H2@Scale: Economic Potential of Hydrogen as an Energy Intermediate

Mark F. Ruth, Paige N. Jadun, Amgad Elgowainy, Bryan Pivovar

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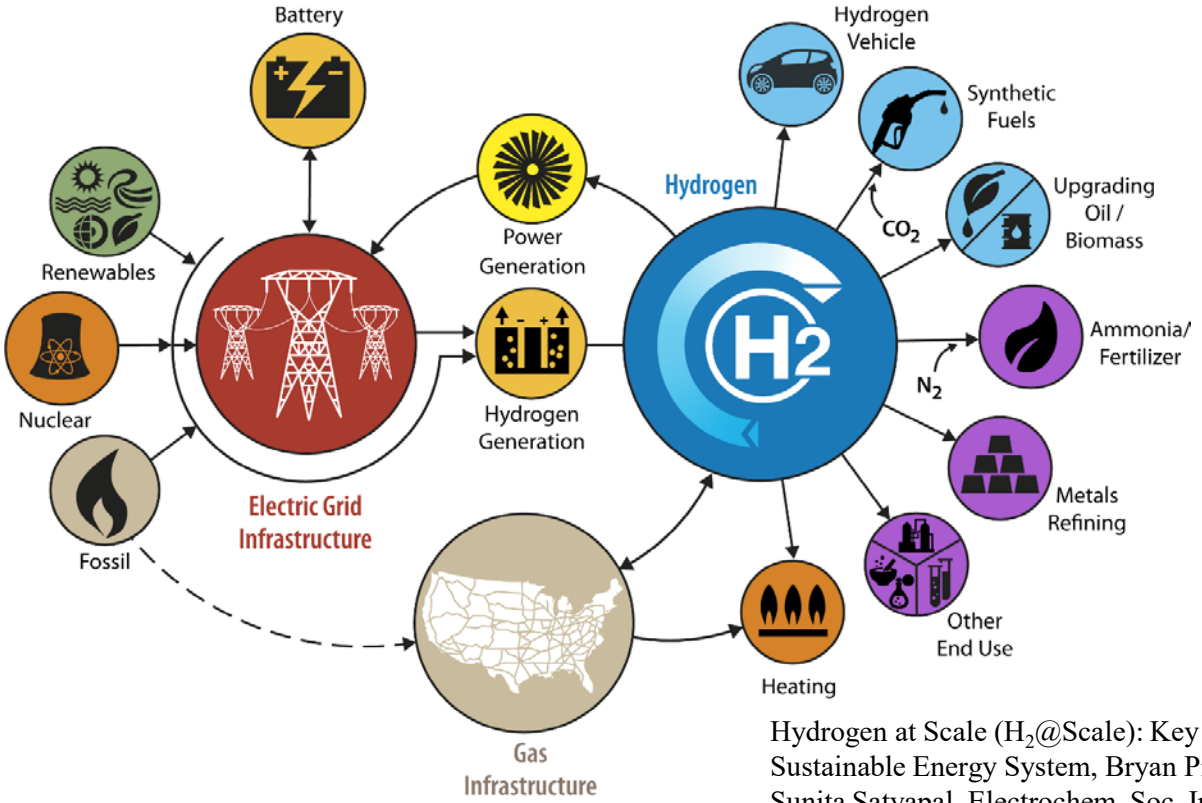
H2@Scale Concept



*Illustrative example, not comprehensive

Hydrogen at Scale (H_2@Scale): Key to a Clean, Economic, and Sustainable Energy System, Bryan Pivovar, Neha Rustagi, Sunita Satyapal, Electrochem. Soc. Interface Spring 2018 27(1): 47-52; doi:10.1149/2.F04181if

Economic Potential: Five National Scenarios

Scenario Name	Reference	Low NG Resource	Improved Electrolysis	Available Biomass Resource	Lowest-Cost Electrolysis
Natural gas price assumption	Reference	Higher			
LTE capital costs	Current Trajectory		Improvements		Aggressive Assumptions
LDE market assumption					
Biomass	Not available			Available	Not Available
Metals demand	Competitive Market		Premium Available		

Key differences in scenarios: 1) natural gas price assumption, 2) electrolyzer cost assumption, 3) electrolyzers' access to grid service markets, 4) increased threshold price in metals industry, & 5) competition for biomass resource

Economic Potential Results

The economic potential of hydrogen demand in the U.S. is 1.4-4X current annual consumption.

Scenario	Insights
Reference	Low-cost natural gas drives growth in H_2 markets with some nuclear participation*
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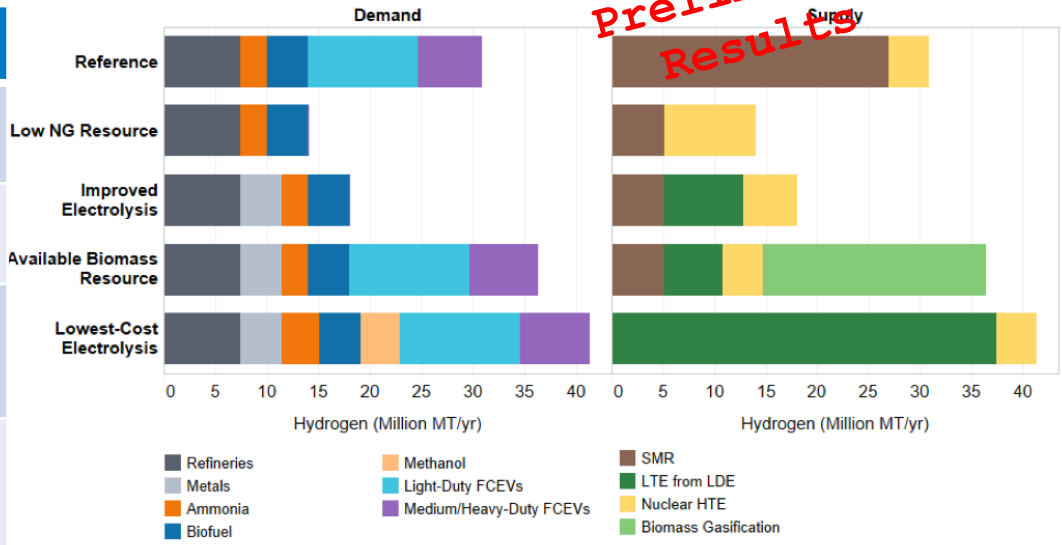
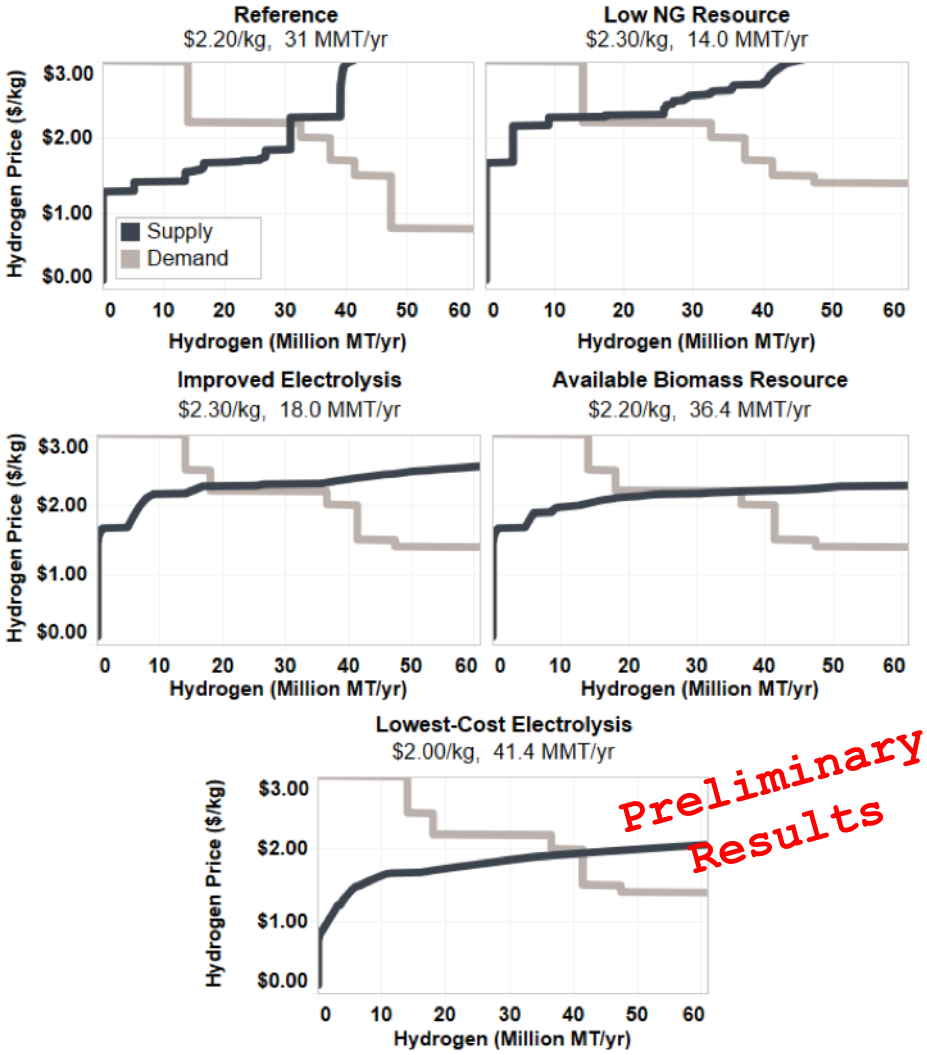
Lowest-Cost Electrolysis	$100/kW electrolyzers with high grid value can enable additional H2 applications



*~20% of U.S. nuclear generation is used for hydrogen production

Economic Potential Methodology

The intersection of the supply and demand curves indicate the market size and price at equilibrium.



Potential Hydrogen Markets: Light-Duty Fuel Cell Vehicles (FCEVs)

- Potential Demand:
  - 40% of LDV fleet in 2050
    - 65 million of 162 million cars:
      - 9.7 MMT_{H2}/yr
    - 61 million of 153 million light-duty trucks:
      - 11.2 MMT_{H2}/yr

Source: NREL Photo Library #49729

- Economic Potential:
  - Calculation
    - MA3T vehicle choice model
    - "Ultimate" H_2 price at pump: $5.0/kg pump ($2.20/kg at terminal) - $5.0/kg is based on the FCTO target of $4/kg in 2007$, inflated to 2015$, with $0.5/kg in taxes added.
  - Hydrogen consumption at market equilibrium (18% of cars and 26% of light-duty trucks), 11.7 MMT H_2/yr

Source: Elgowainy (2019)

Potential Hydrogen Markets: Medium- & Heavy-Duty FCEVs

- Potential Demand:
  - 35% of both HDV and MDV fleet by 2050
  - 4.2 million of 12 million Medium Duty:
    - 2.2 MMT_{H2}/yr
  - 2.0 million of 5.7 million Heavy Duty:
    - 8.6 MMT_{H2}/yr

Source: Nikola Motor Company

- Threshold Price:
  - Based on a 22% market penetration – the weighted average of the LDV penetration at equilibrium
    - H_2 price at pump: $5.0/kg pump ($2.20/kg at terminal) - $5.0/kg is based on the FCTO target of $4/kg in 2007$, inflated to 2015$, with $0.5/kg in taxes added.
  - 6.8 MMT_{H2}/yr

Preliminary Results

Potential Hydrogen Markets: Biofuels

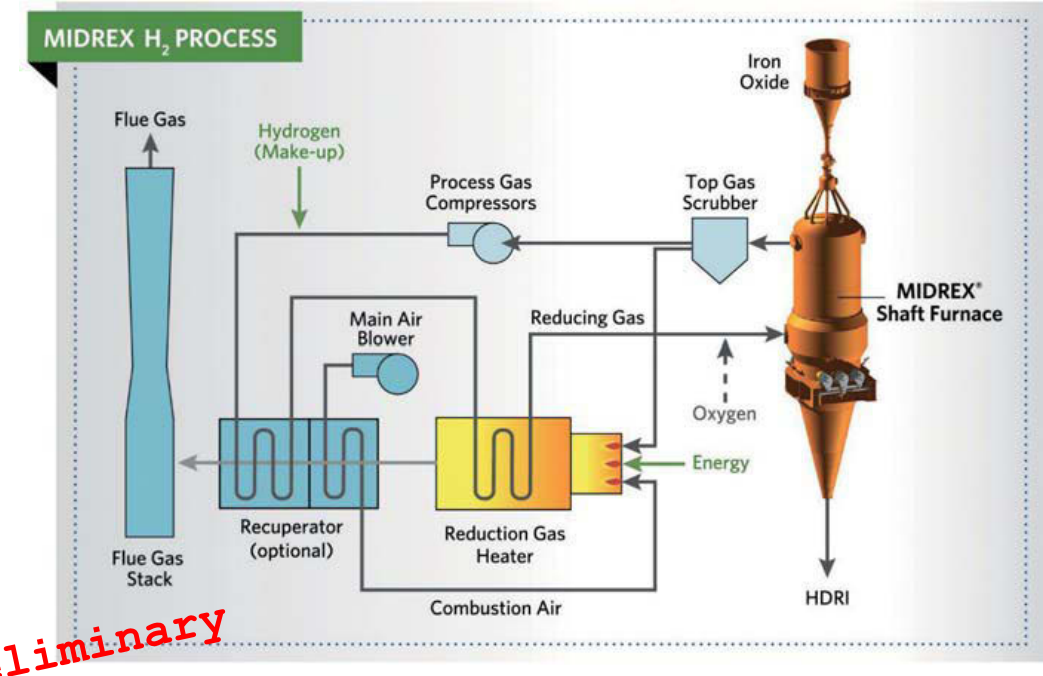
- Opportunity:
  - Renewable Fuel Standard 2 (RFS2) mandates 16 billion gal/yr cellulosic fuels
  - Blendstocks (diesel & naphtha) could require 0.5 kg_{H2} / gal blendstock
- Demand Potential:
  - 4 MMT_{H2}/yr assuming 50% of the biofuel requirement is blendstock
- Threshold Price: High because of non-hydrogen price drivers → \$3.00/kg_{H2}

Preliminary Results

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

Example of Potential Demand: Metals Refining (Steel)

- Status:
  - 81 MMT_{steel}/yr produced in the U.S. project to grow to 120 MMT_{steel}/yr by 2050
  - Blast furnaces: 430 kg_{coke} / MT_{iron}
  - Direct reduced iron optimally uses hydrogen/CO blends, with 30 kg_{H2} /$MT_{hot\ iron}$
    - Can use up to 100% hydrogen (100 kg_{H2}/$MT_{hot\ iron}$)
- Demand Potential:
  - 12 MMT/yr_{H2}
- Threshold Price for Economic Potential:
  - 4 MMT_{H2}/yr for market at positive ROI: \$1.70/kg_{H2}
  - 12 MMT_{H2}/yr: \$0.80/kg_{H2} for positive ROI competing with natural gas heat



Preliminary Results

Source: Steel Times International

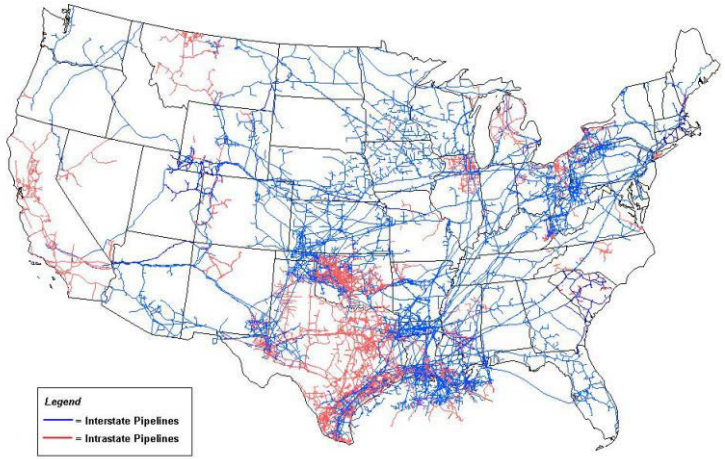
Potential Hydrogen Markets: Natural Gas Supplementation

- Demand Potential:
  - 20% (volume) assumed to not have significant impact on technologies that utilize natural gas
  - 10 MMT_{H2}/yr

Preliminary Results

- 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

Potential Hydrogen Markets: Seasonal Electricity Storage

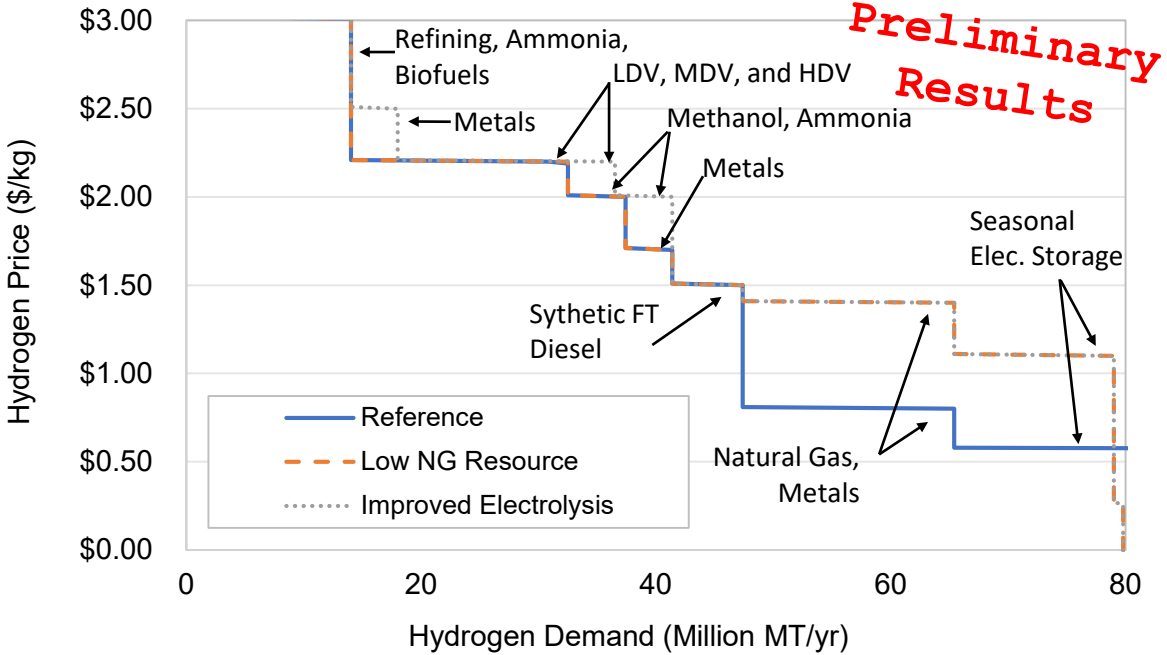
- Opportunity
  - Hydrogen can decouple storage power (W) from energy (Wh) making it a key candidate for seasonal storage
- Demand potential & threshold price:
  - Based on natural gas loads in ReEDS high penetration scenarios
  - 15 MMT/yr demand potential
  - Prices to produce electricity competitively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

	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

Preliminary Results

Aggregated Demand Curves

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

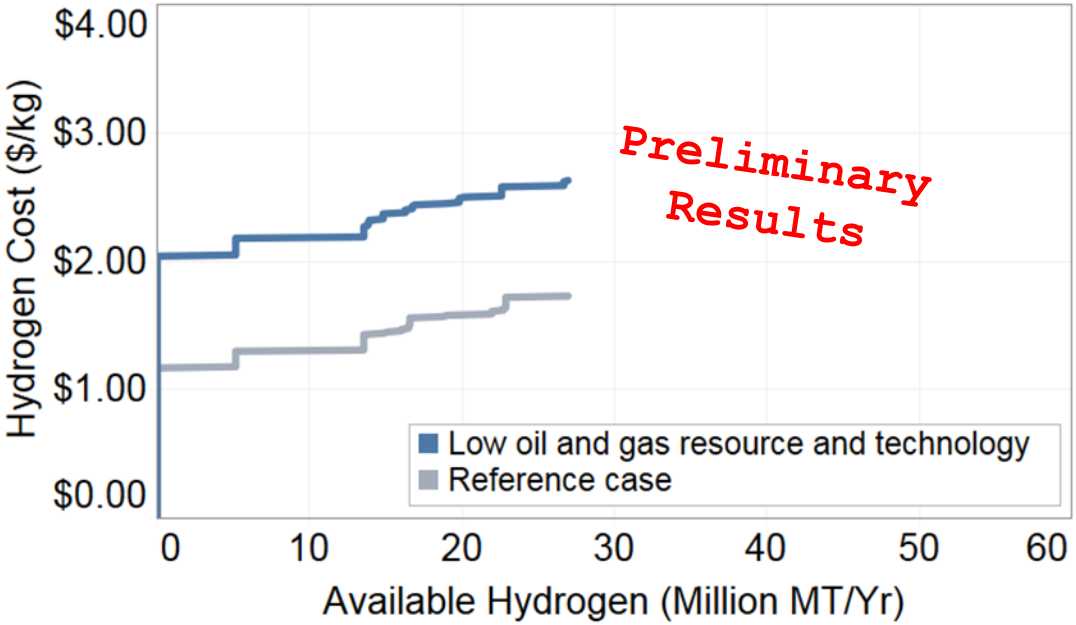


Reported prices for industrial demands / city edge terminals – Thus, pump prices minus delivery & dispensing costs for vehicles

The Available Biomass Resource and Lowest-Cost Electrolysis scenarios assume the same demand curve as the Improved Electrolysis scenario

Supply Curve Data: Steam Methane Reforming of NG

Prices of natural gas-produced hydrogen vary by region and are limited by total resource

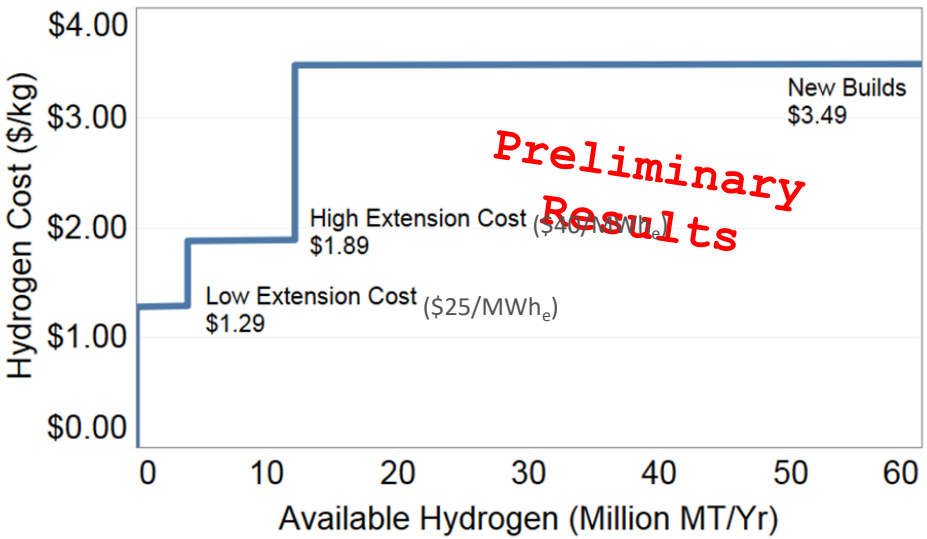


Natural gas reforming to hydrogen:

- Prices based on H2A Future Central Production without CCS and AEO scenarios for 8 census divisions
- Existing sites do not include capital costs; new builds do
- We limit SMR future supply to 3 times current production levels
- Storage and delivery adder of $0.12/kg

Supply Curve Data: High Temperature Electrolysis

Current nuclear fleet may provide a good opportunity for hydrogen production if delivery infrastructure cost is not too high

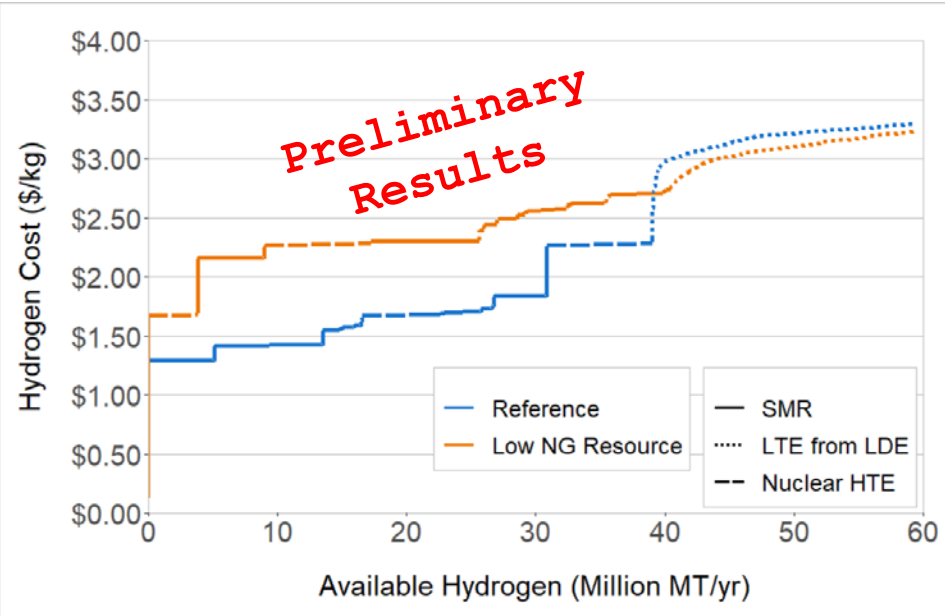


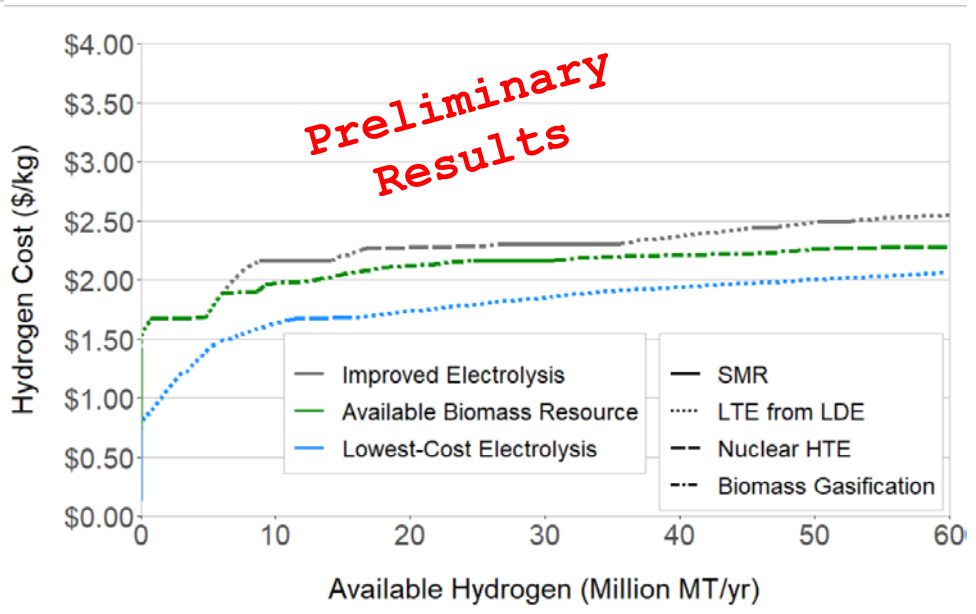
High Temperature Electrolysis Using Nuclear-Generated Heat:

- Capital and operating parameters: H2A SOEC future case study
- Assume 20% of the current U.S. nuclear fleet would convert to hydrogen production if the HTE paid $25/MWh$_e$ for electricity and equivalent for heat
- 40% would convert at $40/MWh$_e$
- New builds would need to sell heat and electricity at $80/Mwh$_e$
- Storage and delivery adder of ~$0.40/kg$_{H2}$

Aggregated Supply Curves

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





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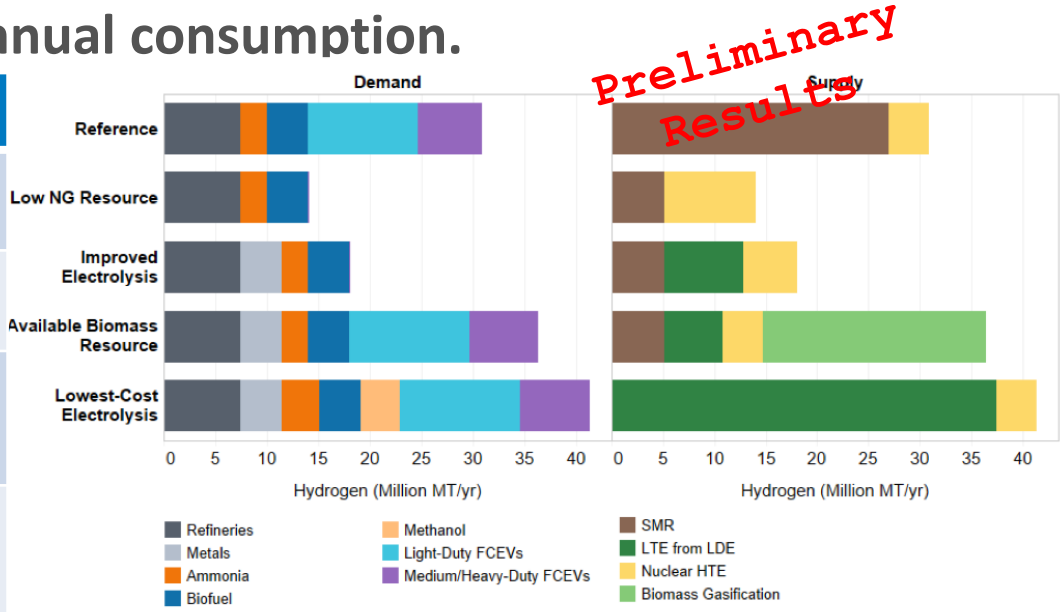

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Key Conclusions

- **The demand potential of hydrogen demand in the U.S. is >9X current annual consumption.**
- **The economic potential of hydrogen demand in the U.S. is 1.4-4X current annual consumption**.
  - Range across 5 scenarios developed using a variety of economic and R&D success assumptions
- **Total U.S. fossil fuel use could decline by up to 11% below a scenario with a high renewable penetration on the grid**
- **Up to 20% of current nuclear power plants could improve their profitability** by producing hydrogen.

Future Work

- Opportunities beyond economic potential limits
- Regional and transition analysis
- Improved analysis of synthetic fuels and chemicals markets
- Improved analysis of potential for seasonal electricity storage
- Improved analysis of potential rebound effects

Thank You

Mark.Ruth@nrel.gov

www.nrel.gov
NREL/PR-6A20-75374

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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