22% of geothermal**
- **160% of biomass technical potential**



Economic Potential Methodology: Market Equilibrium







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

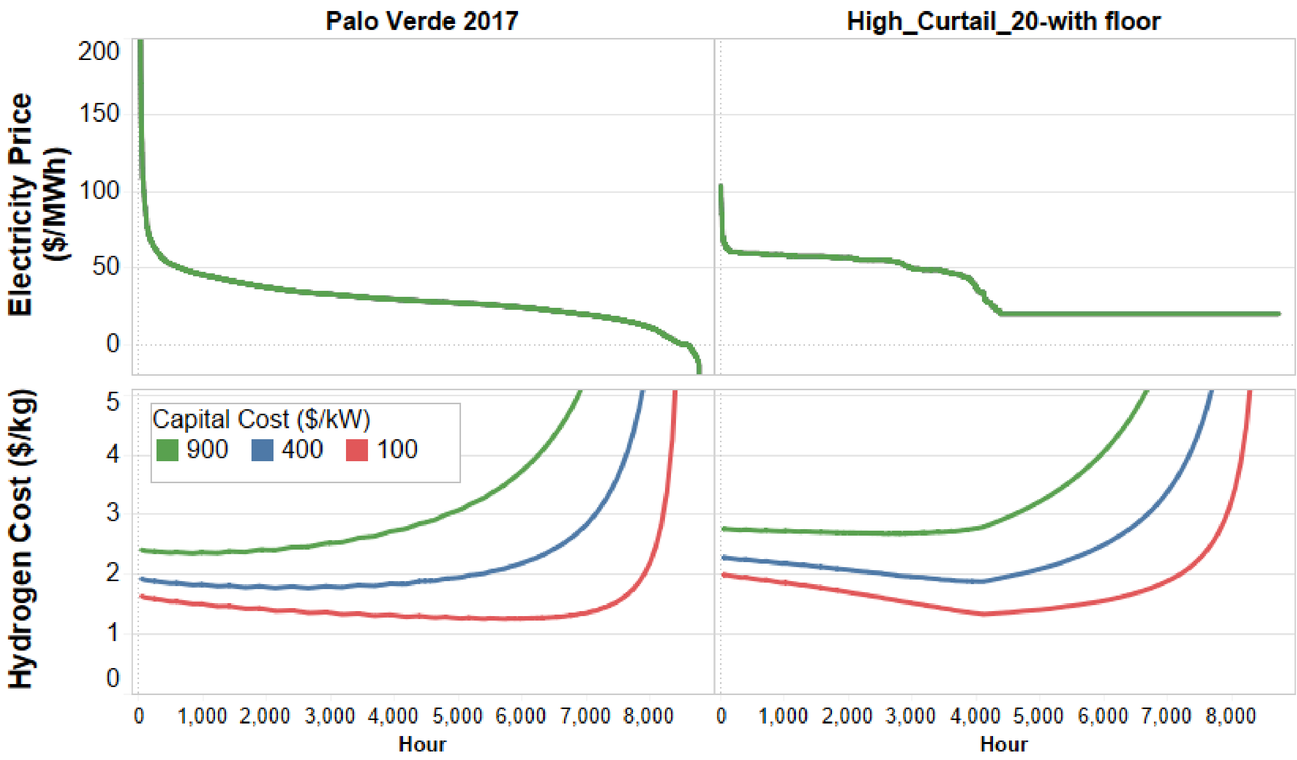
Supply Curve: threshold prices showing how much are producers willing and able to produce at each?

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.

Future Opportunities for LDE Utilization at Palo Verde



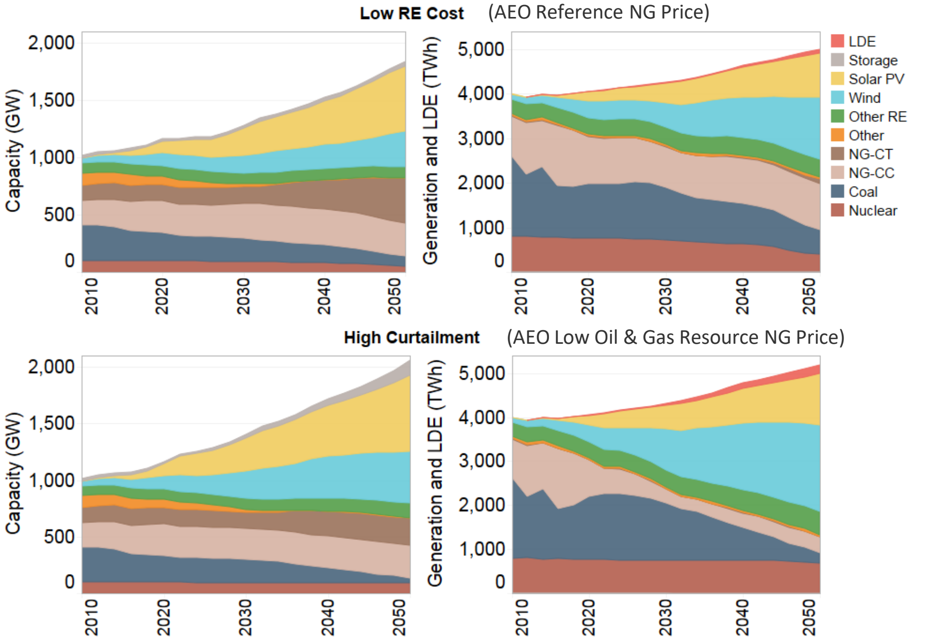
Under parameters that lead to high variable renewable generation and with a $20/MWh price floor,

- Additional LDE is available
- Electrolytic hydrogen can be cost competitive at Palo Verde

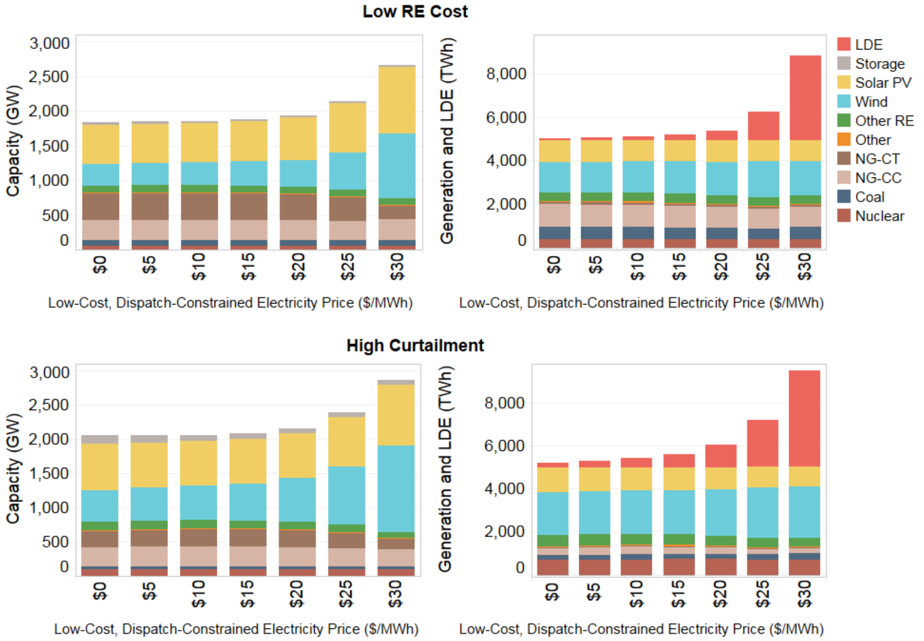
Capacity Expansion with Value for Low-Cost, Dispatch-Constrained Electricity

Used ReEDS to estimate generator fleet and generation mix at multiple low-cost, dispatch-contrained electricity (LDE) values

Buildout with $0/MWh LDE

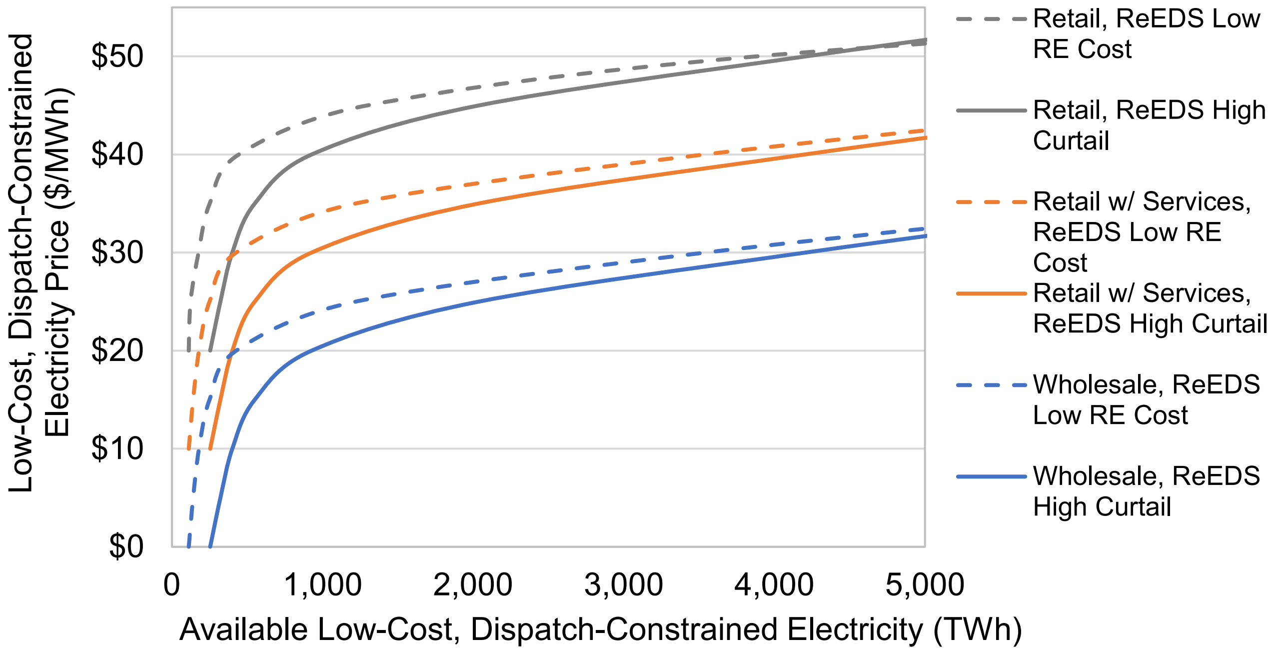


2050 Results at Various LDE Values



Low-Cost, Dispatch-Constrained Supply Curves

Used PLEXOS Unit Commitment Model to create supply / availability curves for LDE



Economic Potential: Limitations and Caveats

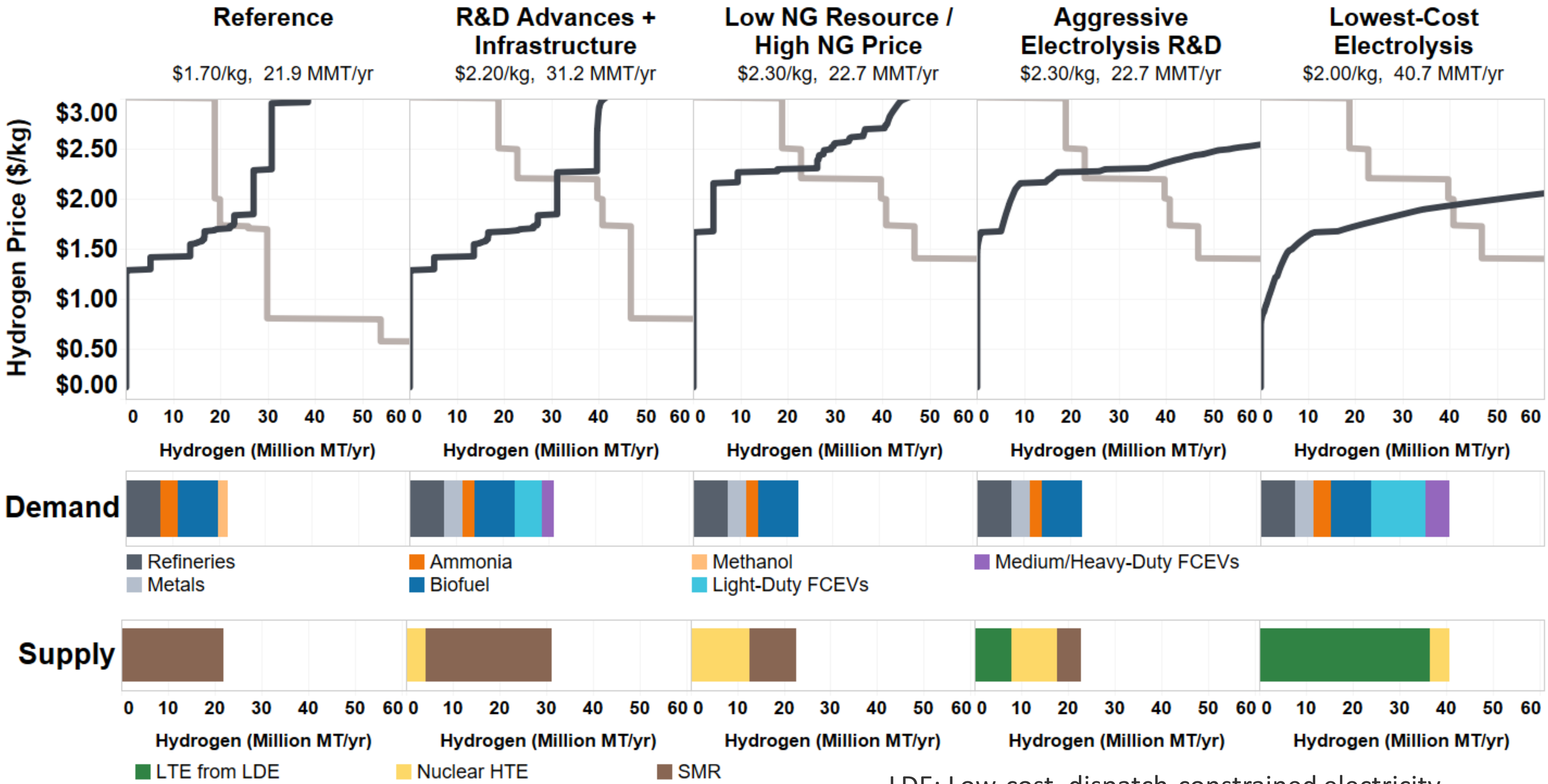
- Market equilibrium methodology and market size estimates in 2050
  - Transition issues such as stock turnover are not considered
- New policy drivers, such as emission policies, are not included either for hydrogen or the grid
- Technology and market performance involve many assumptions about adjacent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

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

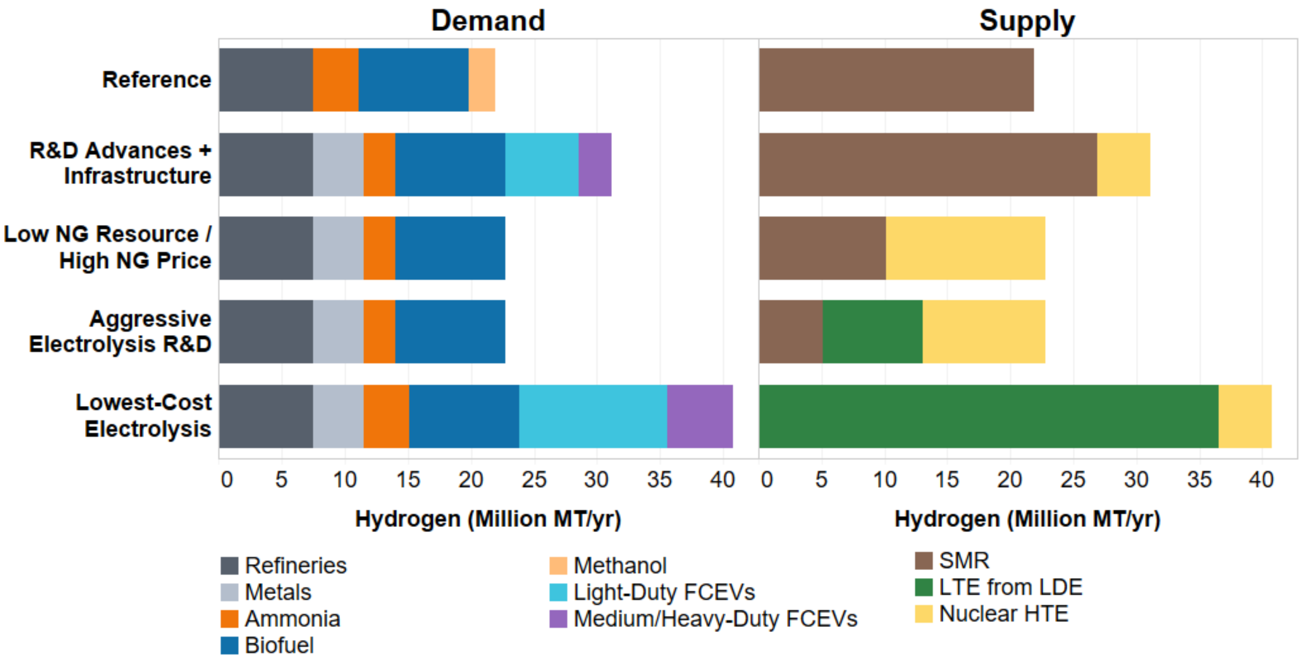
Key differences in scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers' access to grid service markets, and 5) increased threshold price in metals industry

New Economic Potential Results



LDE: Low-cost, dispatch-constrained electricity

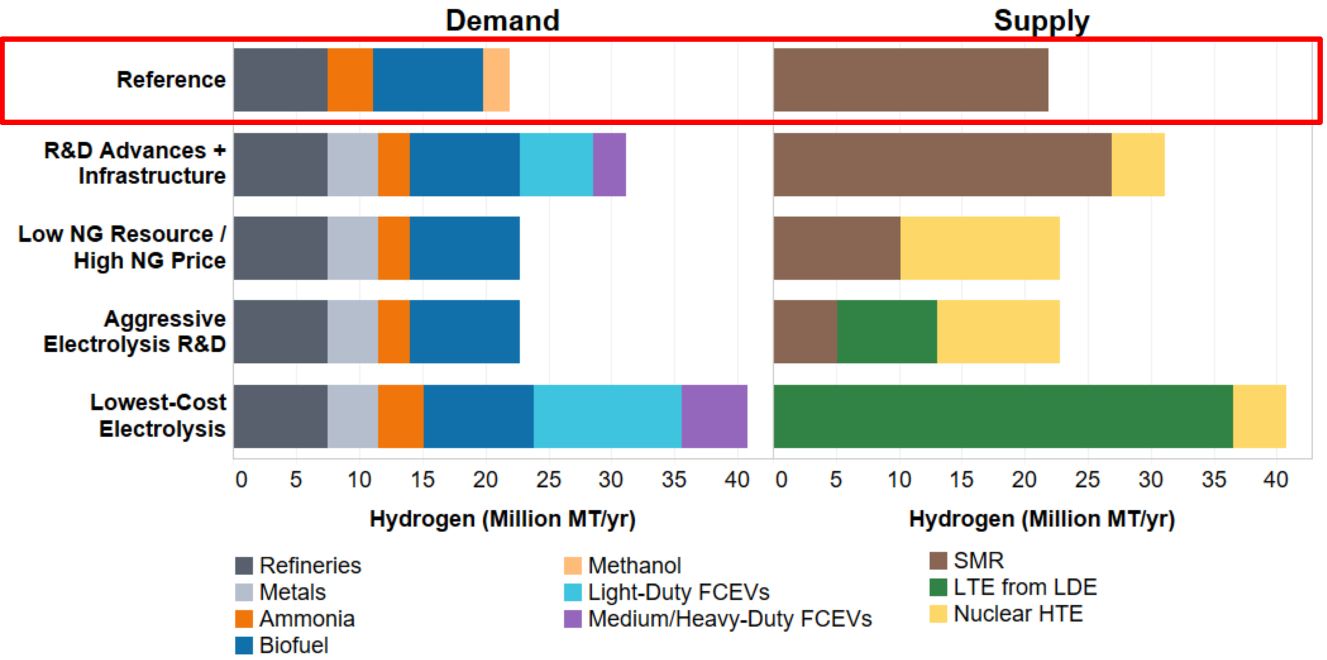
Economic Potential Results



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

LDE: Low-cost, dispatch-constrained electricity

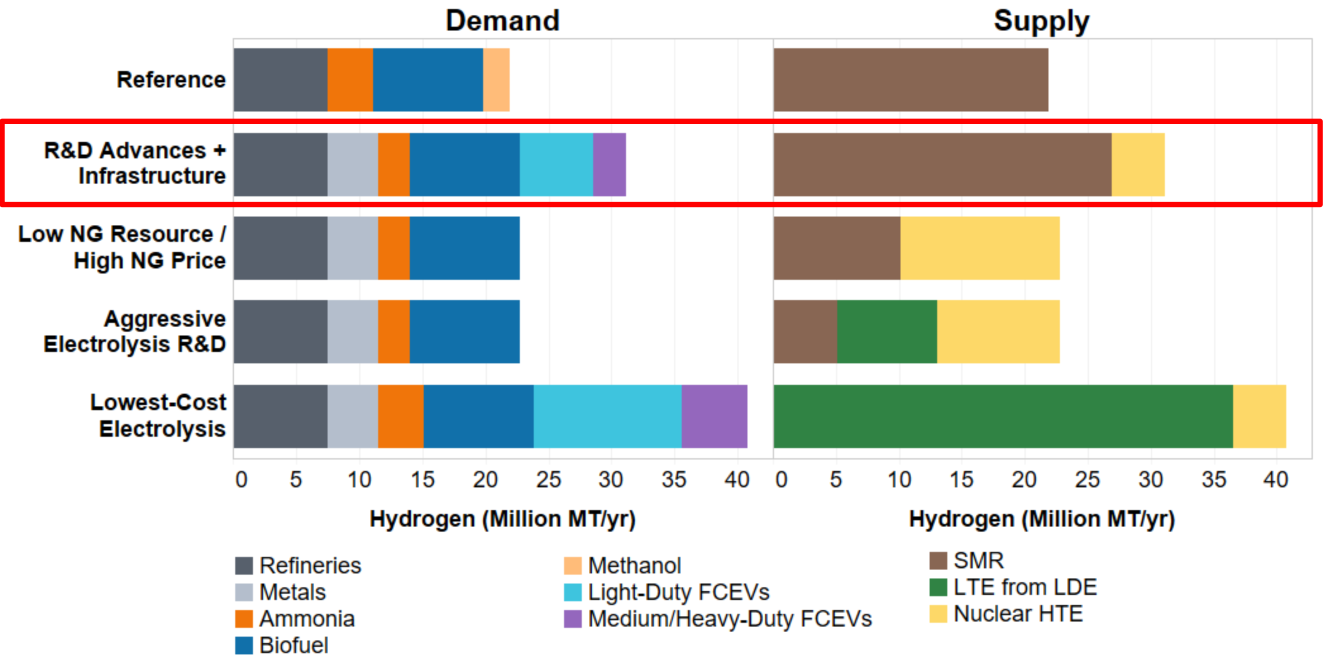
Reference Scenario



- 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

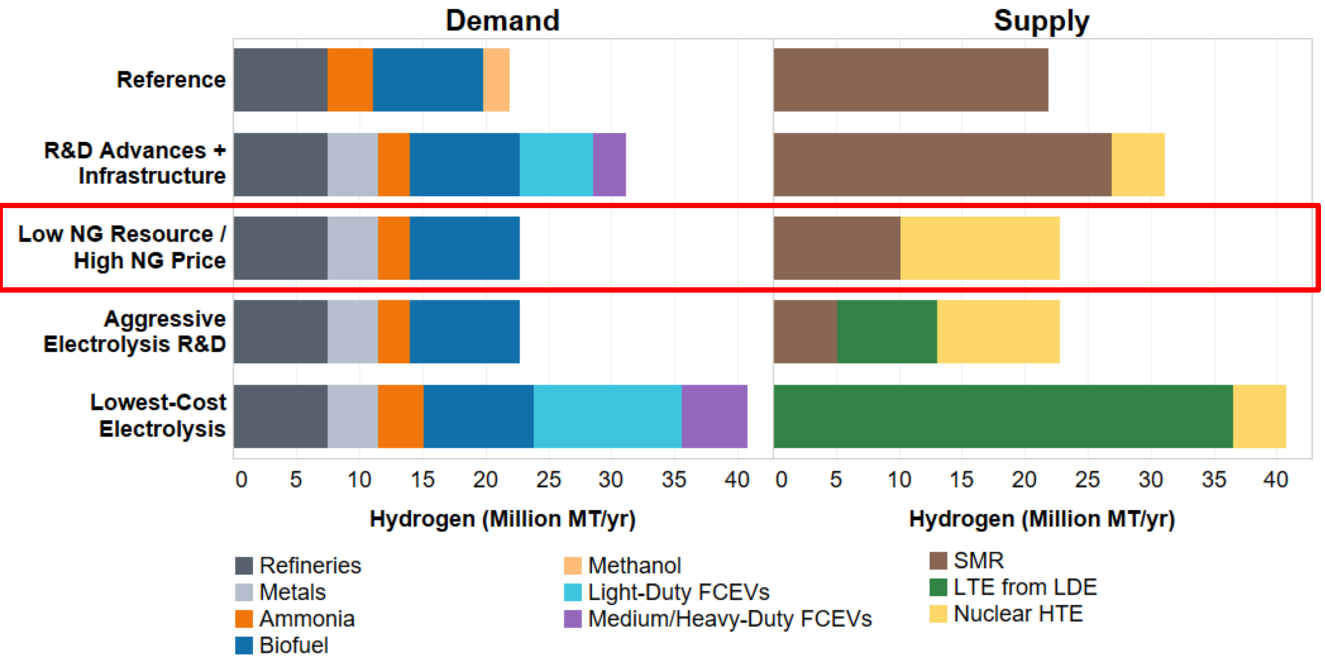
R&D Advances + Infrastructure Scenario



- 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

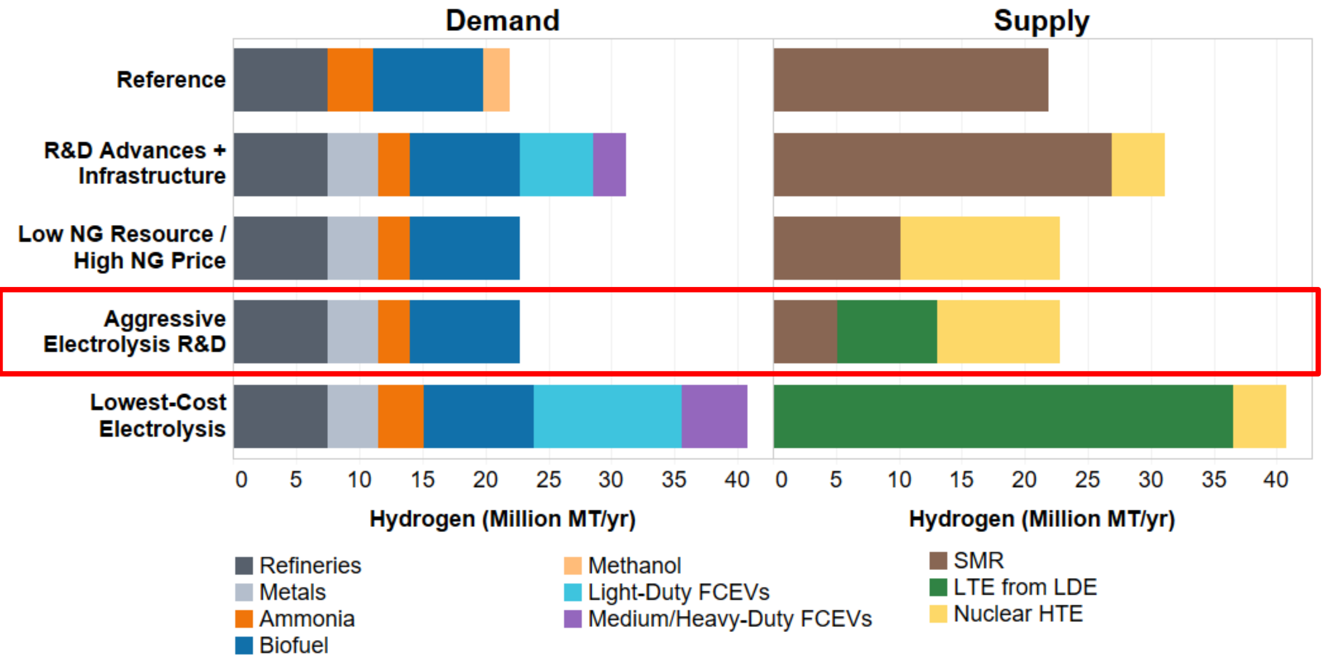
Low Natural Gas Resource / High NG Price Scenario



- 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

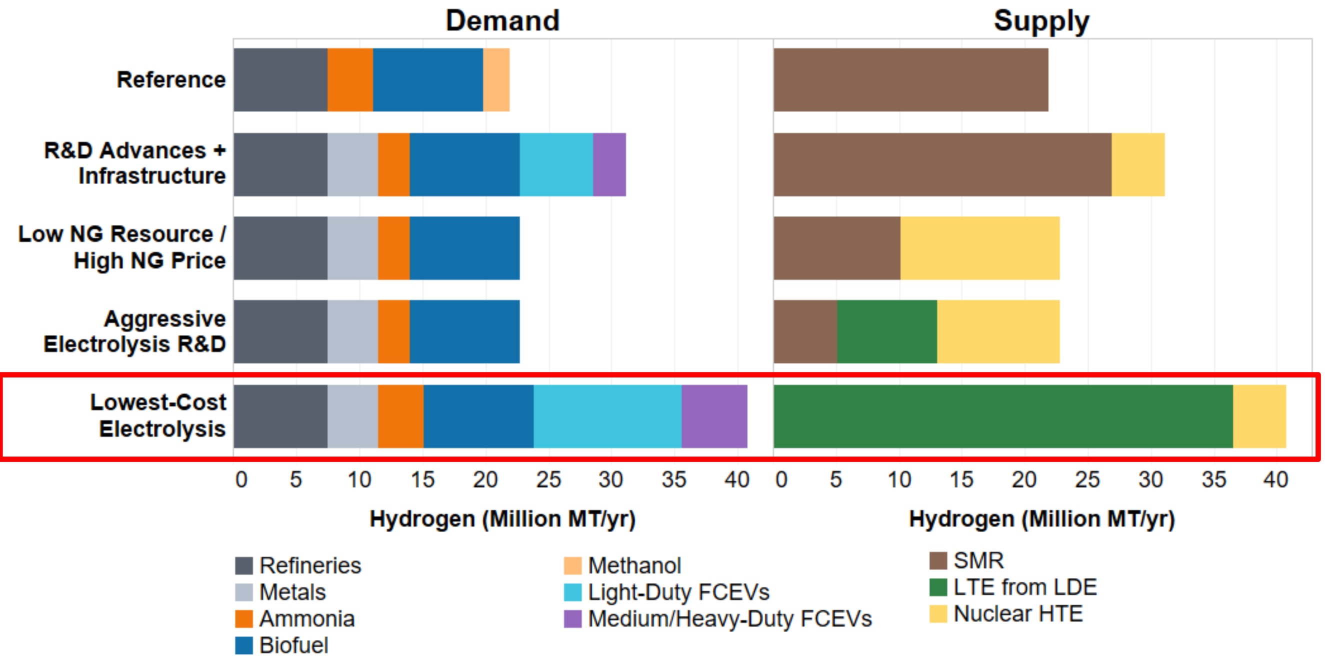
Aggressive Electrolysis R&D Scenario



- 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

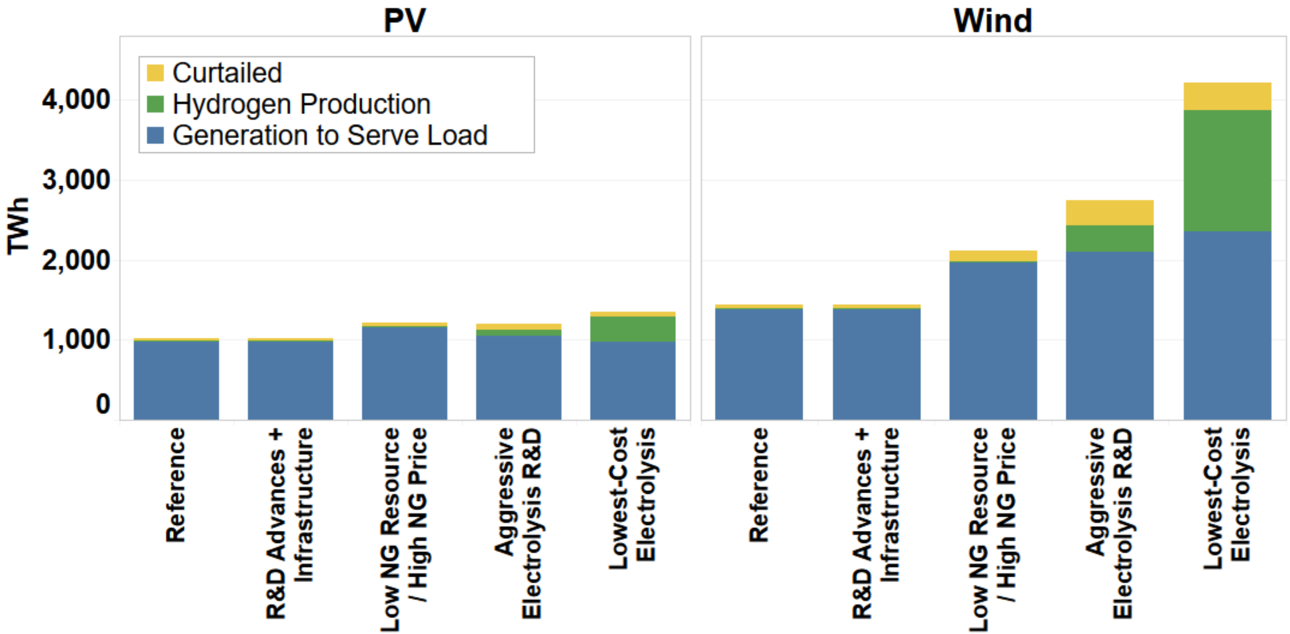


- Electrolytic hydrogen less costly than steam methane reforming due to aggressive R&D and high NG prices (LTE purchase cost reduced to $100/kW & no price adder on LDE)
- LTE dominates the market
- Low-cost H_2, enables increased FCEV penetrations and offsets ammonia imports

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

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-6A20-80942

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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

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

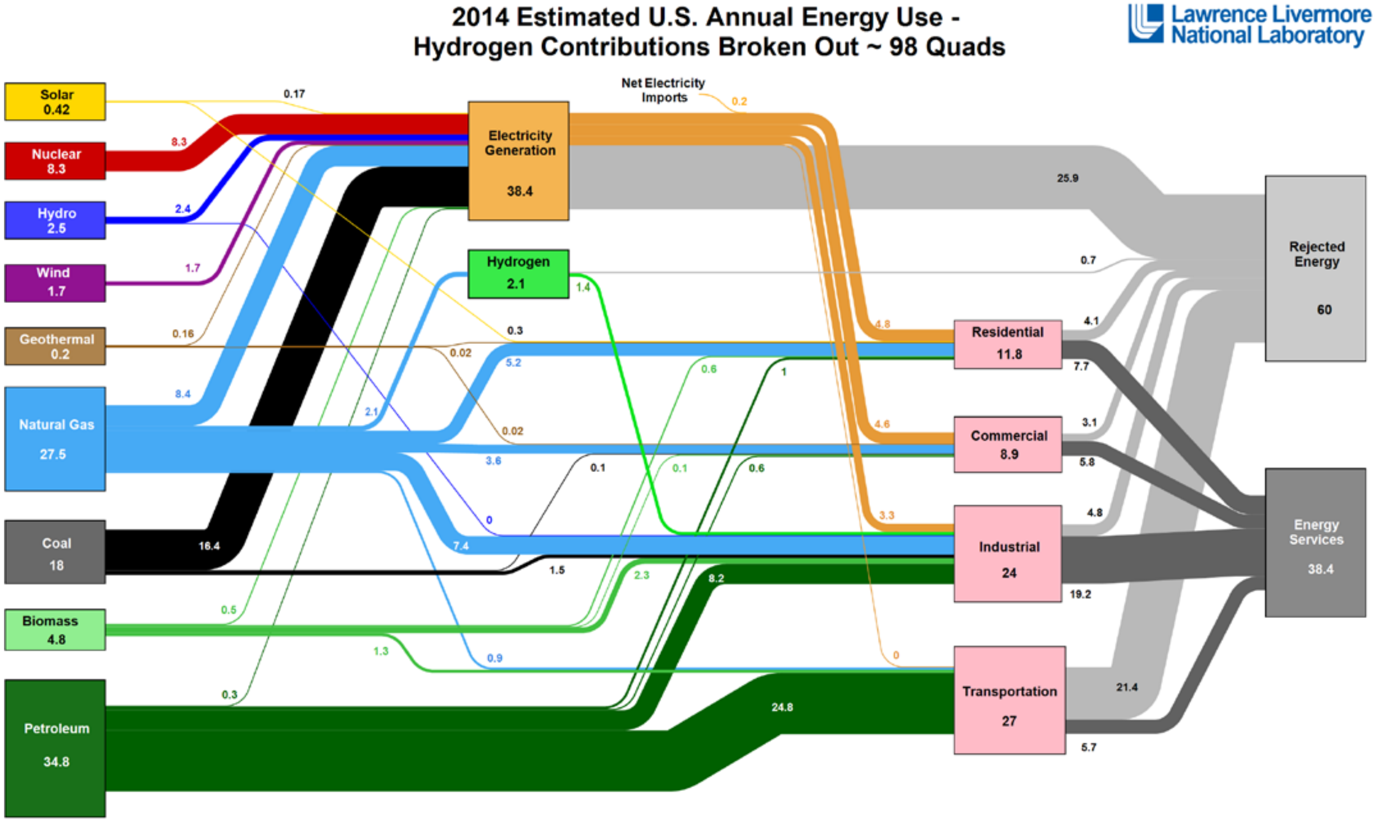
NREL Transforming ENERGY

Backup

H2@Scale Publications Summary

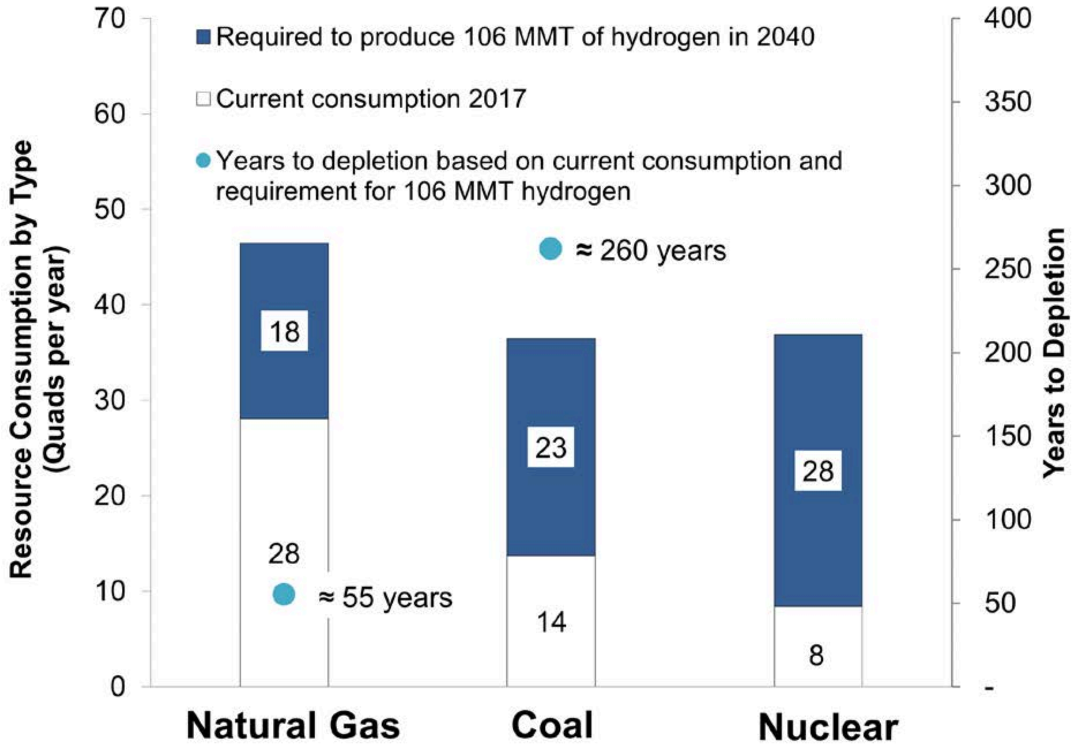
Elizabeth Connelly; Michael Penev; Anelia Milbrandt; Billy. McCall; Nicholas Gilroy; Marc Melaina. 2020. Resource Assessment for Hydrogen Production. NREL/TP-5400-77198. https://www.nrel.gov/docs/fy20osti/77198.pdf.
Elgowainy, A., M. Mintz, U. Lee, T. Stephens, P. Sun, K. Reddi, Y. Zhou, G. Zang, M. Ruth, P. Jadun, E. Connelly, R. Boardman. Assessment of Potential Future Demands for Hydrogen in the United States. Argonne, IL: Argonne National Laboratory. ANL-20/35. https://greet.es.anl.gov/files/us_future_h2
Pivovar, Bryan, Neha Rustagi, and Sunita Satyapal. 2018. "Hydrogen at Scale (H2@Scale): Key to a Clean, Economic, and Sustainable Energy System." The Electrochemical Society Interface, 6.
Chemical Engineering Progress Special Section on Hydrogen Deployment. August 2019. https://www.aiche.org/resources/publications/cep/2019/august/hydrogen-deployment-complete-28-page-special-section
Satyapal, Sunita. 2017. "The Unique Potential of Hydrogen in Energy Infrastructure, Storage and Resiliency." R&D World, https://www.rdworldonline.com/the-unique-potential-of-hydrogen-in-energy-infrastructure-storage-and-resiliency/

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

Technical Potential of Fossil and Nuclear Resources



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

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
Description	Current status of hydrogen technologies; low natural gas (NG) prices	Expected cross-sector hydrogen technology improvement and demand growth; robust hydrogen demand for metals; no grid support; low natural gas (NG) prices	Expected cross-sector hydrogen demand growth; robust hydrogen demand for metals; no electrolysis for grid support; high NG prices	Robust metals hydrogen demand growth; limited electrolysis for grid support; high NG prices	Robust metals hydrogen demand growth; electrolysis providing grid support; high NG prices
Natural gas prices	AEO 2017 Reference scenario		AEO 2017 Low Oil and Gas Resource and Technology scenario		
Availability of SMR facilities	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				
Nuclear costs	20% of current nuclear fleet available at \$25/MWh_e opportunity cost & additional 40% at \$40/MWh_e				
HTE costs	\$820/kW	\$423/kW			
LTE capital costs	\$900/kW	\$400/kW		\$200/kW	\$100/kW
LDE market assumption	Available at retail price			Between retail and wholesale	Wholesale price
Distribution for FCEVs	Current costs	HFTO cost targets met			
Metals demand	Must compete with existing technologies	Markets are willing to pay a premium for metals refined using hydrogen			

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

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.

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%.

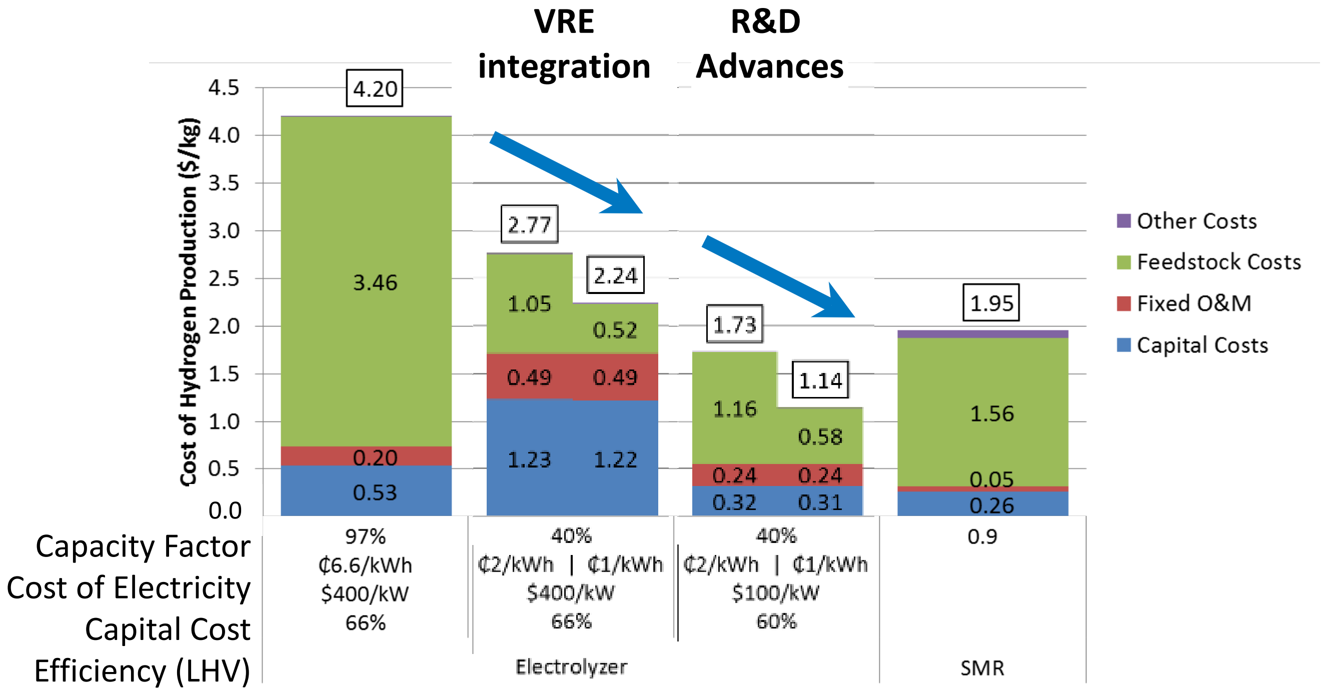
Scenario Name	Reference	R&D Advances + Infrastructure	Low NG Resource / High NG Price	Aggressive Electrolysis R&D	Lowest-Cost Electrolysis
Hydrogen from LTE (MMT/yr)	-	-	-	8	37
Electricity generation that exceeds load (TWh / yr)	80	80	200	790	2,300
Percentage of Electricity Generation that Exceeds Load (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

Conclusions with Implications for Analysis, Research, and Development

- Low-temperature electrolyzer costs needs to be reduced and wholesale electricity markets would need to be accessible for that technology to compete with other hydrogen supply options
- High temperature steam electrolysis technologies need to be commercialized at the assumed prices to realize their potential
- Hydrogen transmission and storage costs are represented in a simple manner in this analysis. Subsequent analysis could improve them and the results.
- Metal refining is a consistent growth market in this analysis, but additional research is needed to achieve cost parity with traditional methods
- Biofuels is a consistent growth market based on the assumption that biofuels will be used in aviation. Further analysis is needed to better quantify that opportunity and those technologies need to be developed.
- Seasonal energy storage is not cost-competitive but that may be due to the national nature of this study and the lack of new policies like 100% renewable energy standards that could increase the potential. In addition, regional/local opportunities may exist that were not captured in this analysis
- Injection into NG is not cost competitive in this study. However, regional congestion or policy may change that situation
- External non-technical/market drivers (e.g., policy) would impact hydrogen markets

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



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

Additional Demand Info

Market Data Sources

Estimated prices for industrial demands / city edge terminals; thus, reported prices are market prices minus delivery from city edge as necessary

Refineries & CPI	From Elgowainy, et al (2020)
Metals	From Elgowainy, et al (2020)
Ammonia	From Elgowainy, et al (2020)
Biofuels	From Elgowainy, et al (2020)
Synthetic hydrocarbons	From Elgowainy, et al (2020)
Nat. Gas Supplement	From Elgowainy, et al (2020)
Light-Duty FCEVs	From Elgowainy, et al (2020) but used the market equilibrium (mature market corresponding to 2075) penetration for light-duty vehicles applied to the 2050 vehicle stock; Serviceable Consumption Potential penetration from Roadmap to a U.S. Hydrogen Economy (2020)
Medium- and Heavy-Duty FCEVs	Assumed consistent penetration as light-duty vehicles (above); Serviceable Consumption Potential penetration from Roadmap to a U.S. Hydrogen Economy (2020)
Seasonal Electricity Storage	Quantity and price required to **supply dispatchable electricity competitive with natural gas** in a scenario with very high renewable energy generation

Potential Hydrogen Markets: Biofuels

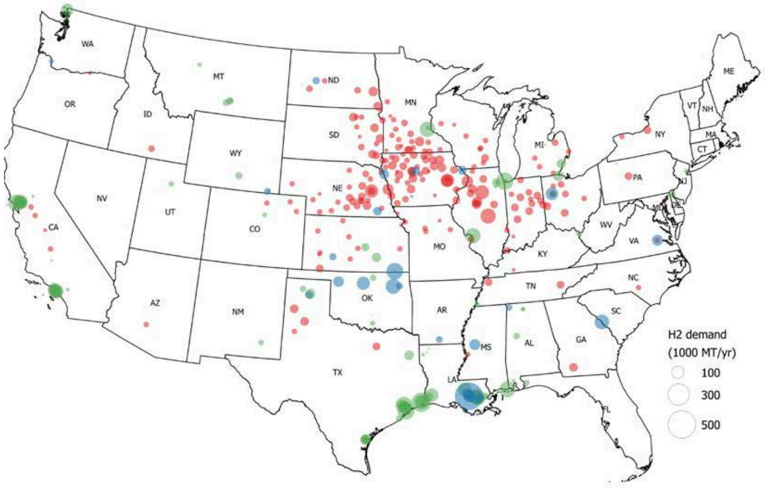
- Opportunity:
  - 50% of total jet fuel demand in 2050 (38.6 billion gal/yr AEO Reference)
  - 1.8 billion gal/yr is from fats, oils, & greases (FOGs)
  - 17.5 billion gal/yr based on catalytic fast pyrolysis of biomass
- Serviceable Consumption Potential:
  - FOGs require 76 g H_2/gal → 0.1 MMT/yr
  - Catalytic fast pyrolysis requires 490 g H_2/gal → 8.6 MMT/yr*
  - Total: 8.7 MMT H_2/yr
- Threshold Price: High because of non-hydrogen price drivers → $\$3.00/kg_{H2}$

Source: http://yelloblu.com/blog/biofuels-part-three-biomass-future-fuels

* Designs have hydrogen produced from non-condensibles in the process. We assume those can go to higher value products. Further analysis is needed

Potential Hydrogen Markets: Synthetic Hydrocarbons

- Methanol
  - Methanol: Current capacity 9.4 MMT methanol/yr and EIA projects 34.9 MMT methanol/yr by 2030
  - Producing additional 25.5 MMT methanol/yr would require 44 MMT/yr CO_2 (equal to annual ethanol plants production)*
  - Serviceable consumption potential of 6 MMT H_2/yr to convert 44 MMT/yr CO_2 to methanol
  - Threshold price: \$1.73/kg H_2 for methanol price equivalent to NG-sourced methanol (\$0.5/kg methanol)
- Methanol-to-Gasoline (MTG) **
  - 56 MMT CO_2/yr from SMR and ammonia production could be used to produce MTG
  - Serviceable consumption potential of 8.0 MMT H_2/yr to convert that 56 MMT/yr CO_2 to methanol (no additional H_2 needed for MTG)
  - That 56 MMT CO_2/yr would need concentrating thus not in economic potential (i.e., H_2 price point is too low for any of our scenarios so shows up as \$0/kg H_2 in demand curves)
- Total serviceable consumption potential: 14.0 MMT H_2/yr



Source: Supekar and Skerlos, ES&T (2014)

* 3:1 H_2:CO_2 molar ratio and 79% CO_2 selectivity
** Other chemicals and products are possible and could be considered with further analysis