



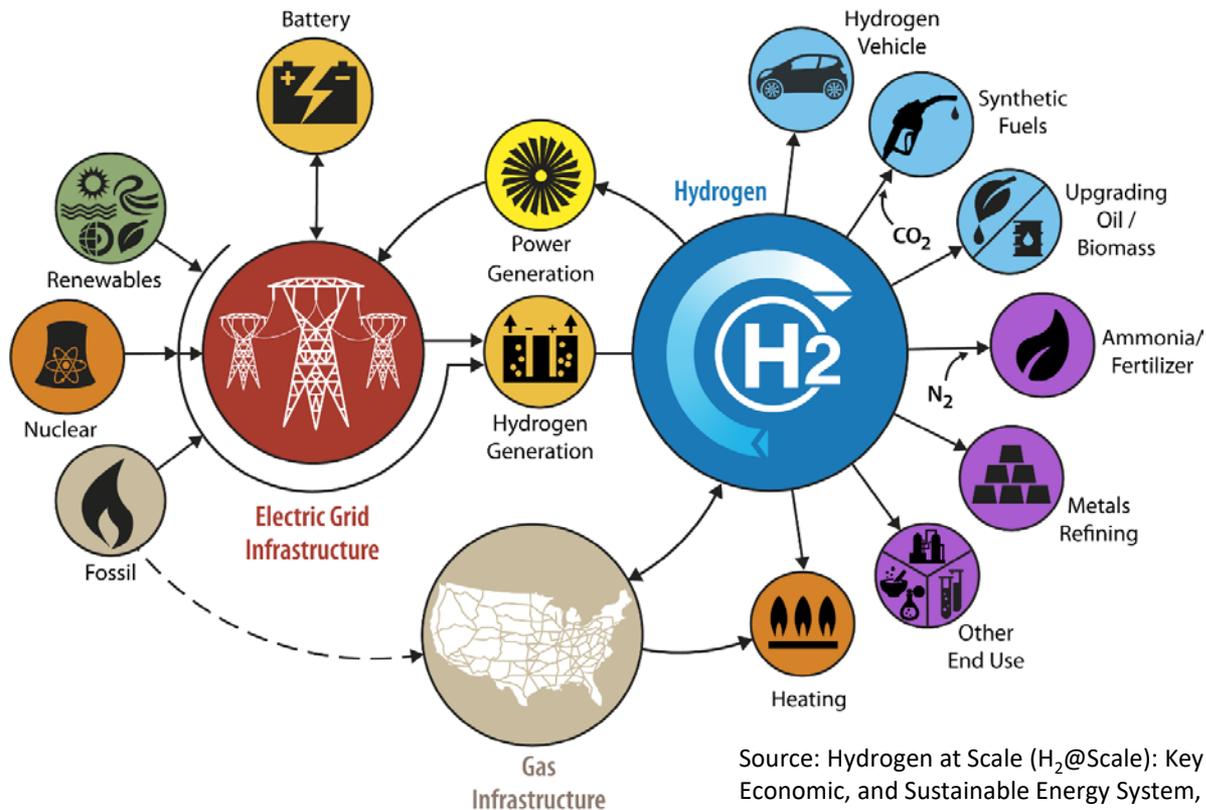
# Hydrogen's Potential Role in Future Energy Systems

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# H2@Scale Concept

Hydrogen has the potential to be an energy interface that complements electricity and natural gas systems

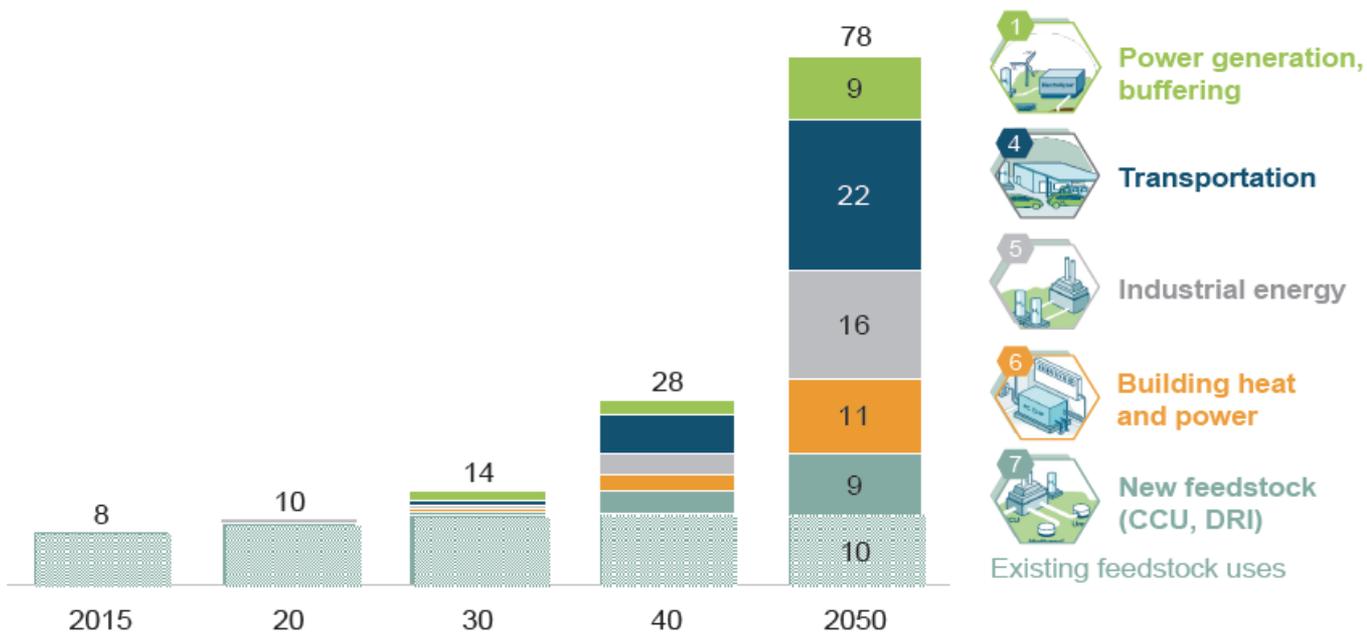


\*Illustrative example, not comprehensive

Source: Hydrogen at Scale (H<sub>2</sub>@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 NREL | 2

# Hydrogen Demand Potential

Global energy demand supplied with hydrogen, EJ



The Hydrogen Council found that 10-fold growth from 60 MMT/yr to 600 MMT/yr is possible providing hydrogen prices are competitive in non-traditional markets

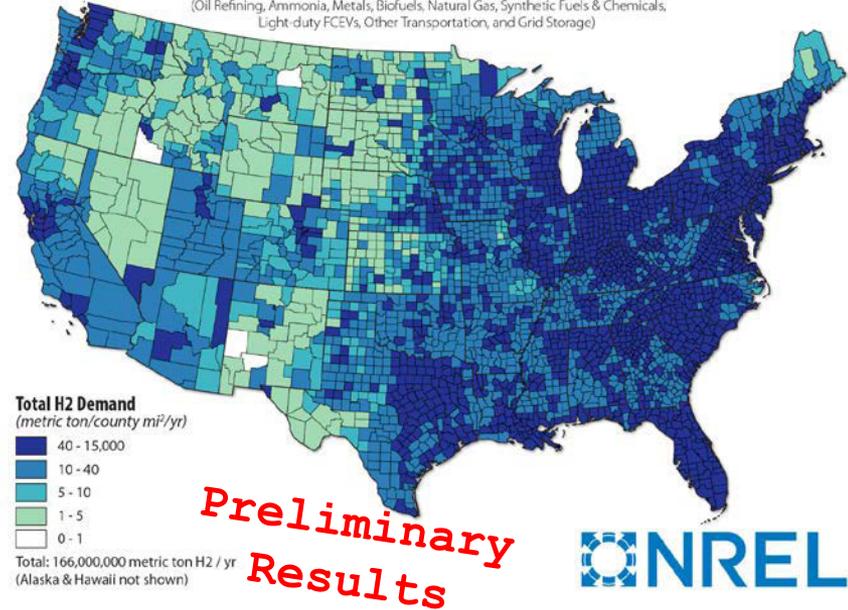
# Maximum Market Potential

Application	Maximum Market Potential (MMT/yr)	2015 Market for On-Purpose H2 (MMT/yr)
Refineries and the chemical processing industry (CPI) <sup>a</sup>	8	6
Metals	12	0
Ammonia	4	3
Biofuels	4	0
Synthetic fuels and chemicals	14	1
Natural gas supplementation	10	0
Light-duty fuel cell electric vehicles (FCEVs)	57	0
Other transportation (Medium- & Heavy-Duty)	29	0
Seasonal energy storage for the electricity grid	28	0
<b>Total</b>	<b>166</b>	<b>10</b>

Definition: The maximum market 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.

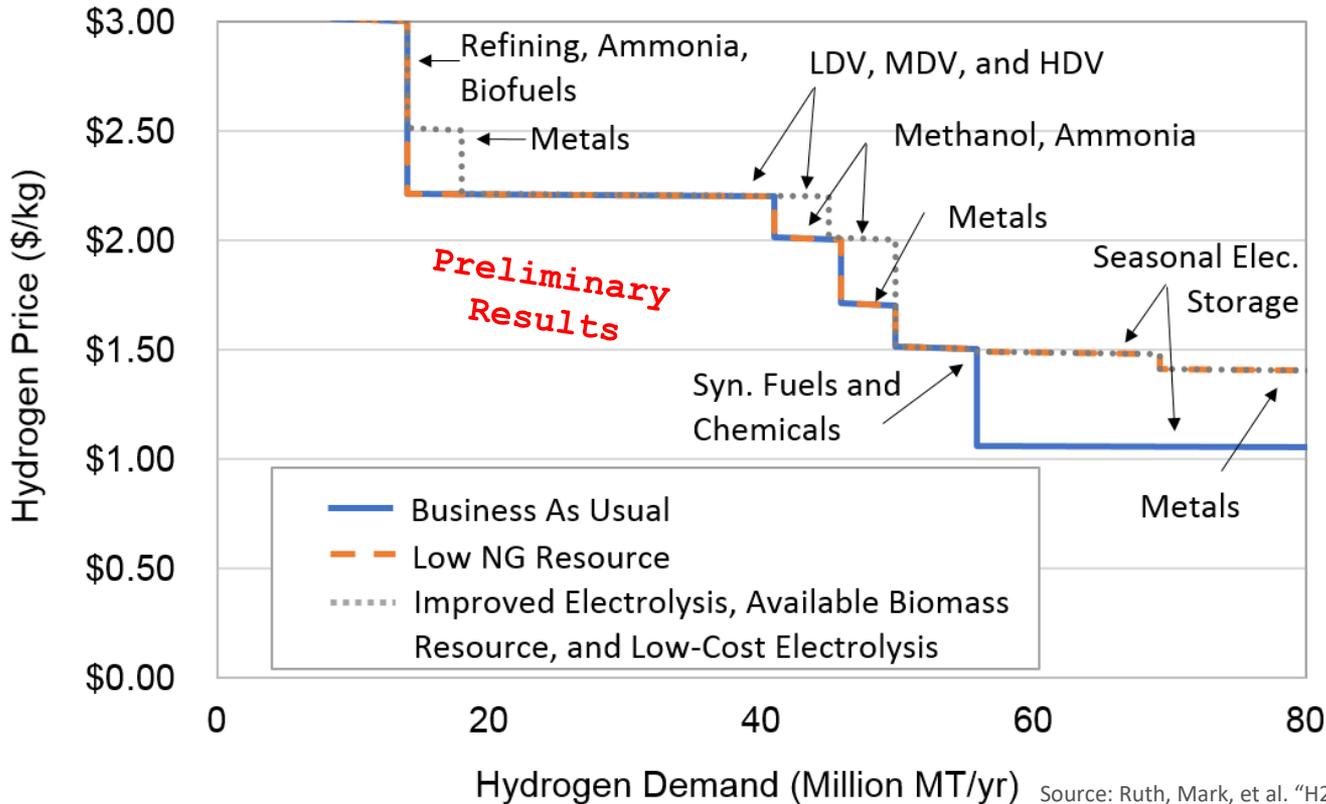
Maximum growth potential of hydrogen market by 2050 is 17X.

Maximum Market Potential for the Industrial & Transport Sectors, Natural Gas, and Storage  
(Oil Refining, Ammonia, Metals, Biofuels, Natural Gas, Synthetic Fuels & Chemicals, Light-duty FCEVs, Other Transportation, and Grid Storage)



Source: Ruth, Mark, et al. "H2@Scale" 2019 Annual Merit Review. Crystal City, VA (April 30, 2019)

# Market Competitiveness

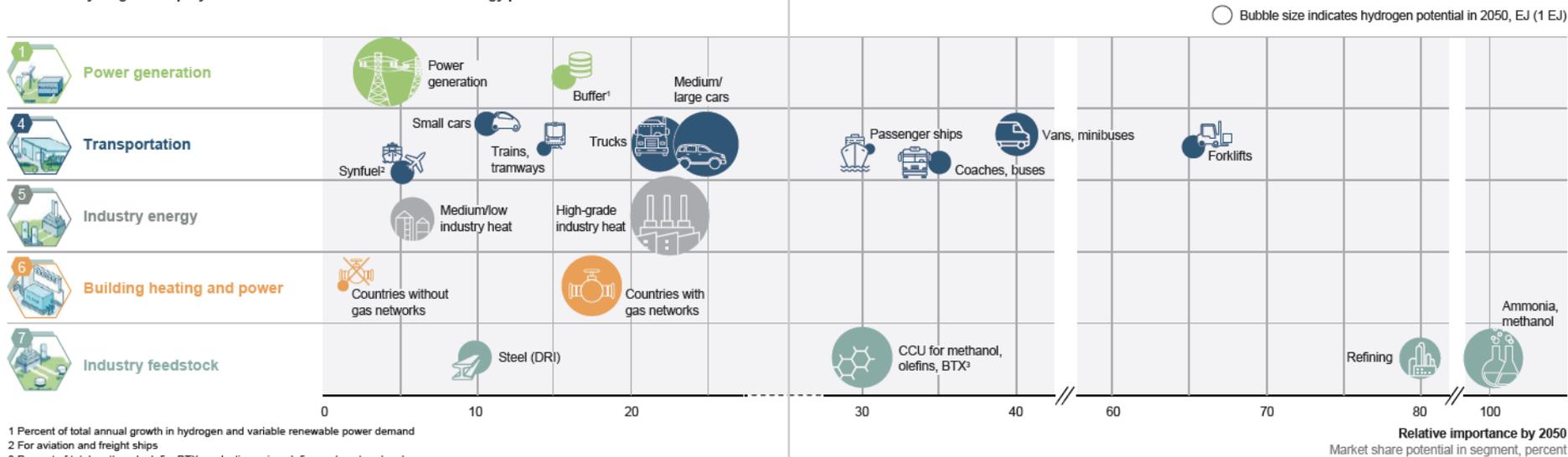


**At lower prices, hydrogen is competitive in more markets. Prices must be very low to approach the maximum market potential.**

# Potential Hydrogen Applications

Ten-fold growth is likely to be driven by the number of markets – not by being the only option in any market

Exhibit 4: Hydrogen can play a critical role in the low-carbon technology portfolio

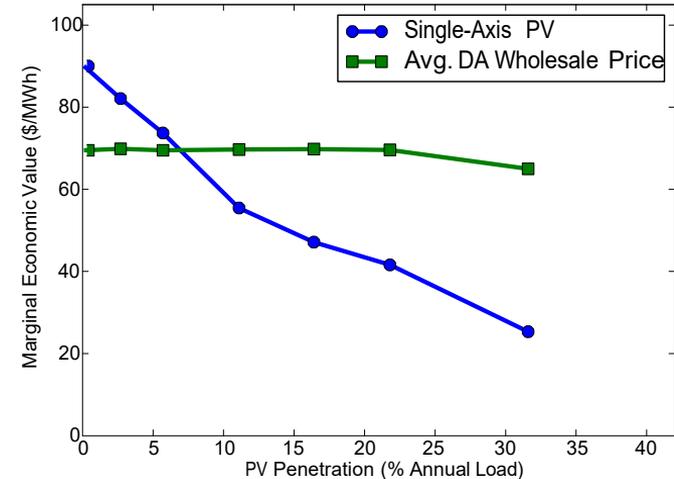
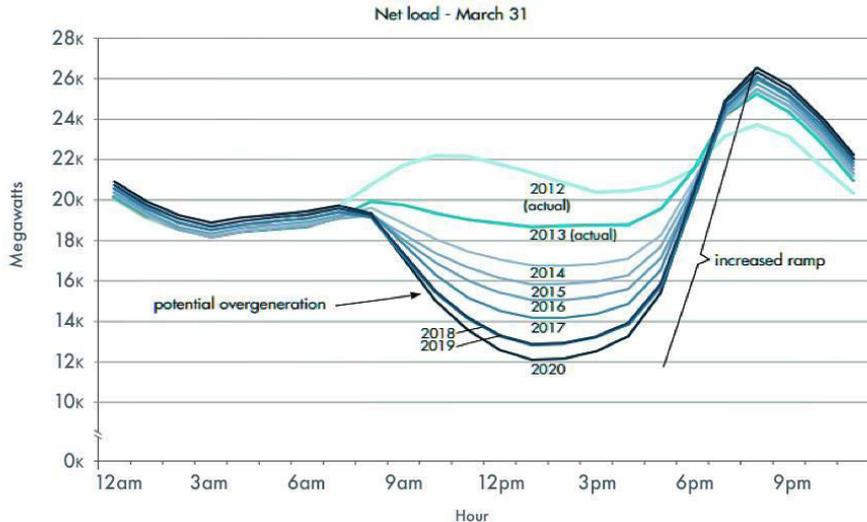


Source: Hydrogen Council. Hydrogen: Scaling Up. (November 2017)

# Low-Cost, Dispatch-Constrained Electricity

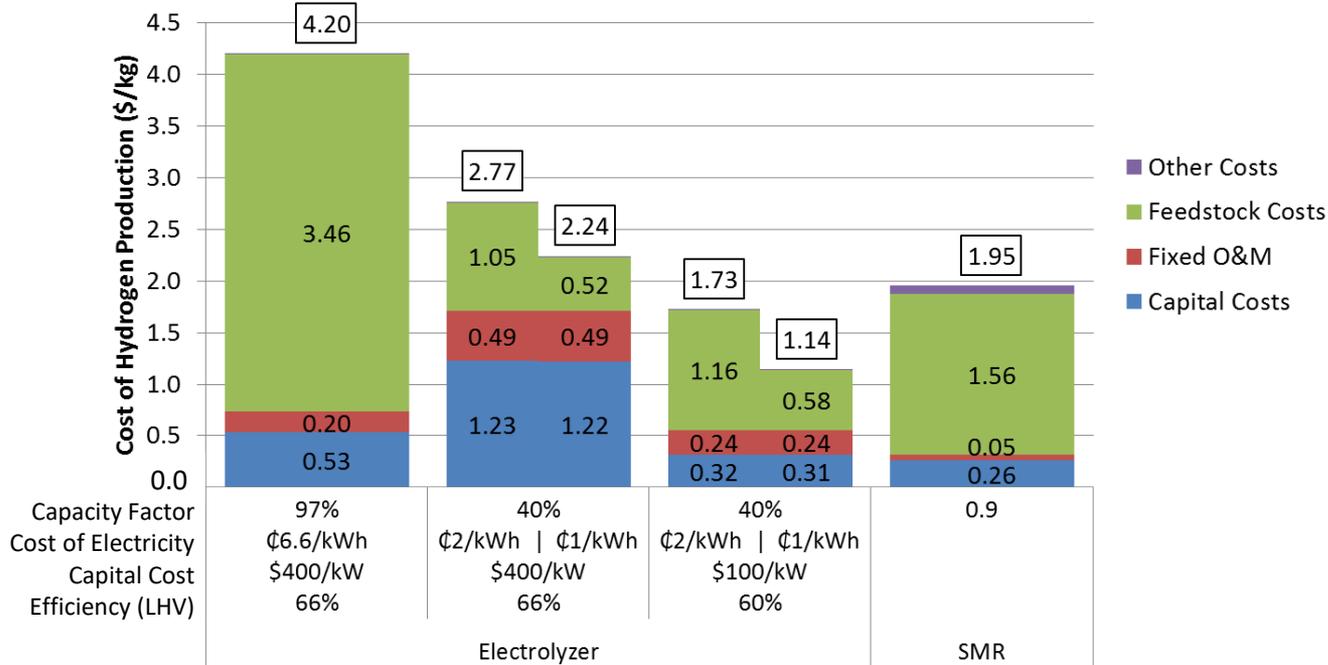
As renewable penetration increases, overgeneration and transients become larger concerns.

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



# Development Opportunity: Low Temperature Electrolysis

## Potential Levelized Costs of H<sub>2</sub> Production



The availability of low-cost, dispatch constrained electricity (LDE) provides an opportunity for hydrogen production providing electrolyzer capital costs can be reduced sufficiently.

# Development Opportunity: High Temperature Electrolysis

High-temperature electrolysis coupled with baseload power generation could potentially have a high capacity factor while supporting grid needs.

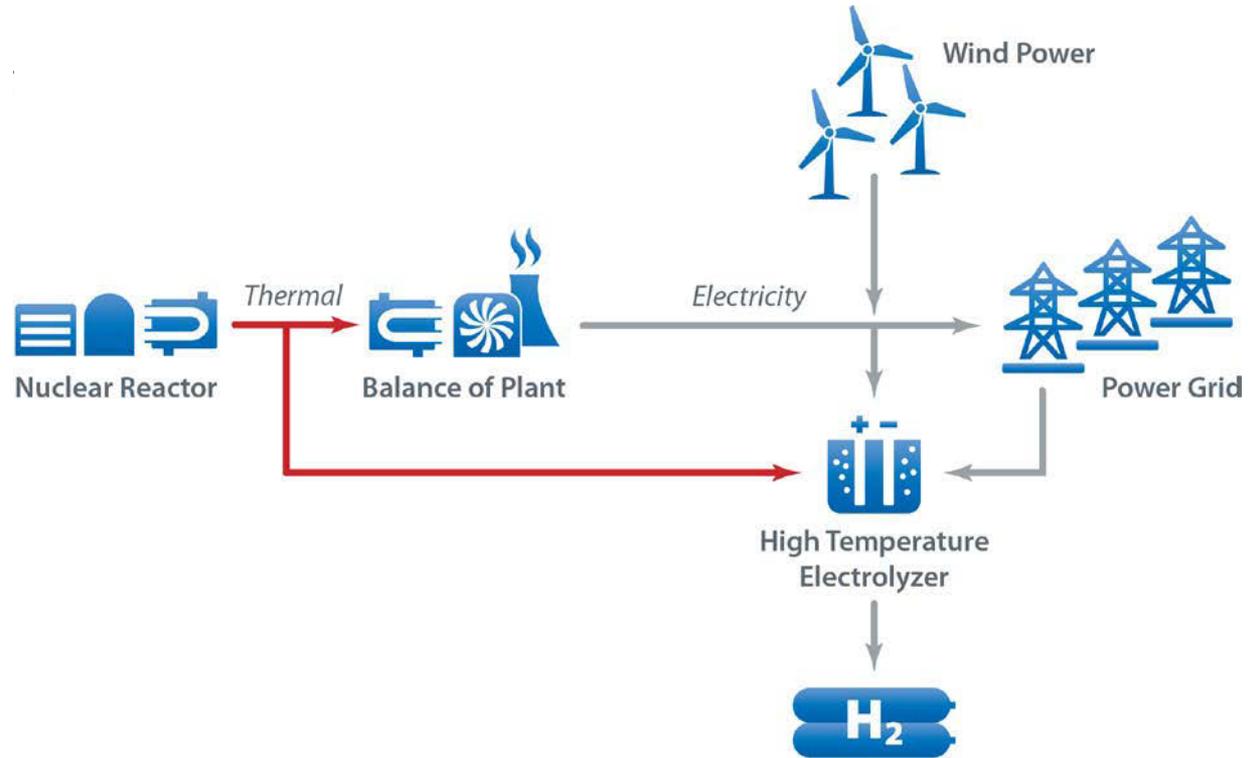
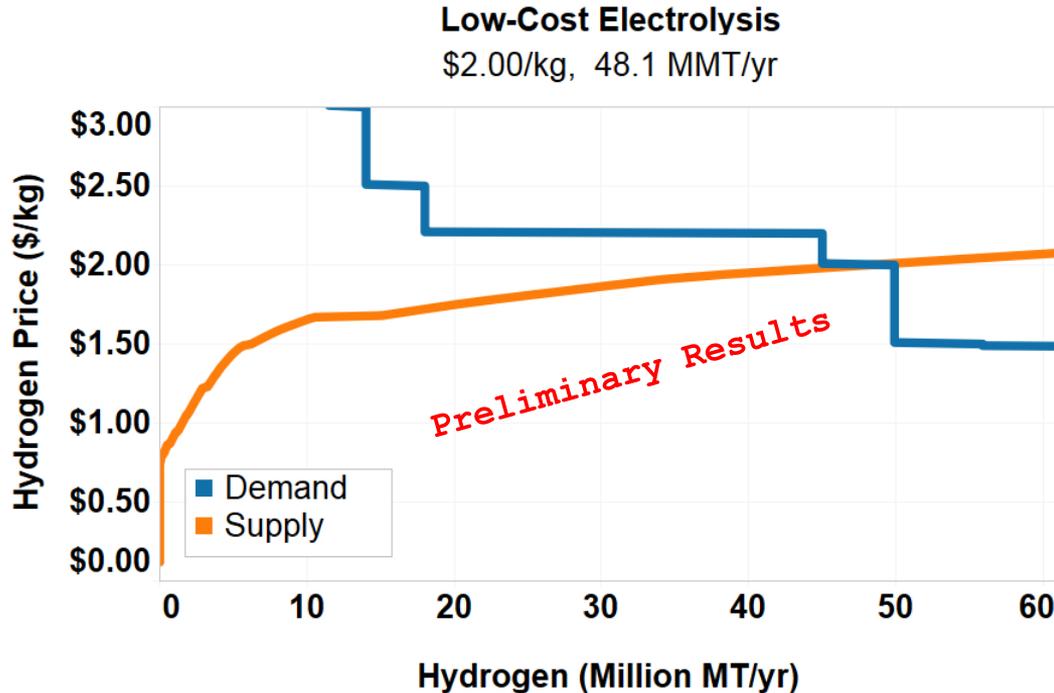


Figure Source: Ruth, Mark, Cutler, Dylan, Flores-Espino, Francisco, and Stark, Greg. The Economic Potential of Nuclear-Renewable Hybrid Energy Systems Producing Hydrogen (2017). NREL/TP-6A50-66764. <http://www.nrel.gov/docs/fy17osti/66764.pdf>

# Both Supply and Demand Are Governed by Market Rules

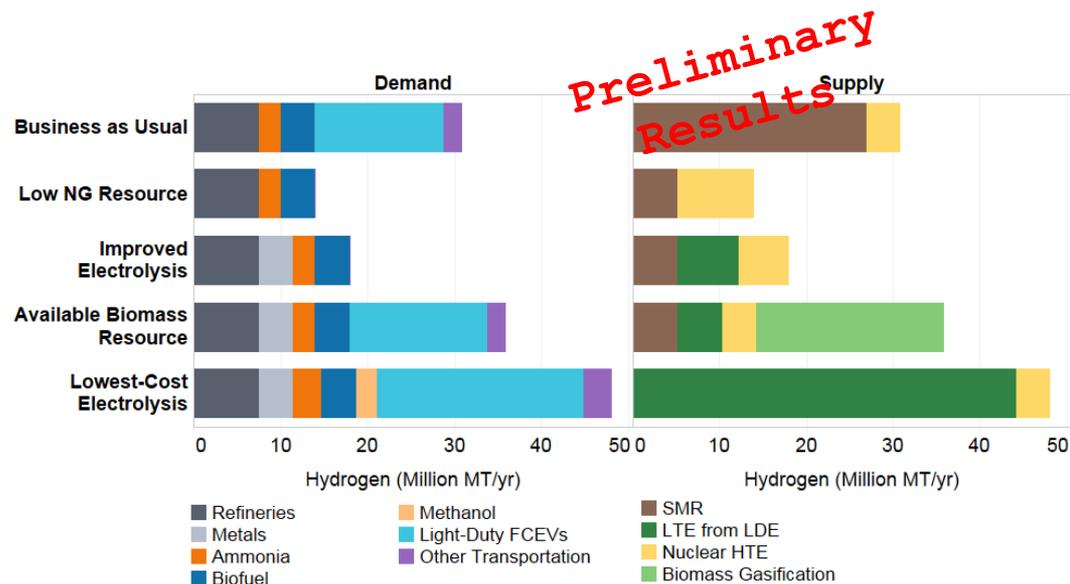
Minus key policy drivers, hydrogen needs to be produced at a cost that is sufficiently low for it to compete against alternatives



# Economic Potential in Five Scenarios

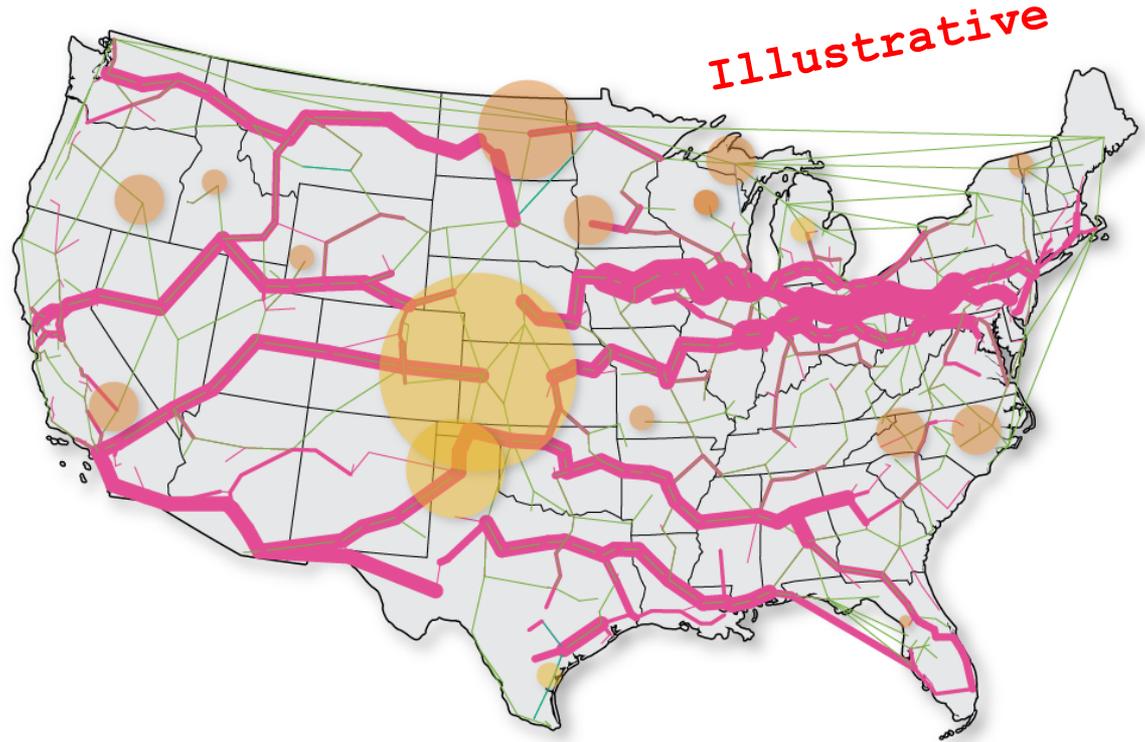
The economic potential of hydrogen demand in the U.S. is 1.5-5X current annual consumption.

Scenario	Insights
Business as Usual	Low-cost natural gas drives growth in H <sub>2</sub> markets with some nuclear participation
Low NG Resources	Higher cost natural gas results in minimal growth in H <sub>2</sub> applications
Improved Electrolysis	Drivers for metals applications increase market. Some LTE penetration at \$200/kW capital cost with grid value.
Available Biomass Resources	If the biomass is not used for higher value purposes, it could be a key resource
Lowest-Cost Electrolysis	Low-cost electrolyzers with high grid value can enable additional H <sub>2</sub> applications



# Delivery & Storage Opportunities

Delivery and storage infrastructure will need to be developed to realize much larger hydrogen markets



Illustrative transport and storage requirements for lowest-cost electrolysis scenario

# Concluding Thoughts

- A gigatonne market may be possible but requires growth at or exceeding current market potential analyses
- Developing applications that economically compete with alternatives is critical
- The key development opportunity for low temperature electrolysis is capital cost reduction
- High temperature electrolysis will be dependent upon its ability to provide electricity to the grid
- Continental and trans-continental infrastructure is probably a key growth challenge

# Thank you

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