H2@Scale: Opportunities for Hydrogen as an Energy Intermediate

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University of Toledo
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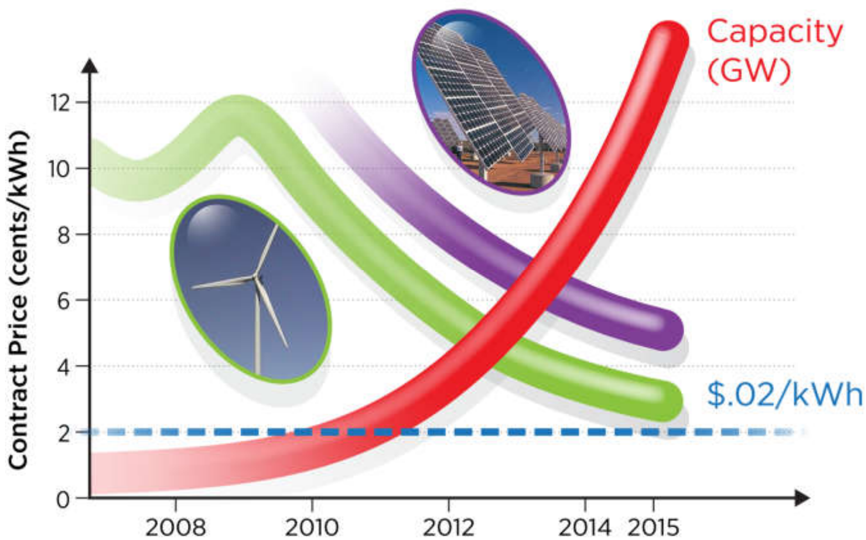
Changing Energy System

- Falling renewable costs
- Low cost, intermittent renewable electrons
- Energy policy
- Increased electrification



Source: (Arun Majumdar) 1. DOE EERE Sunshot Q1'15 Report, 2. DOE EERE Wind Report, 2015

Zero Emission Vehicles

2016 ZEV Action Plan toward 1.5 million ZEVs by 2025

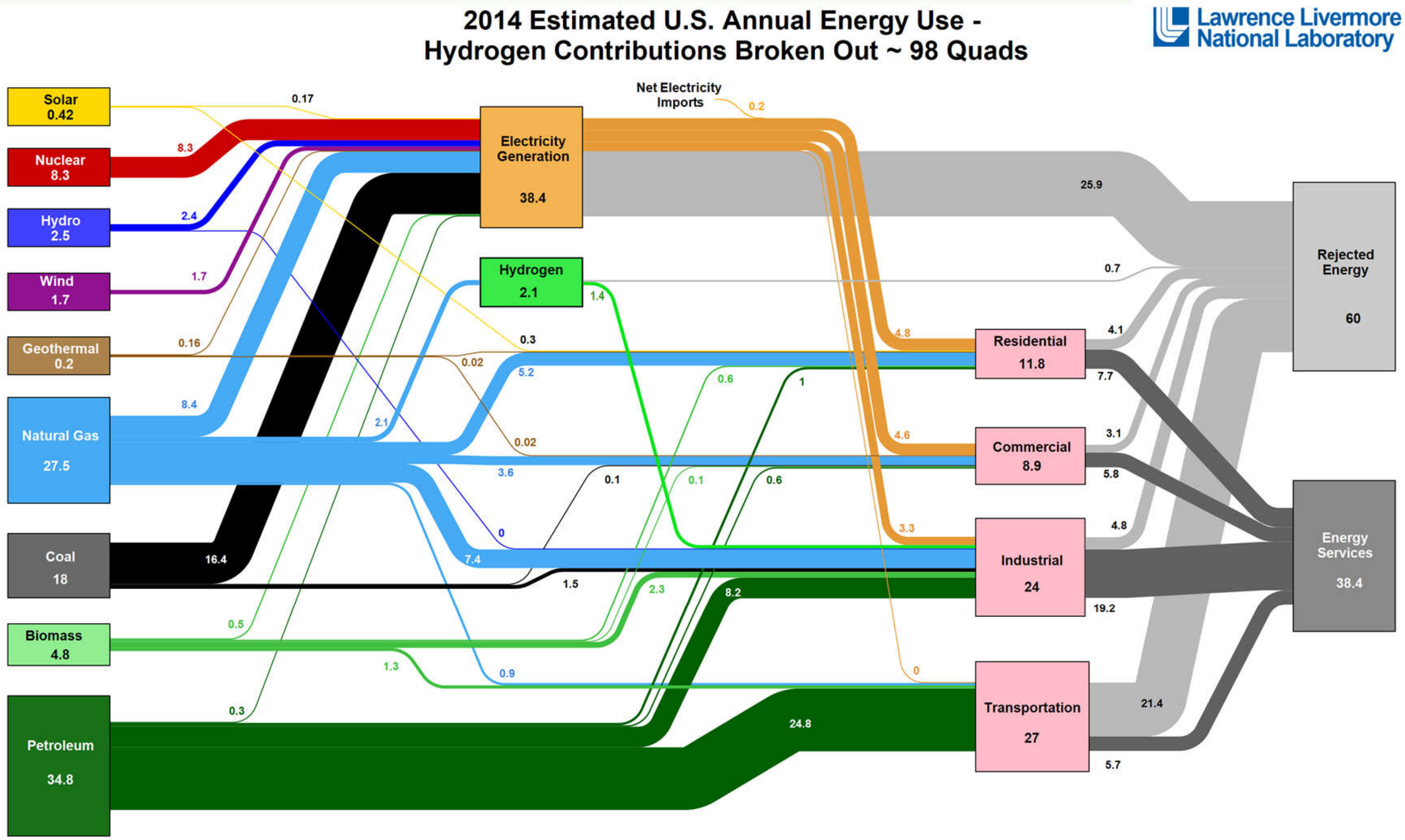
https://www.gov.ca.gov/docs/2016_ZEV_Action_Plan.pdf

Renewable Portfolio Standards

Senate Bill 100, signed by Gov. Edmund G. Brown, Jr. codifies 60% by 2030 & 100% by 2045

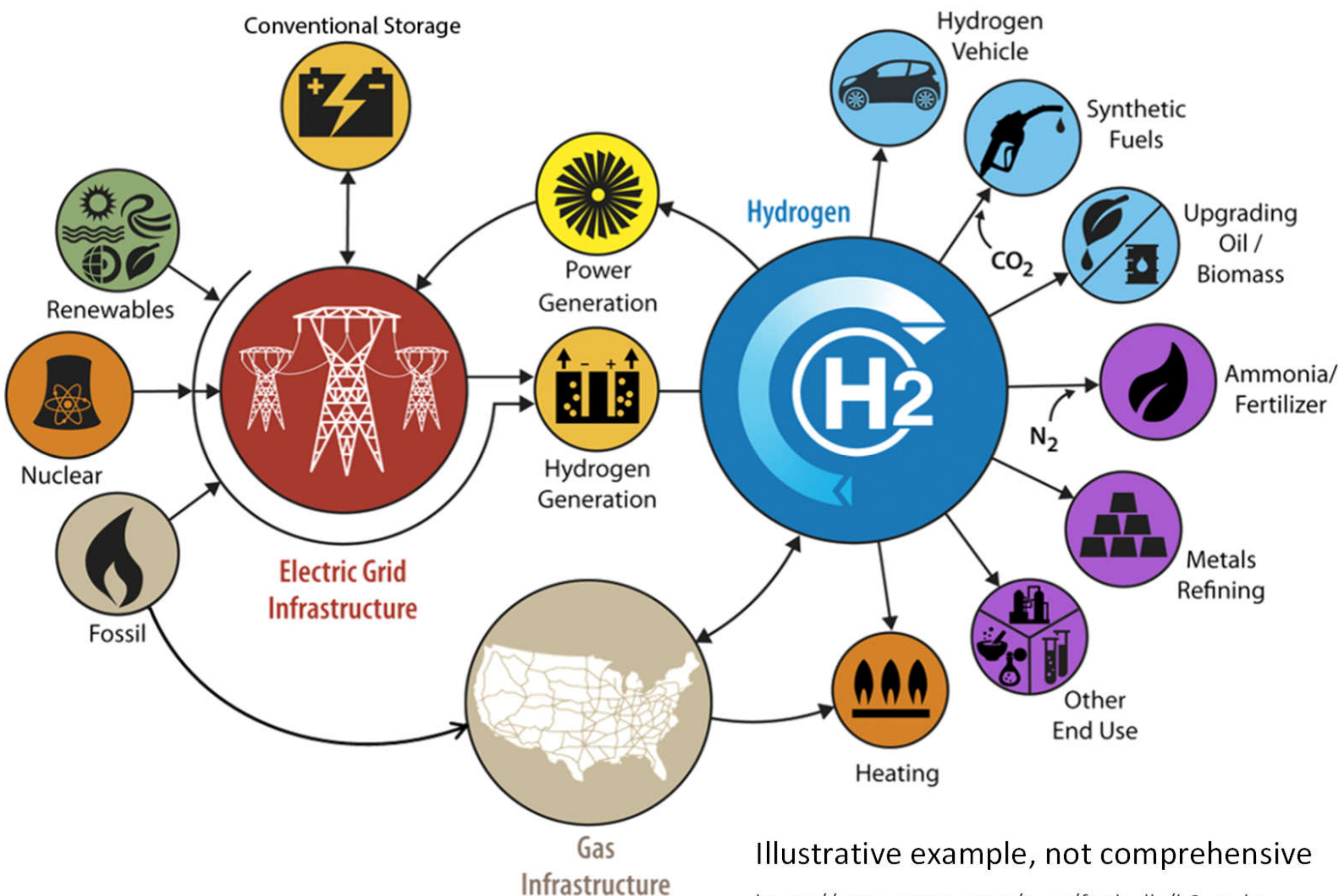
http://www.energy.ca.gov/renewables/

Hydrogen in Today’s Energy System



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

H2@Scale Opportunity



Illustrative example, not comprehensive

https://www.energy.gov/eere/fuelcells/h2-scale

Serviceable Consumption Potential

Serviceable Consumption Potential of hydrogen market by 2050 is >9X.

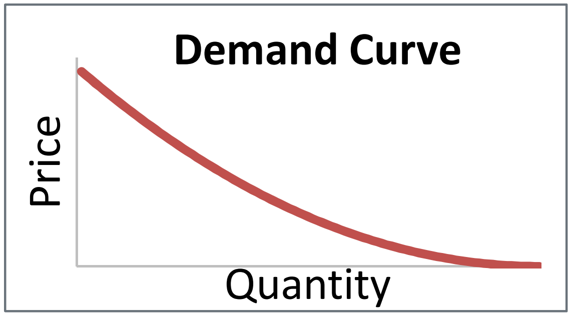
Other applications are possible based on technology and policy growth as well as smaller applications

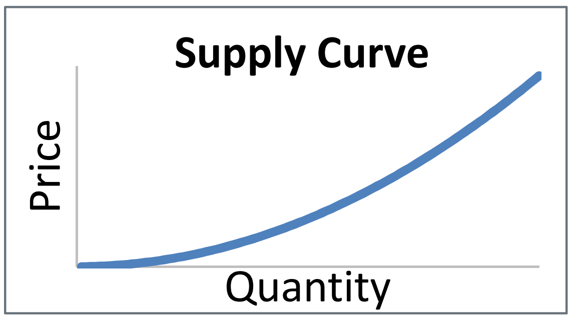
Application	Serviceable Consumption Potential (MMT/yr)	2015 Market for On-Purpose H2 (MMT/yr)
Refineries and the chemical processing industry (CPI) [a]	8	6
Metals	12	0
Ammonia	4	3
Biofuels	4	0
Synthetic fuels and chemicals	14	1
Natural gas supplementation	10	0
Seasonal energy storage for the electricity grid	15	0
Industry and Storage Subtotal	**67**	**10**
Light-duty fuel cell electric vehicles (FCEVs)	21	0
Medium- & Heavy-Duty FCEVs	8	0
Transportation Fuel Subtotal	**29**	**0**
Total	**96**	**10**

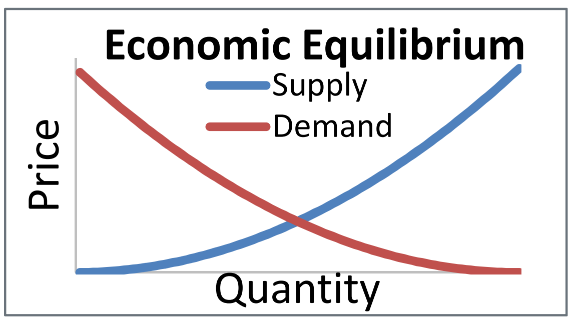
Preliminary Results

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.

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

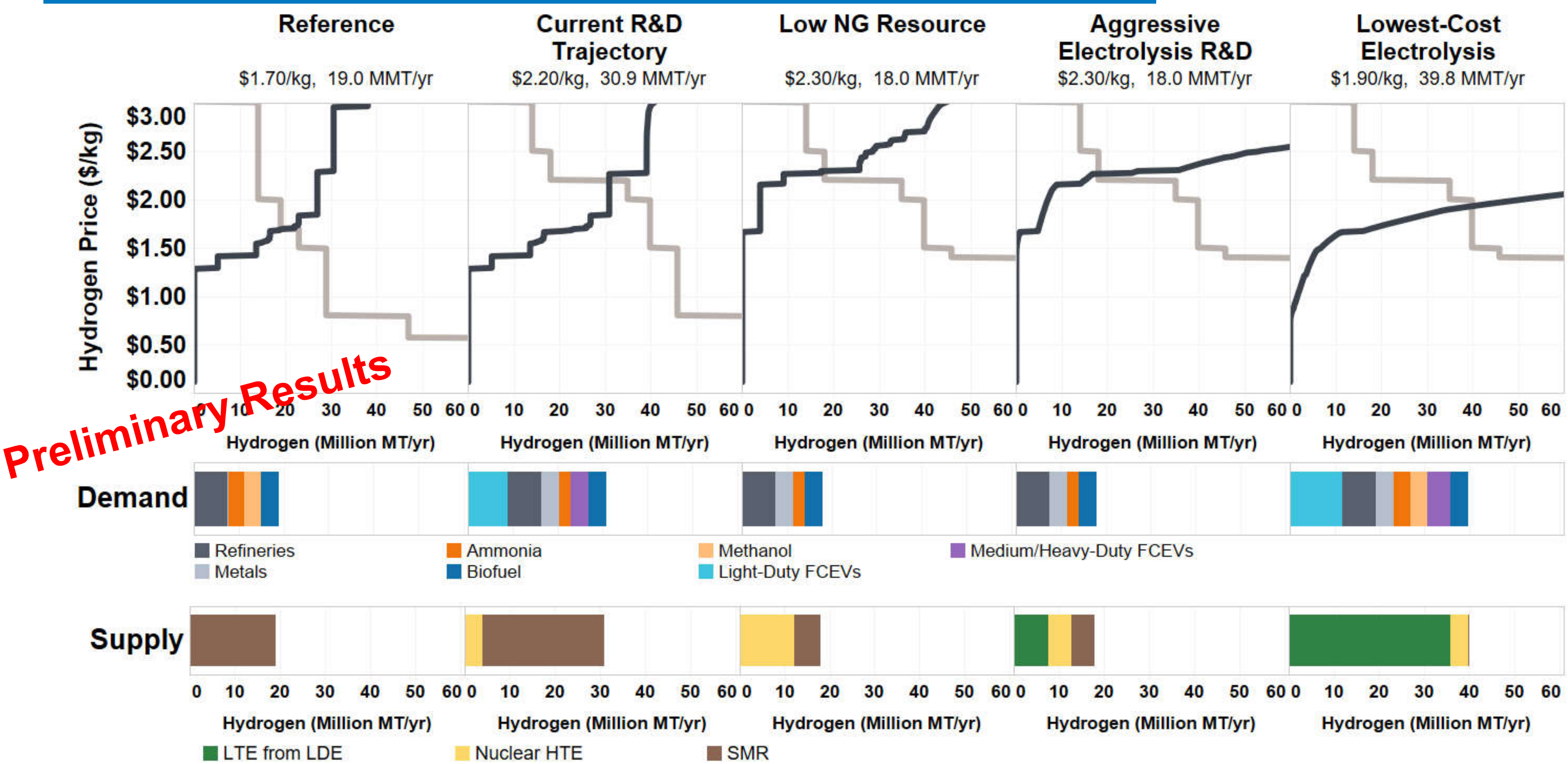
- Market equilibrium methodology and market size estimates in 2050
  - Transition issues such as stock turnover are not considered
- New policy drivers, such as emission policies, are not included either for hydrogen or the grid
- Technology and market performance involve many assumptions about adjacent technologies
- Demand analysis is limited to sectors that could be forecast for the foreseeable future
  - Hydrogen use to convert biomass based only on renewable fuel standard demands
  - Hydrogen for industrial heat is not included
  - Single price point only for all fuel cell vehicle estimates
- Potential long-term production technologies (e.g., photo-electrochemical) not included
- Estimates of delivery costs were standardized and without location specificity
- 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	Current R&D Trajectory	Low NG Resource	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			

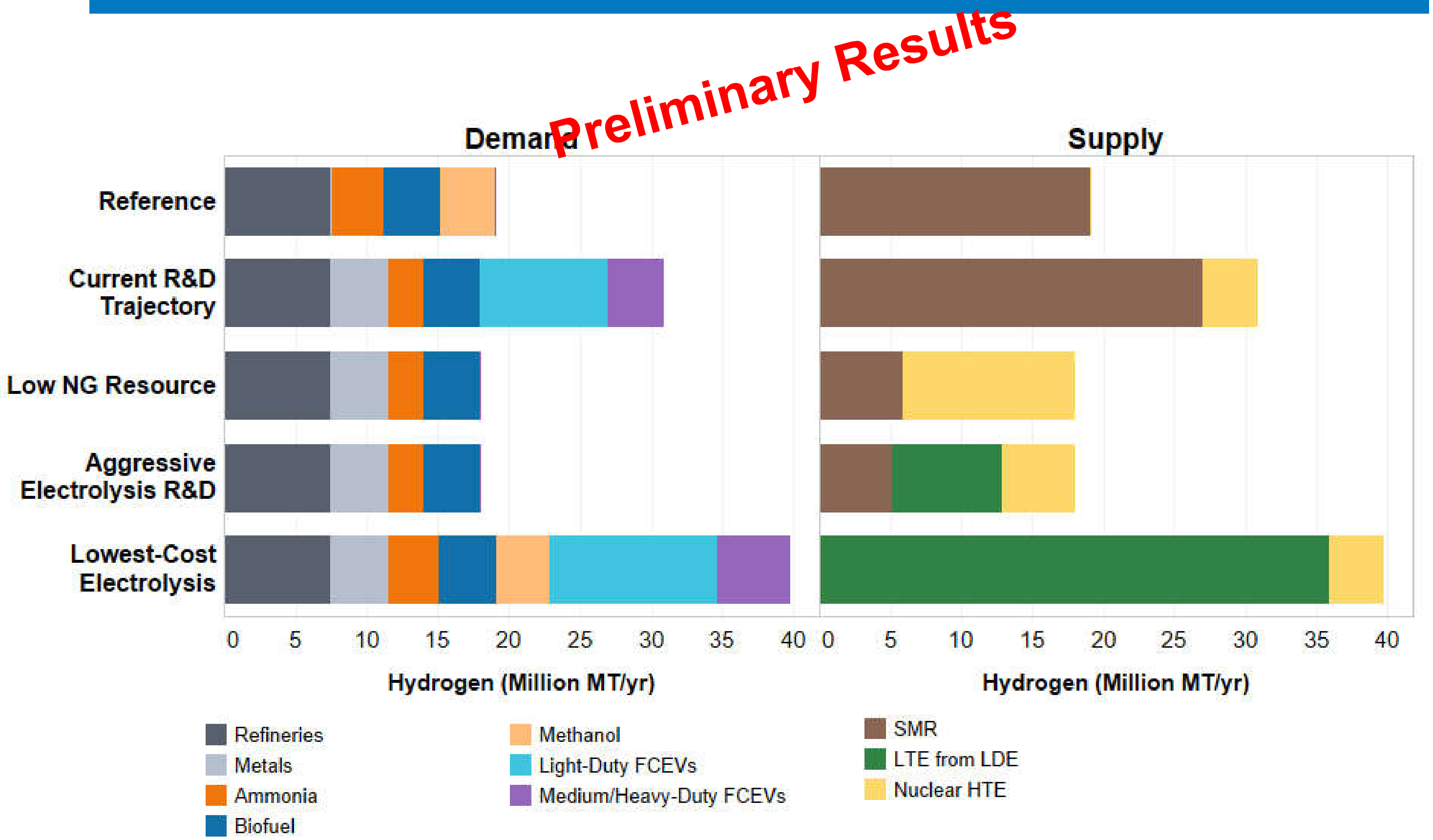
Key differences in scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers' access to grid service markets, and 5) increased price point in metals industry

Economic Potential Results



LDE: Low-cost, dispatch-constrained electricity

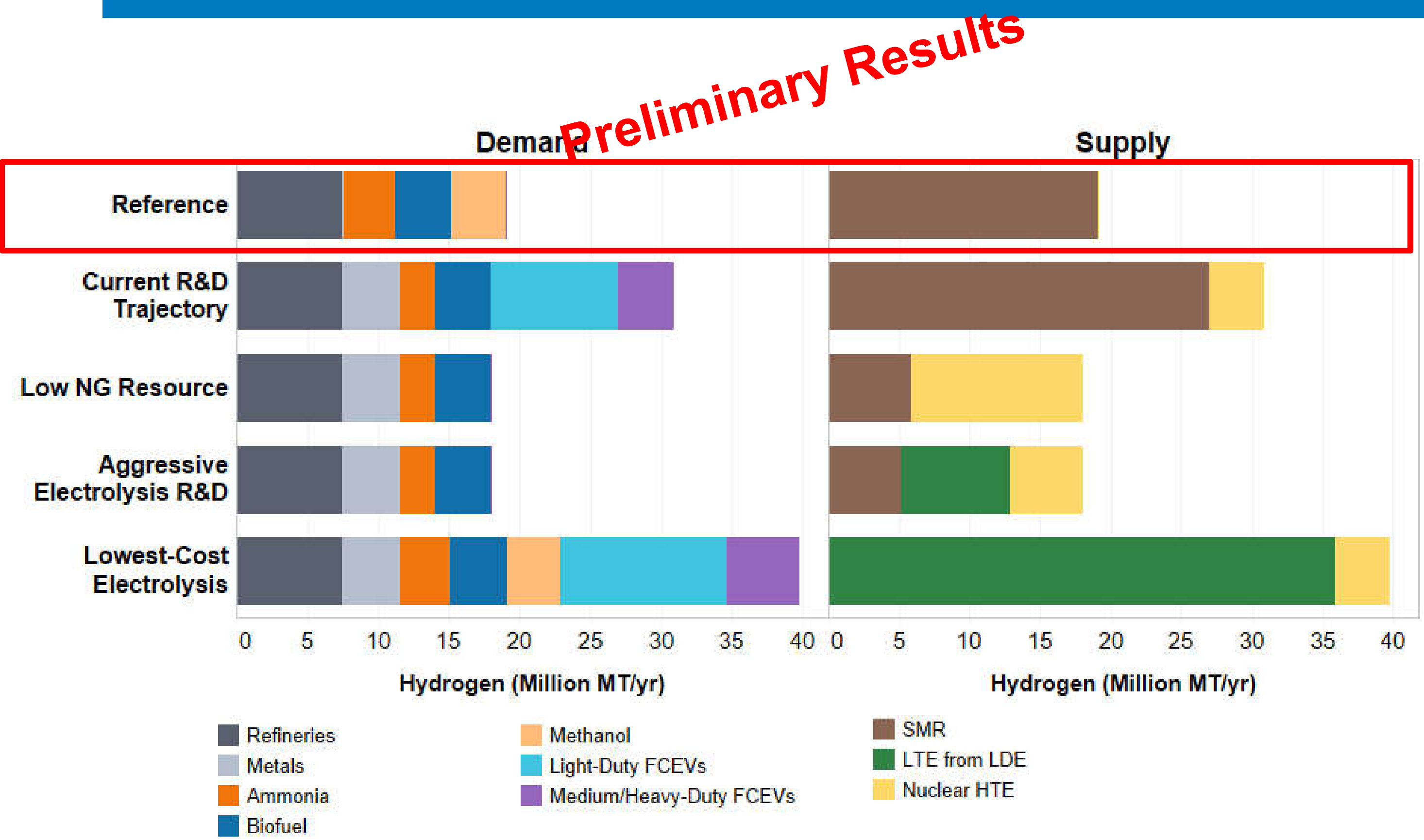
Economic Potential Results



The economic potential of hydrogen demand in the U.S. is 1.8-4X current annual consumption.

LDE: Low-cost, dispatch-constrained electricity

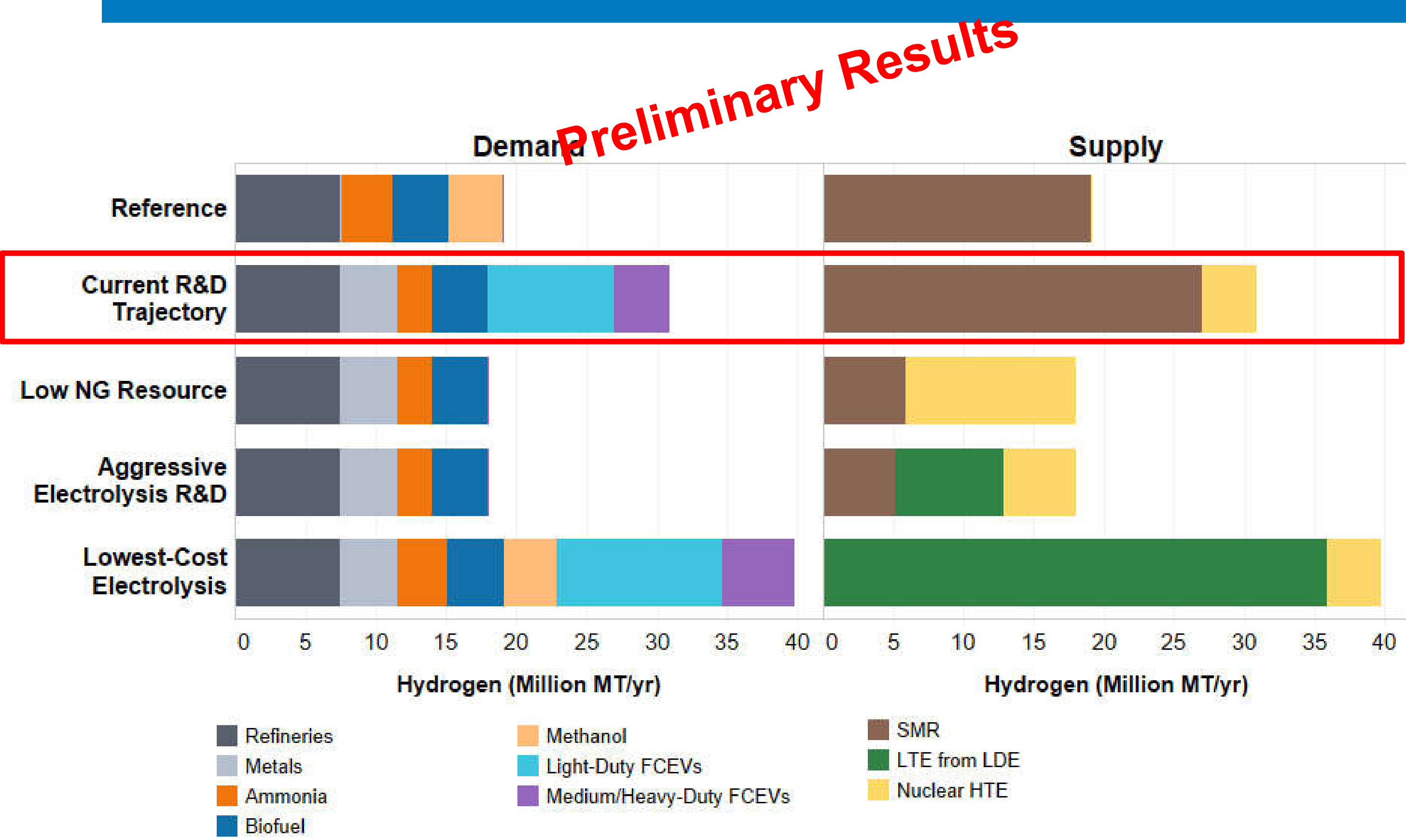
Reference Scenario



- Refineries and ammonia demands based on growing markets
- Biofuels demand limited to Renewable Fuels Standard
- No advancement in electrolysis, fuel cells, and hydrogen distribution technologies. SMR continues to dominate of supply. FCEVs do not penetrate markets.

LDE: Low-cost, dispatch-constrained electricity

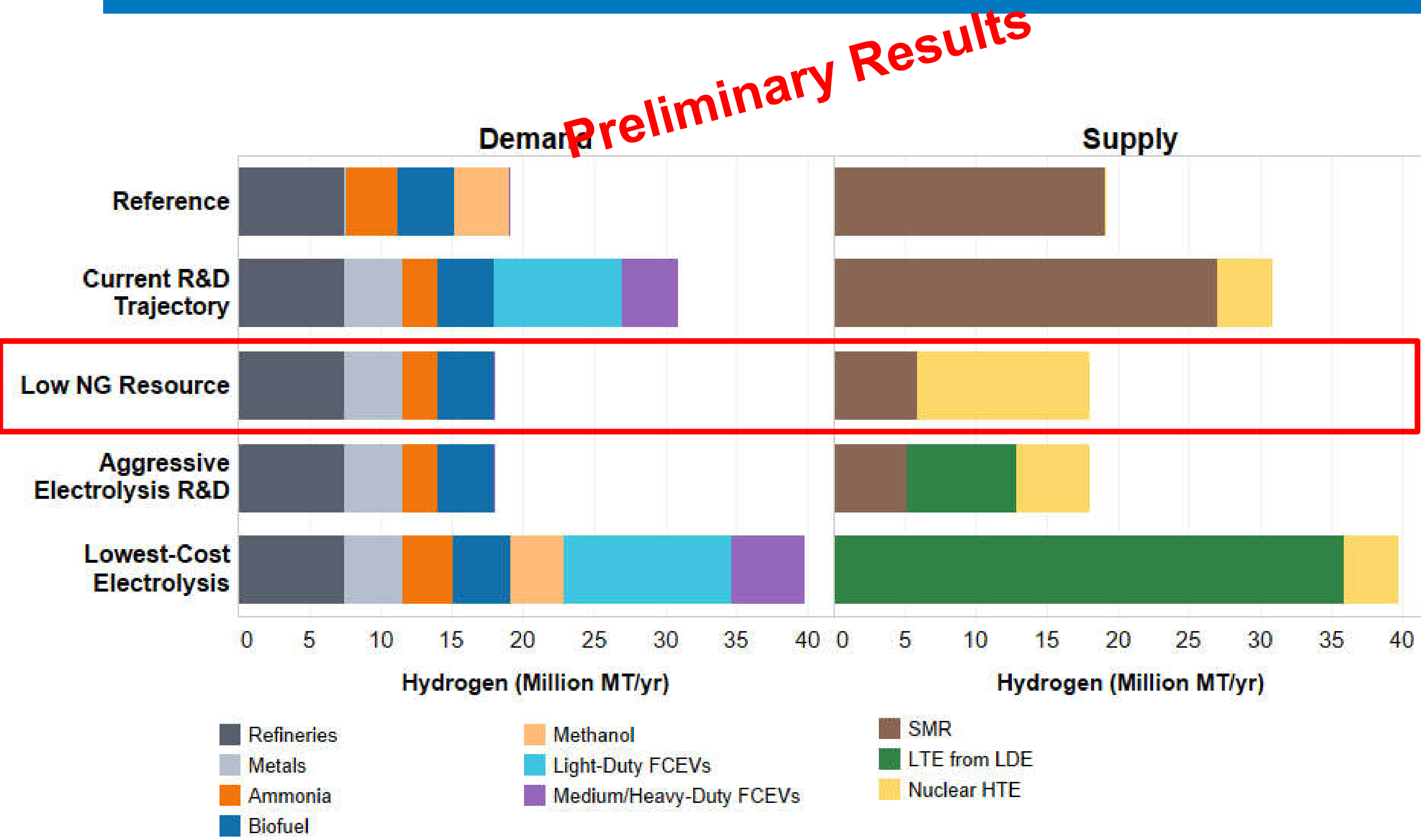
Current R&D Trajectory Scenario



- Low natural gas prices and reduced delivery costs for FCEVs; thus, higher penetrations of FCEVs
- About 10% of U.S. nuclear generation to H_2
- Increased willingness to pay for H2 for metals refining
- Biofuels demand limited to Renewable Fuels Standard

LDE: Low-cost, dispatch-constrained electricity

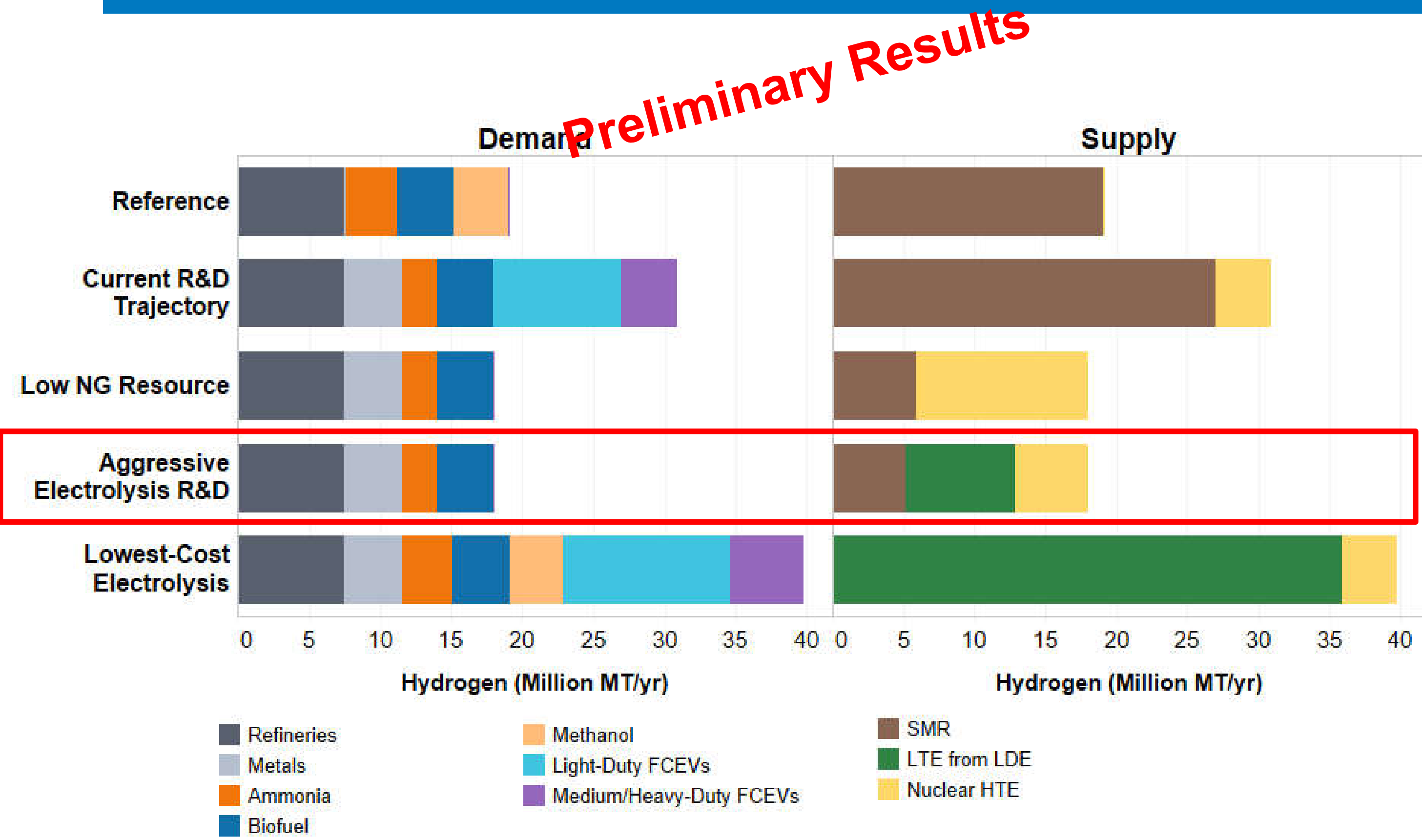
Low Natural Gas Resource Scenario



- **Higher natural gas prices than reference scenario**
- **Thus, negligible growth in hydrogen demand**
- **Only economic demands: refining, ammonia, biofuels**

LDE: Low-cost, dispatch-constrained electricity

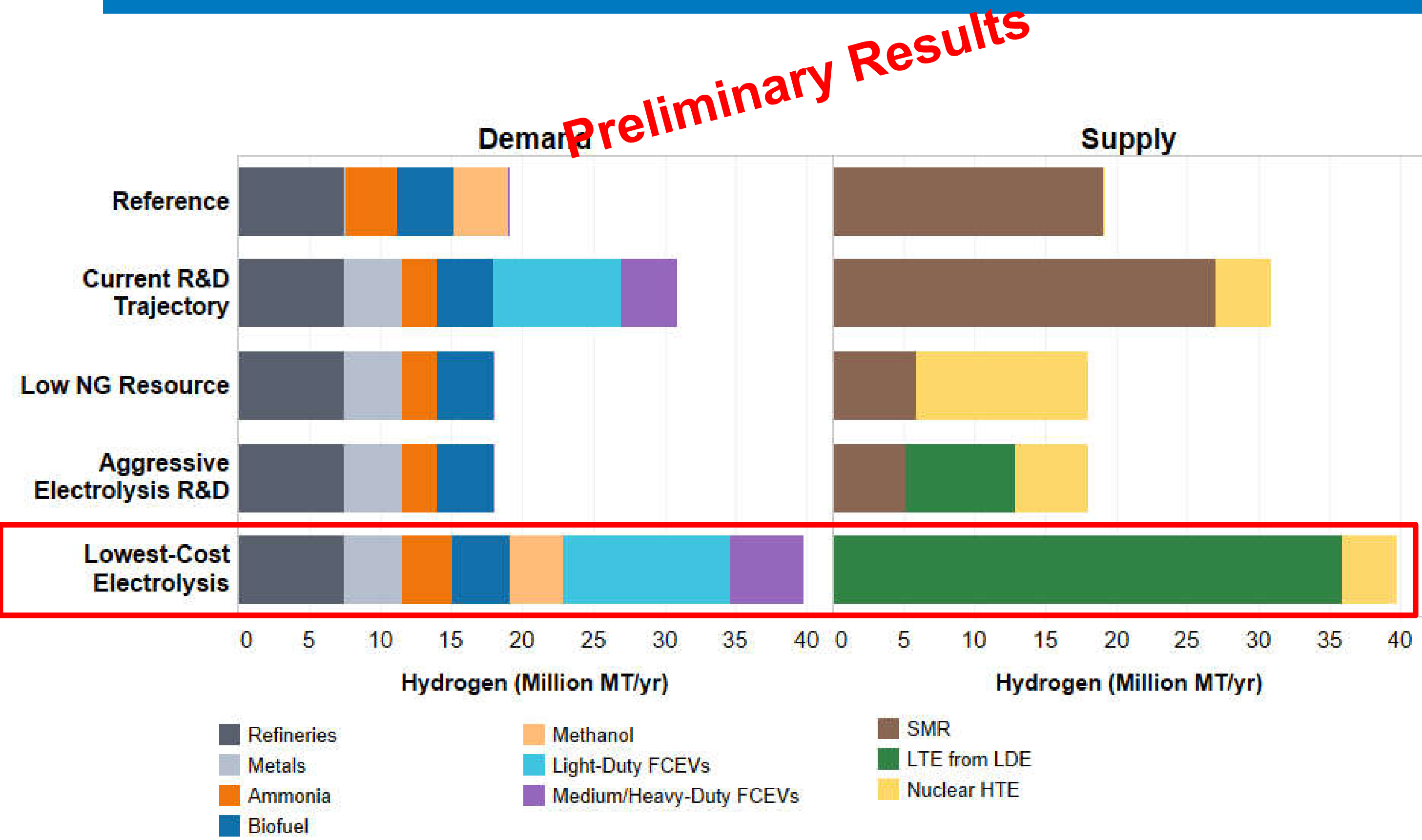
Aggressive Electrolysis R&D Scenario



- Low-Temperature electrolyzer (LTE) purchase cost reduced to $200/kW & reduced electricity adder
- Electrolytic hydrogen share increase

LDE: Low-cost, dispatch-constrained electricity

Lowest-Cost Electrolysis Scenario

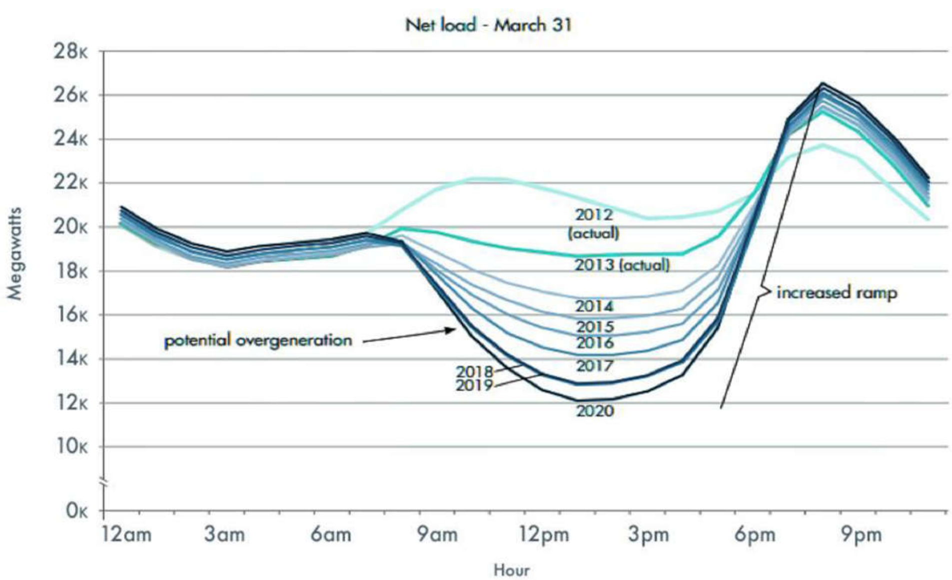


- **Low-Temperature electrolyzer (LTE) purchase cost reduced to $100/kW & no electricity price adder**
- **Electrolytic hydrogen less costly than steam methane reforming because of aggressive R&D and high NG prices**
- **Larger ammonia and chemicals opportunities than other non-reference scenarios**

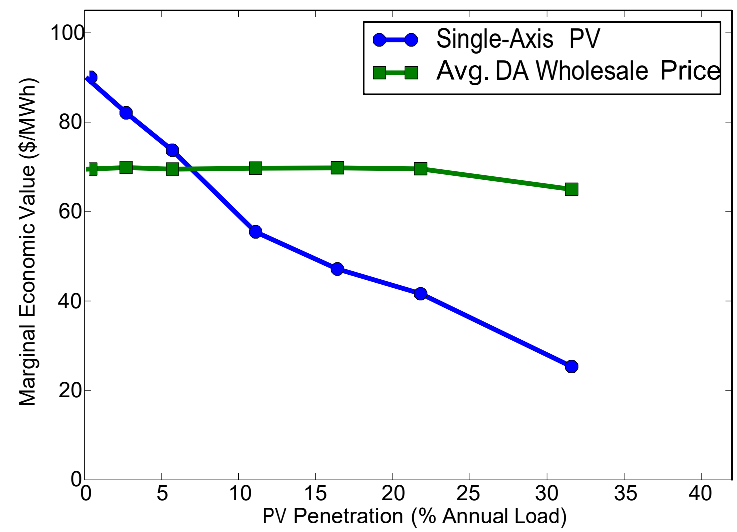
LDE: Low-cost, dispatch-constrained electricity

Low-Cost, Dispatch-Constrained Electricity

As renewable penetration increases, overgeneration and transients become larger concerns.

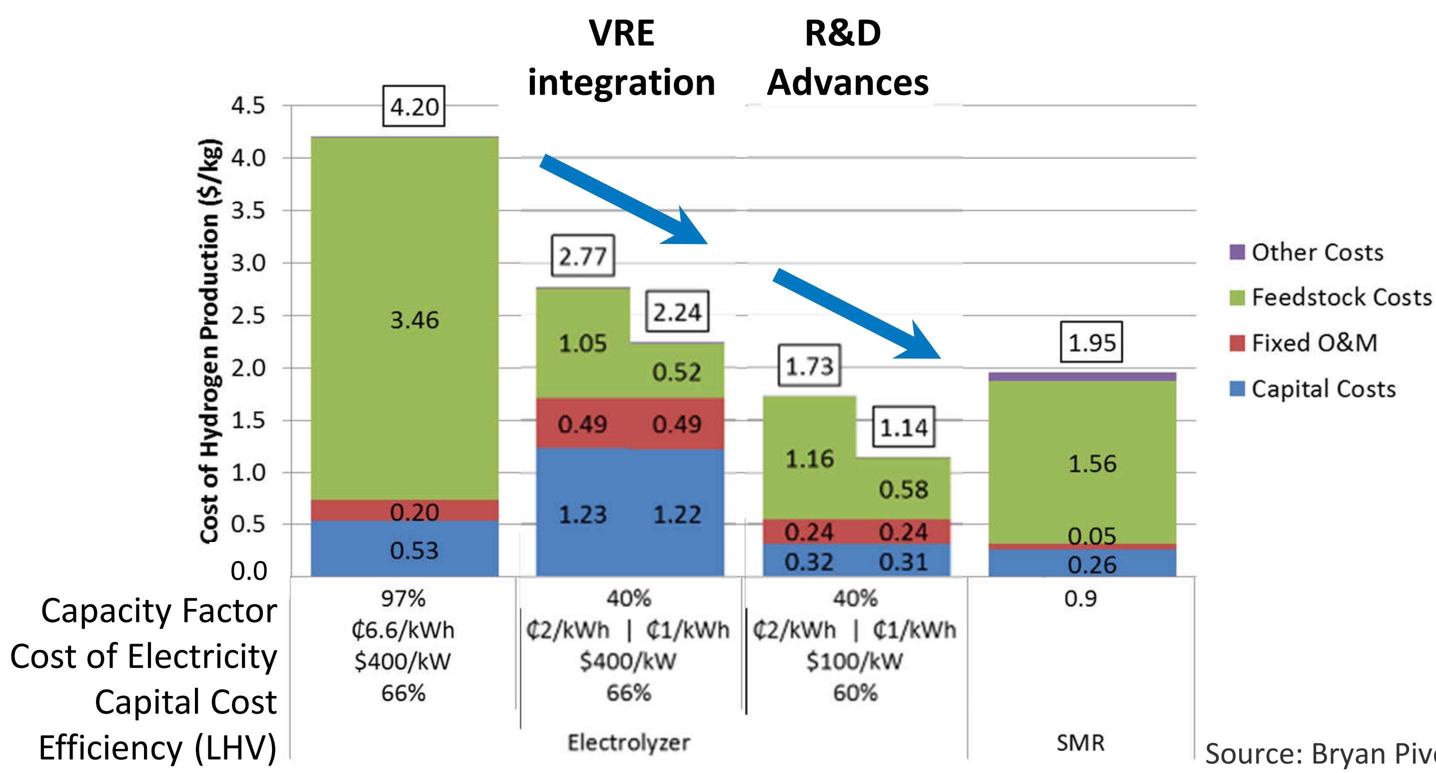


The economic value of renewable electricity generation decreases significantly with increasing penetration. Causes risk of RE deployment being limited.



Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California Andrew Mills and Ryan Wiser, June 2012, http://eetd.lbl.gov/EA/EMP

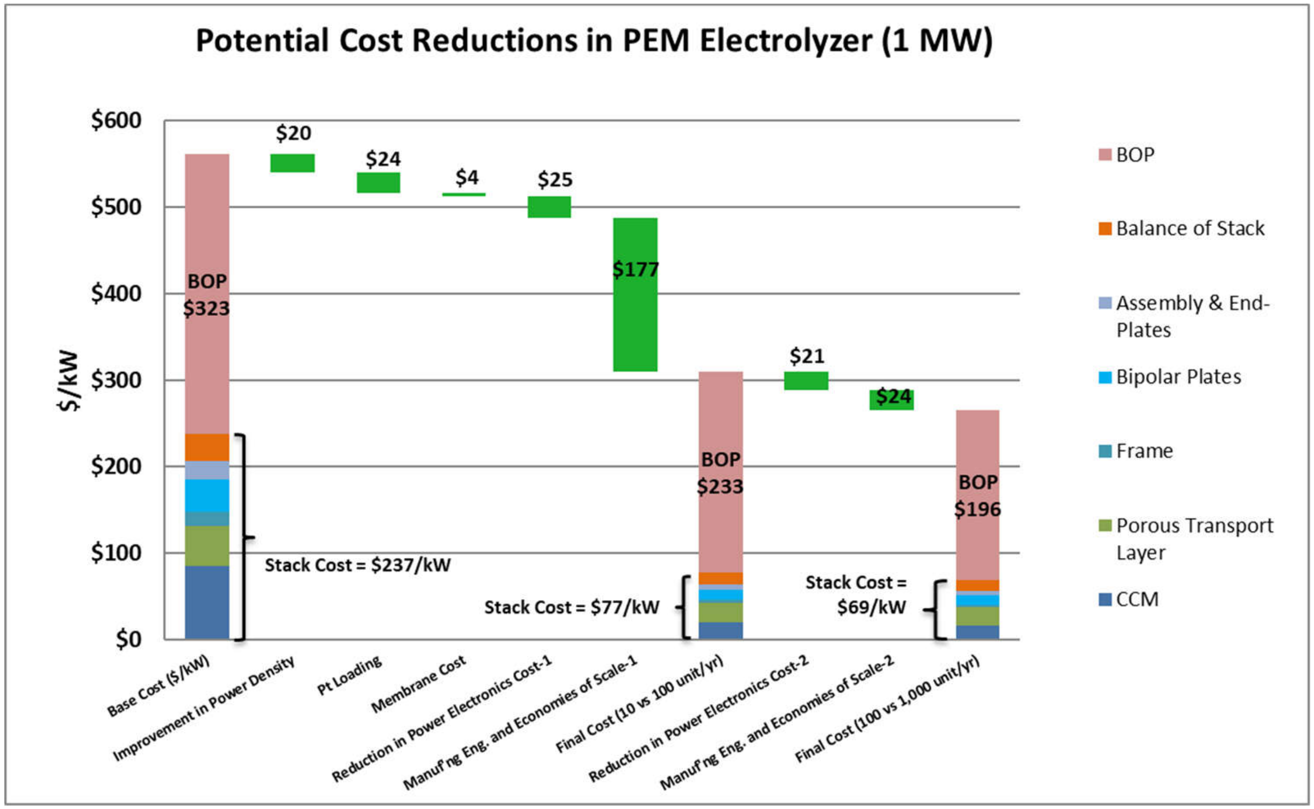
Low-Cost, Variable Electricity Could Be Source for Low-Cost Hydrogen with Low-Capital Electrolyzers



Source: Bryan Pivovar & Josh Eichman

The combination of low-cost, dispatch-constrained electricity and low-capital electrolyzers could be competitive.

Potential Cost Reductions for Low-Temperature Electrolyzers



- Requires manufacturing engineering development
- R&D brings down some costs
- Caveat: Balance of Plant cost estimates are not rigorous

Mayyas, Ahmad, Mark Ruth, Bryan Pivovar, Guido Bender, Keith Wipke. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers (2019). NREL/TP-6A20-72740. https://www.nrel.gov/docs/fy19osti/72740.pdf

Summary of Key Conclusions

- **Hydrogen's serviceable consumption potential in the U.S. (not constrained by economics) is >9X current annual consumption.**
- **The economic potential of hydrogen demand in the U.S. is 1.8-4X current annual consumption**.
  - Range across 5 scenarios developed using a variety of economic and R&D success assumptions
- **Hydrogen production & utilization technology R&D or other market drivers are needed to achieve those potentials. Key opportunities:**
  - Reducing electrolyzer capital costs while maintaining or increasing flexibility
  - R&D targets need to be met for utilization technologies: fuel cell electric vehicles, metals production, biofuels, synthetic fuels/chemicals

Thank You

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www.nrel.gov

Additional information on H2@Scale can be found at:

https://www.hydrogen.energy.gov/pdfs/review18/h2000_pivovar_2018_o.pdf
https://www.hydrogen.energy.gov/pdfs/review19/sa171_ruth_2019_o.pdf
http://energy.gov/eere/fuelcells/downloads/h2-scale-potential-opportunity-webinar

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