NREL
NATIONAL RENEWABLE ENERGY LABORATORY

40
1977 – 2017





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

Mark F. Ruth*, Paige Jadun, Bryan Pivovar

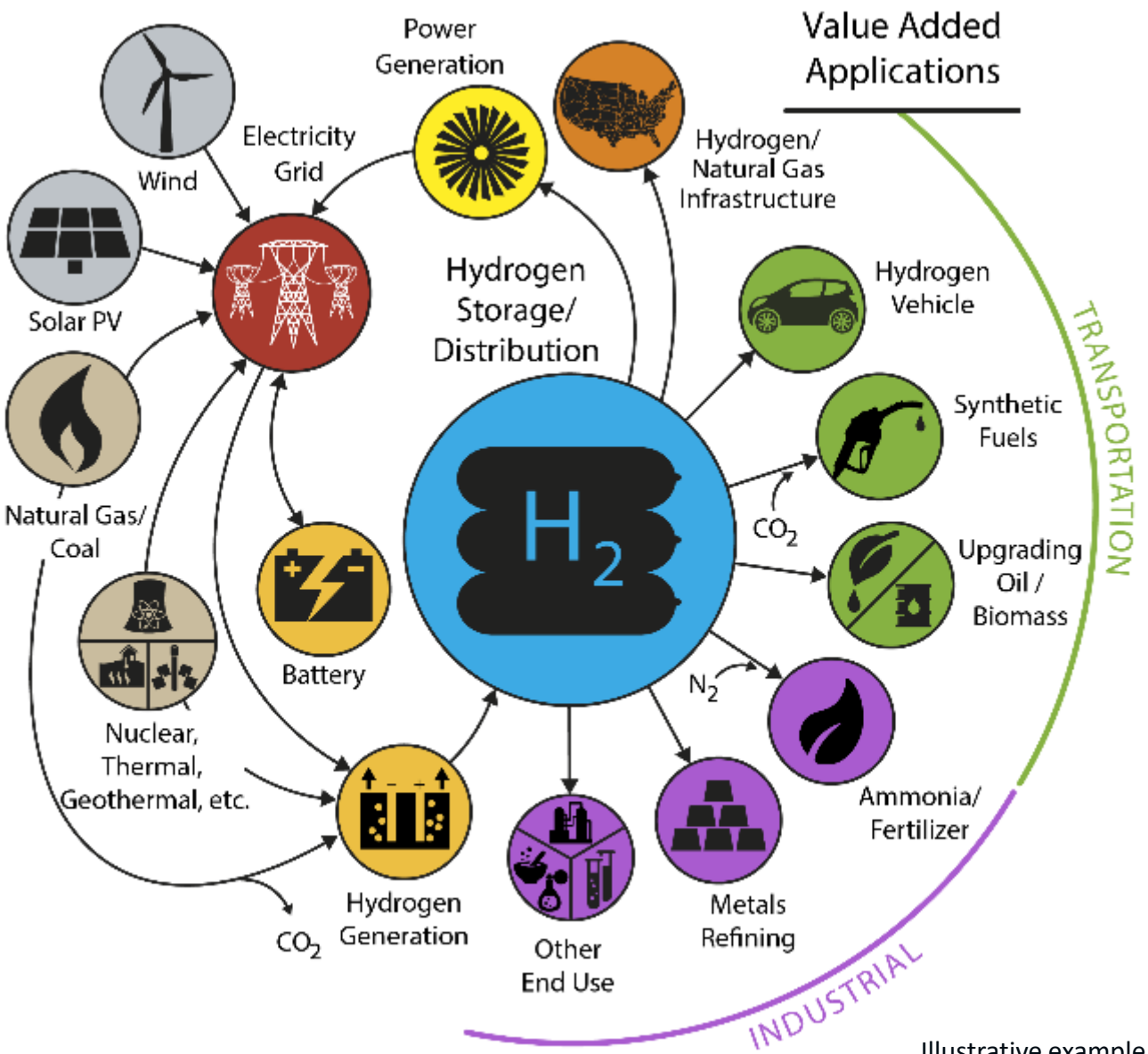
Fuel Cell Seminar and Energy Exposition

November 9, 2017

Long Beach, California

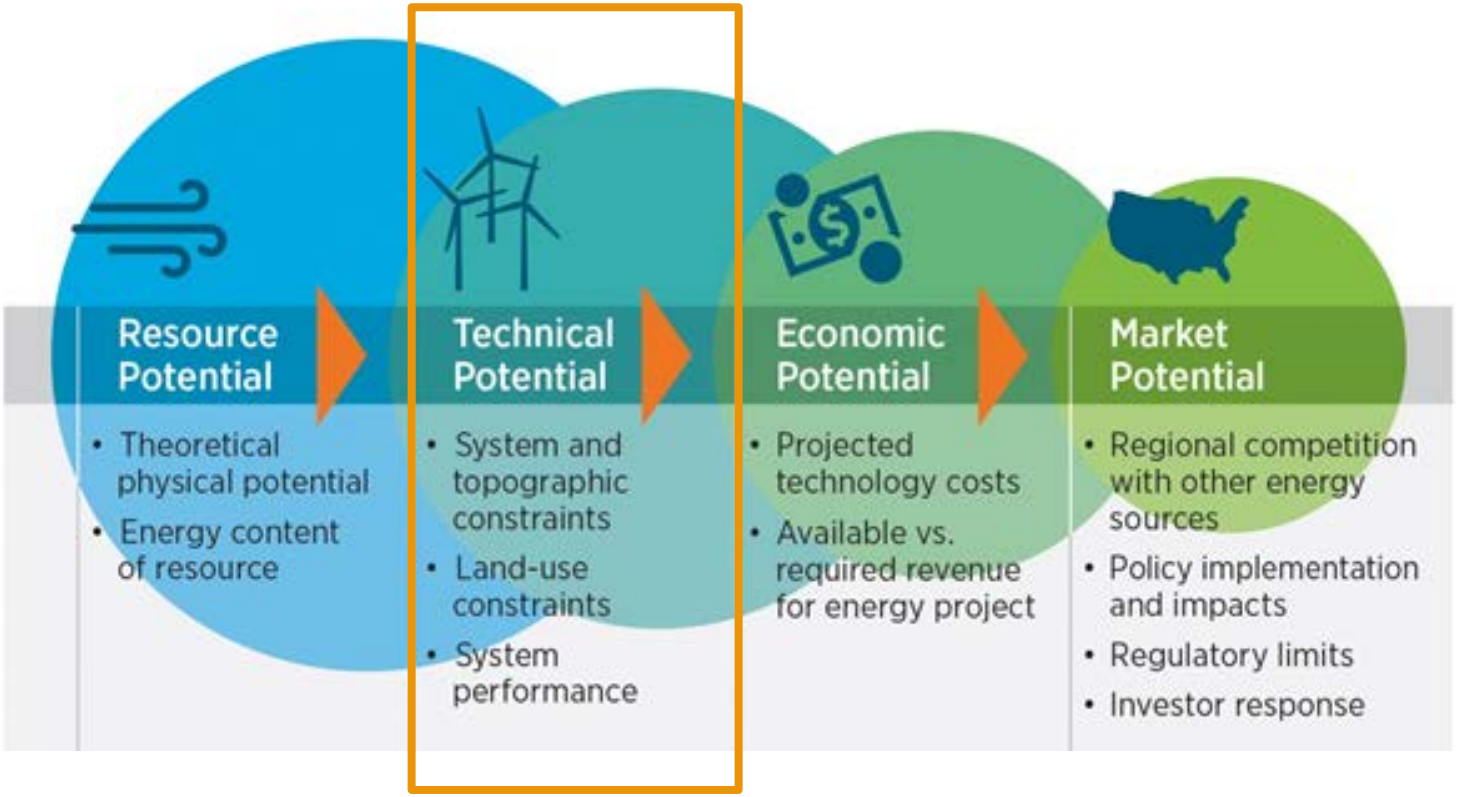
NREL/PR-6A20-70456

H2@Scale Energy System



Illustrative example, not comprehensive

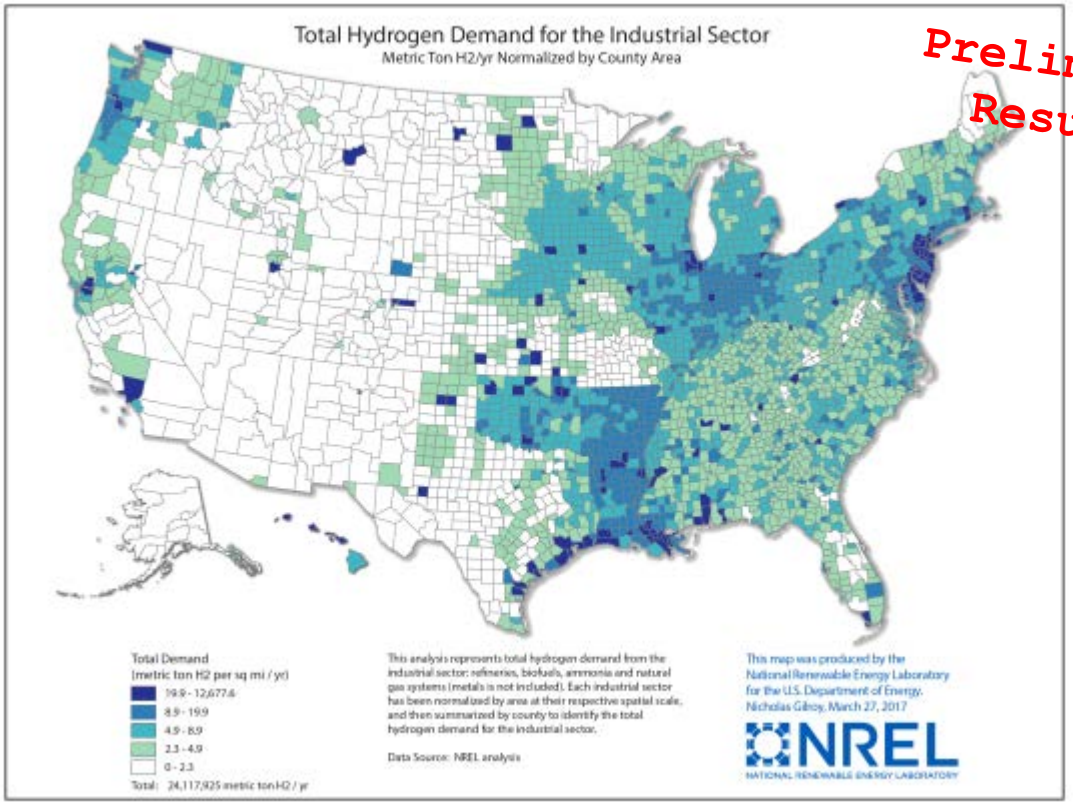
Technical Potential: Definition



Technical potential is the **subset of the available resource potential** that is **constrained by real-world geography and system performance but not economics**

Brown, A., P. Beiter, D. Heimiller, C. Davidson, P. Denholm, J. Melius, A. Lopez, D. Hettinger, D. Mulcahy, and G. Porro. 2015. *Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-64503

Technical Potential Hydrogen Demand



Preliminary Results

Use	Market potential (million metric tonne H_2 / year)
Industrial Use	
Refineries & CPI§	8*
Metals	5
Ammonia	5
Natural Gas	7
Biofuels	4
Light Duty Vehicles	28
Other Transport	3
Total	**60**

Total market potential:

60 MMT/yr

Current U.S. market: ≈ 10 MMT/yr

Near-term Outlook for Hydrogen Production Volume: 5% CAGR (2014-2019)[1]

§ CPI: Chemical Processing Industry not including metals, biofuels, or ammonia

* Current potential used due to lack of consistent future projections

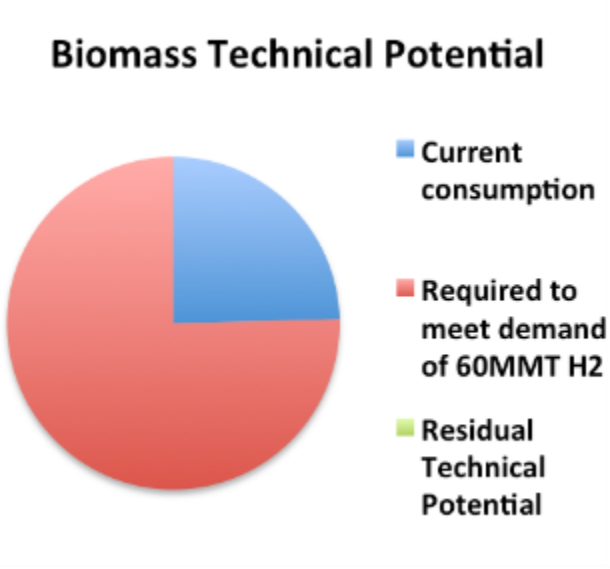
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

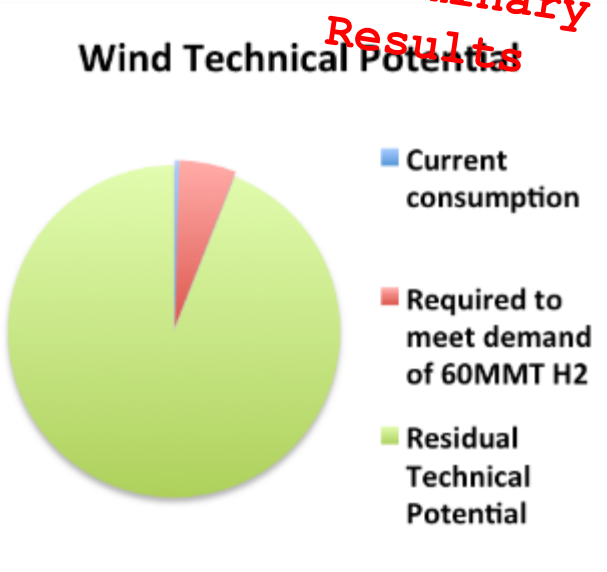
1. Global hydrogen Generation Market by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology- Trends & Forecasts (2011-2016)

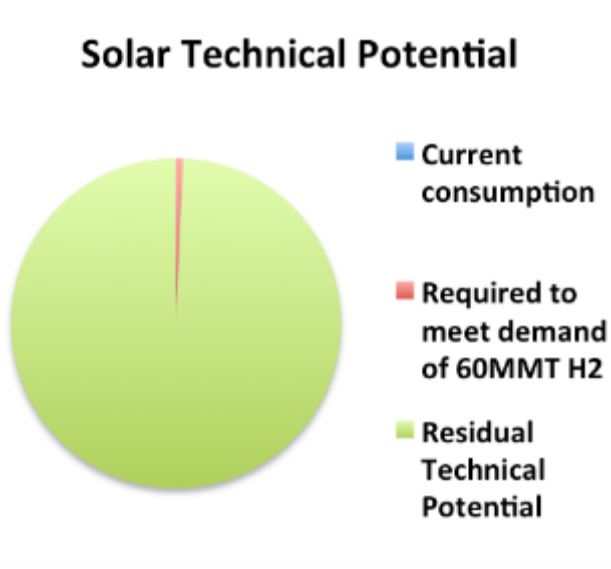
Technical Potential: Impact on Renewable Resources

	EIA 2015 current consumption (quads/yr)	Required to meet demand of 60 MMT / yr (quads/yr)	Technical Potential (quads/yr)
Solid Biomass	4.7	15	20
Wind Electrolysis	0.7	9	170
Solar Electrolysis	0.1	9	1,364

Preliminary Results

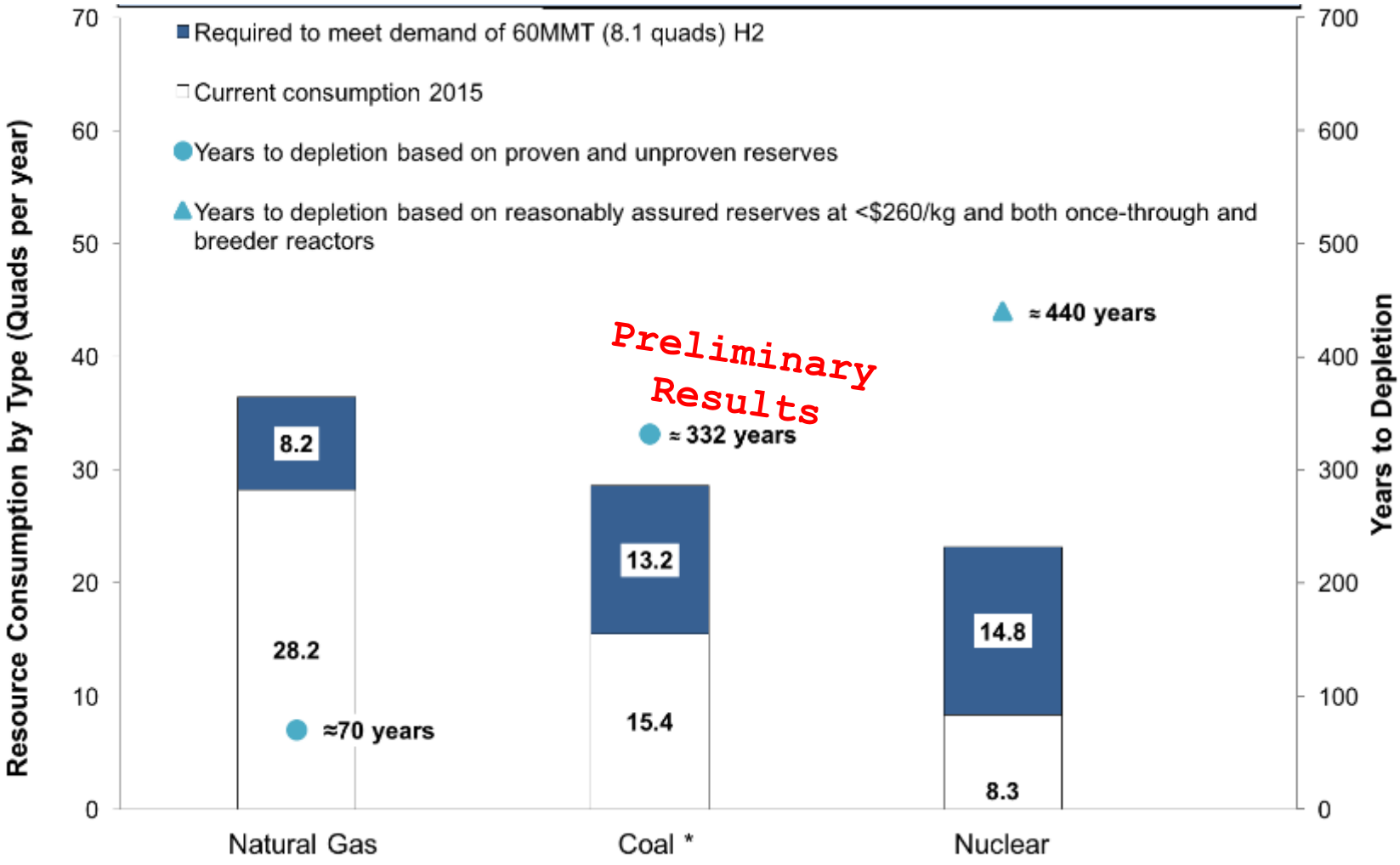






Total demand including hydrogen is satisfied by ≈6% of wind, <1% of solar, and ≈100% of biomass technical potential

Technical Potential: Impact on Fossil & Nuclear Resources



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

* Based on estimated recoverable reserves

Technical Potential: Impacts on Resources

Use	H_2 Consumed	*Resource Savings*		Emissions Reduction
	MMT / yr	Petroleum (bbl/yr)	Natural Gas (quad btu/yr)	CO2 (million metric ton/yr)
Refineries	8	900,000	1.332	87
Metals	5	0	0.365	78
Ammonia	5	500,000	0.833	54
Natural Gas System	7	700,000	0.923	63
Biofuels§	4	77,500,000	-0.026*	28
Light Duty Vehicles	28	1,017,600,000	0.629	469
Other Transport	3	113,400,000	0.051	50
Total	60	1.2 Billion bbl	4.1 Quads	830 Million MT

Preliminary Results

~17% of U.S. petroleum consumption in 2016

~14% of U.S. natural gas consumption in 2016

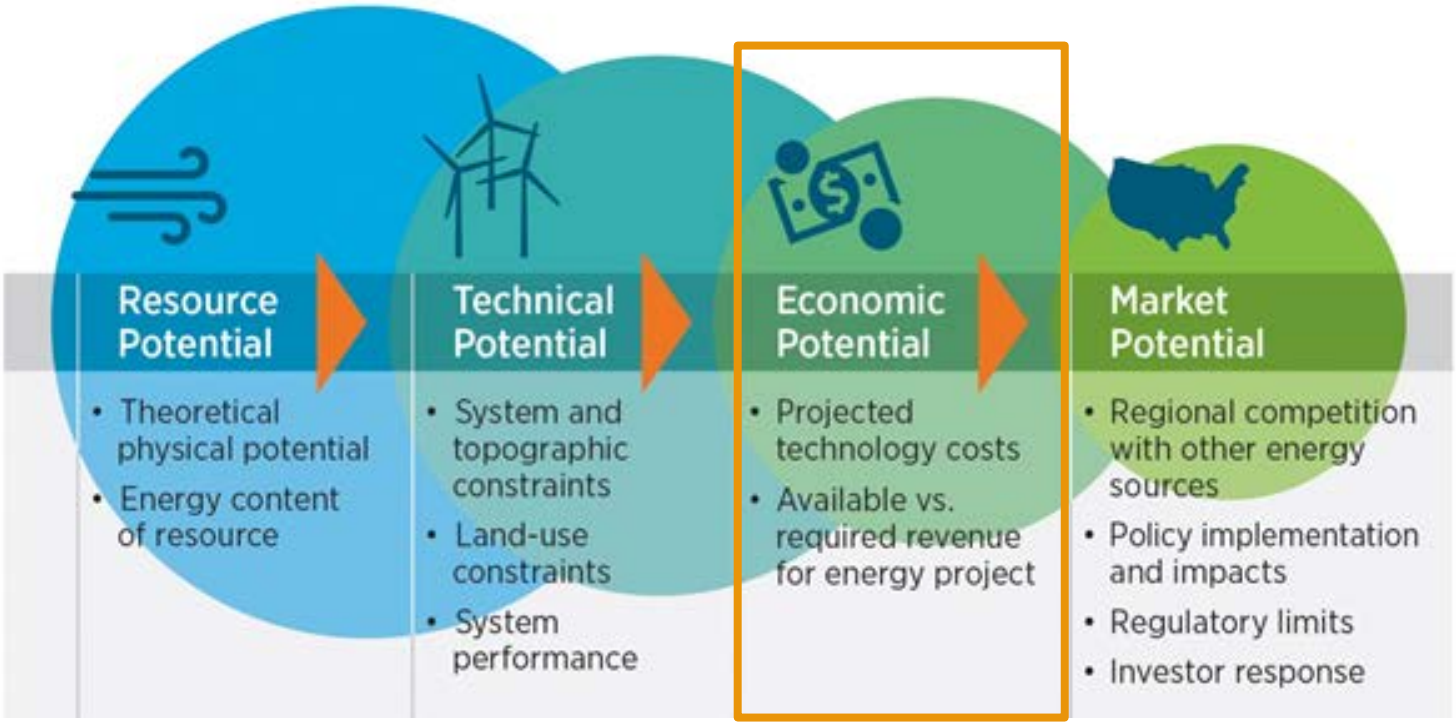
~16% of U.S. energy-related emissions in 2016

Growth in electrolytic hydrogen using renewable electricity can reduce petroleum and natural gas utilization by ≥15%

*Negative values represent increase in use due to fertilizer production

§ 12% of the benefits of hydrogenated biofuels are credited to hydrogen

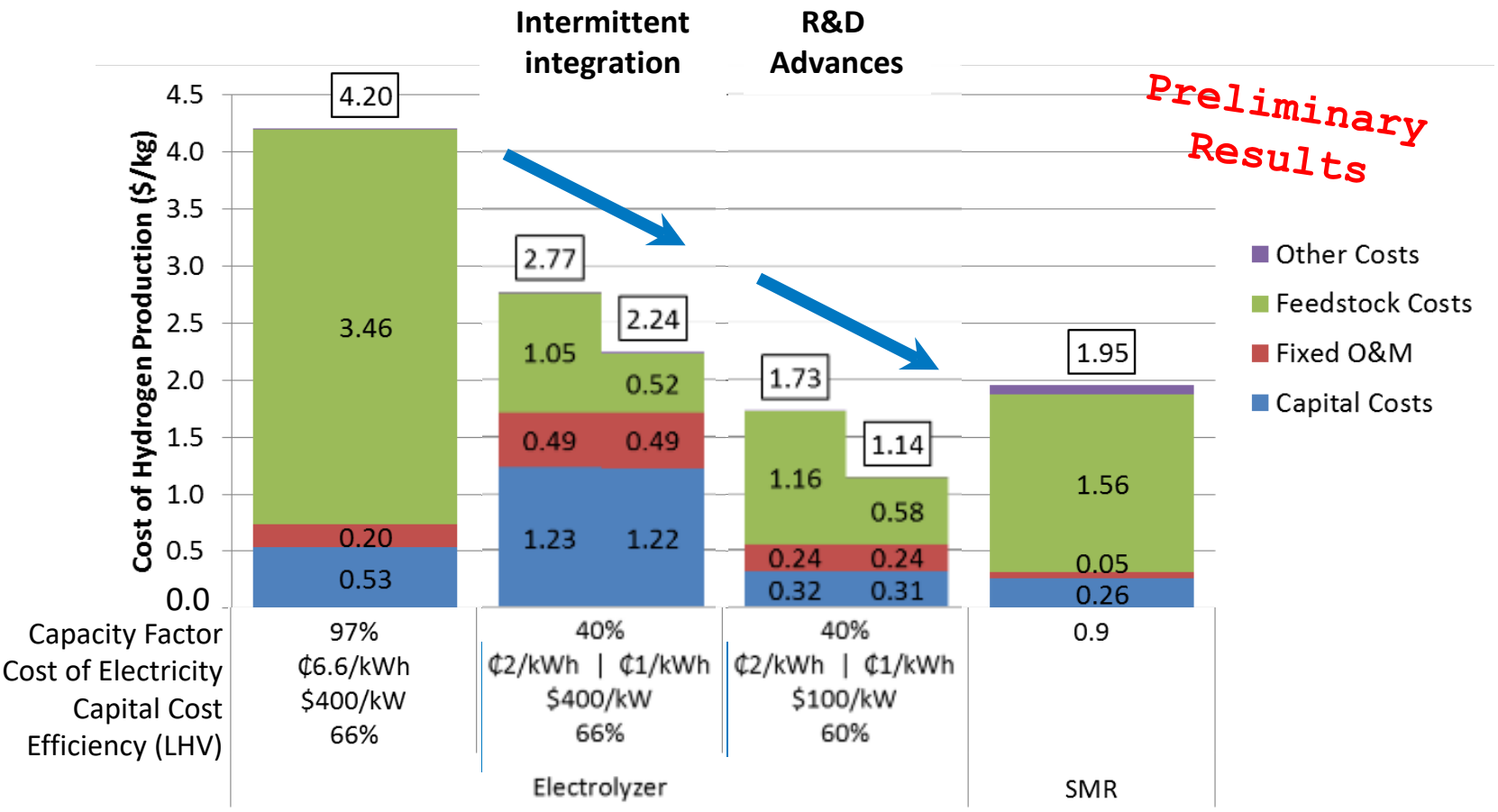
Economic Potential: Definition



Economic potential is the **subset of the technical potential** where the **cost required** to produce hydrogen **is below** the **revenue available**

Brown, A., P. Beiter, D. Heimiller, C. Davidson, P. Denholm, J. Melius, A. Lopez, D. Hettinger, D. Mulcahy, and G. Porro. 2015. *Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results.* Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-64503

Improvements Enabling Use of Low-Cost Electricity

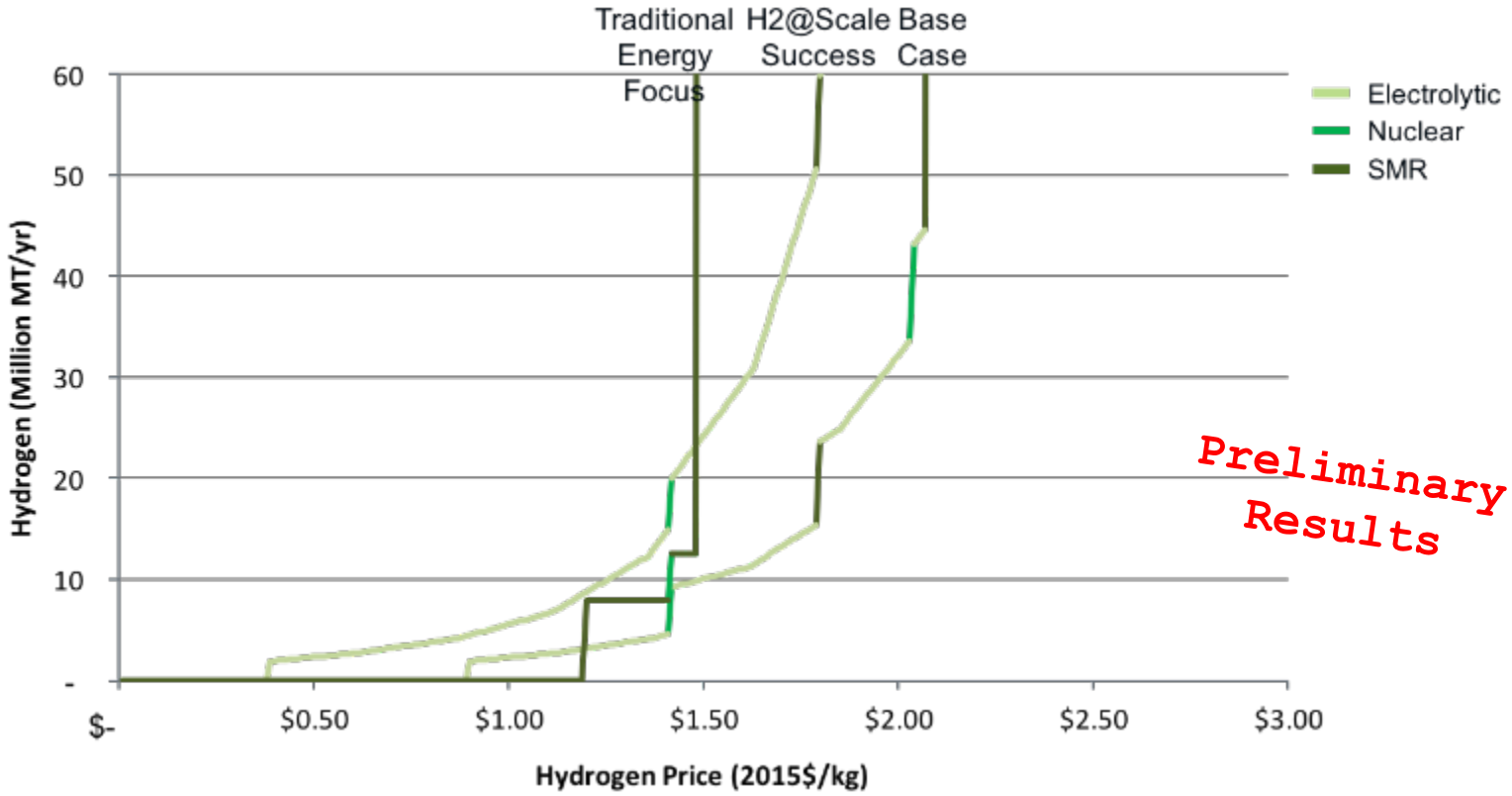


Leveraging of intermittent low-cost electricity can enable low-cost hydrogen production and also support grid stability.

Economic Potential: Supply Curves

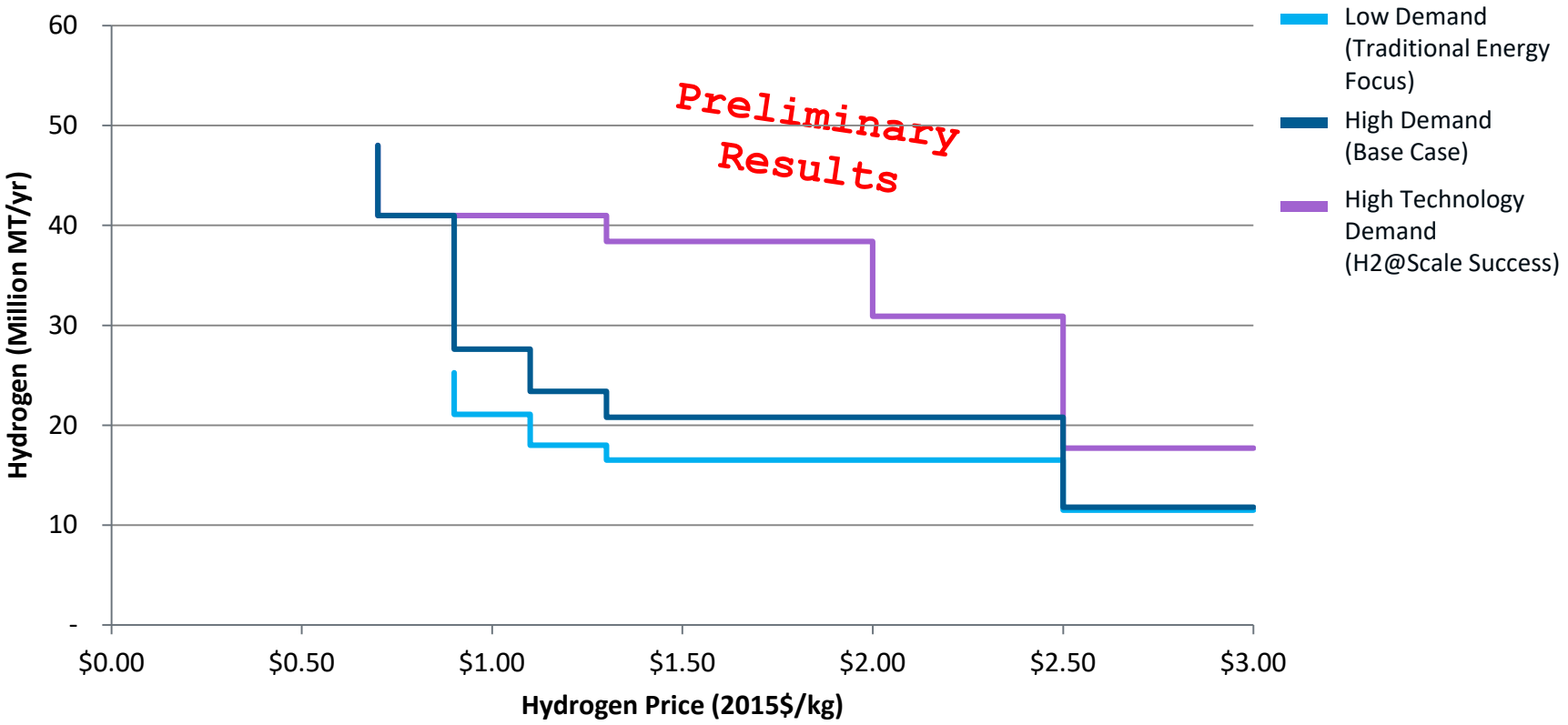
Developed supply curves using three resources

- Steam methane reforming (SMR)
- Nuclear generation
- Otherwise curtailed electricity with high penetrations of variable renewable generators on the grid and no transmission costs



Economic Potential: Demand Curves

Developed demand curves under three paradigms



Demand	Base Case (High)	H2@Scale Success (High Tech.)	Traditional Energy Focus (Low)
Metals Reshoring	Economically competitive	Willingness to pay for H2 for metals	Economically competitive
LDV	Economically competitive	Full potential at $2.50/kg	Economically competitive
Synthetic Fuels	Economically competitive	Full potential at $2.00/kg	Economically competitive

Economic Potential: Scenario Summary

Preliminary Results

	Base Case	H2@Scale Success	Traditional Energy Focus
H_2 Use	21 MMT/yr	38 MMT/yr	17 MMT/yr
H_2 Price	$1.80/kg	$1.70/kg	$1.49/kg
Demand (MMT/yr)	• Refining (8), • Ammonia (3), • Synthetic fuel (1), • LDVs (9)	• Refining (8), • Ammonia (3), • Synthetic fuel (9), • Metals (6), • LDVs (13)	• Refining (8), • Ammonia (3), • Synthetic fuel (1), • LDVs (5)
Supply (MMT/yr)	• Low-temperature electrolysis (11), • Existing nuclear plants (5), • Existing NG reforming (5)	• Low-temperature electrolysis (33), • Existing nuclear plants (5)	• Existing nuclear plants (5) • NG reforming (8 MMT/yr from existing and 4 MMT/yr from new)
Electrolysis	10% curtailment, $19/MWh wholesale price	25% curtailment, $26/MWh wholesale price	No grid electrolysis

Economic Potential: Energy Use and Emissions Summary

H2@Scale can reduce emissions by up to 20% on top of baseline electricity sector emission reductions

Preliminary Results

Reduction Metric	Base Case	H2@Scale Success	Traditional Energy Focus
NO_X (Thousand MT)	130 (1%)	230 (2%)	61 (1%)
SO_X (Thousand MT)	33 (1%)	170 (5%)	13 (0%)
PM_{10} (Thousand MT)	10 (0%)	59 (2%)	4.0 (0%)
Crude Oil (Million Barrels)	470 (7%)	800 (12%)	280 (4%)
CO_2 (Million MT)	280 (9%)	590 (19%)	110 (4%)

Conclusions and Future Work

H2@Scale can transform our energy system by providing value for otherwise-curtailed electricity and a clean feedstock for numerous industries

- Technical potential:
  60MMT H_2/ yr can reduce emissions by 15%

- Economic potential:
  17-38 MMT H_2 / yr can be produced, given R&D advancements and access to low-cost intermittent power

Further analysis into regional issues and temporal issues is warranted to better quantify H2@Scale potential

www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Economic Potential Analysis Caveats

- Ideal markets
- Hydrogen storage and transportation requirements and costs are negligible
- Technology improvement and market assumptions in ReEDS result in a high VRE penetration and quantity of curtailed electricity
- Electrolyzer capacity factors are estimated using coarse temporal resolution of ReEDS (16 time slices representative of entire year)
- Low-temperature electrolyzer system costs achieve a target of $100/kW
- Nuclear-generated hydrogen costs do not include potential value to the grid in capacity and/or flexibility
- Economic rebound effects are negligible
- Additional hydrogen markets outside of our analysis may develop