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H_2@Scale Analysis and Project Developments

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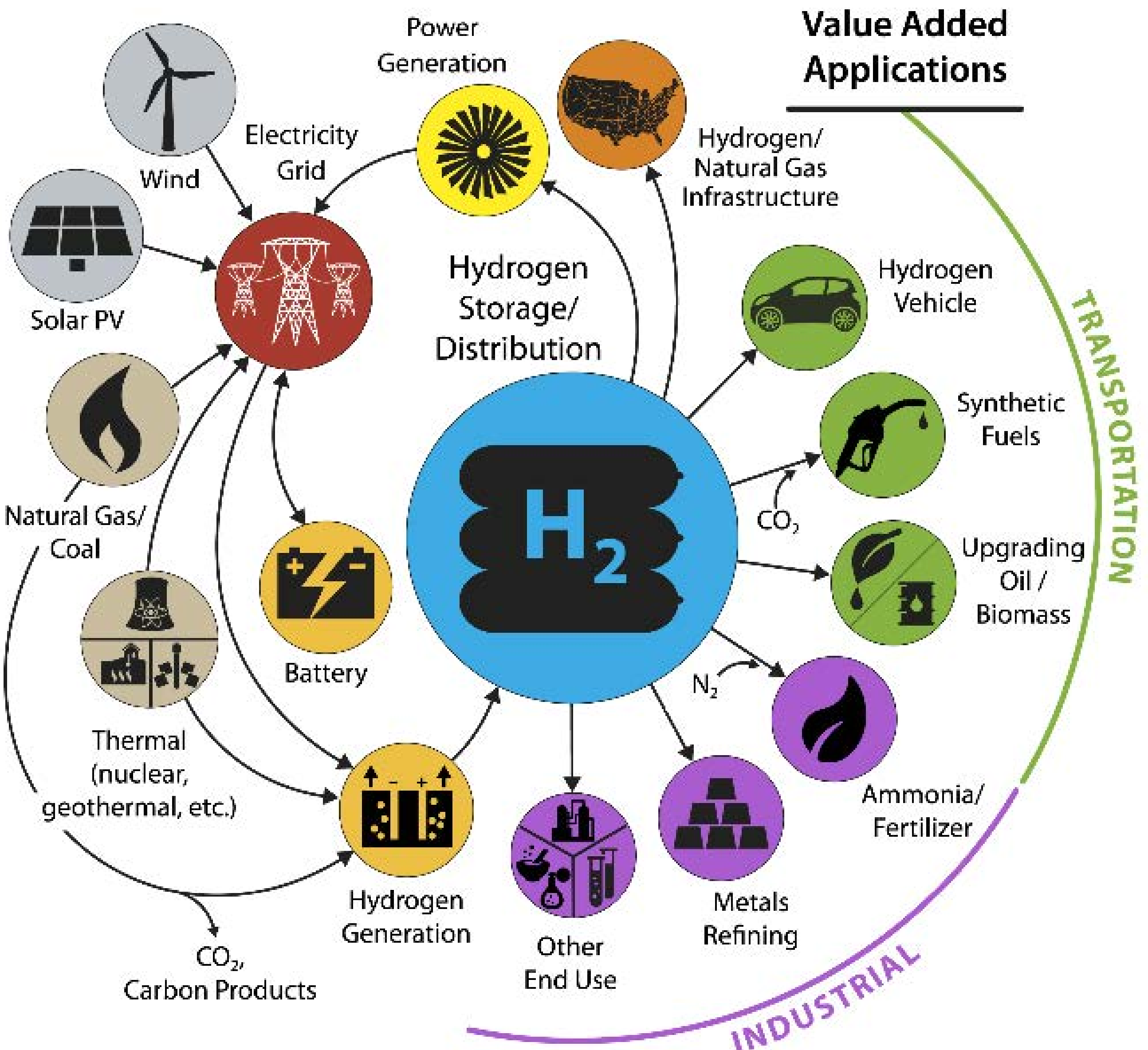
Conceptual H_2@Scale Energy System

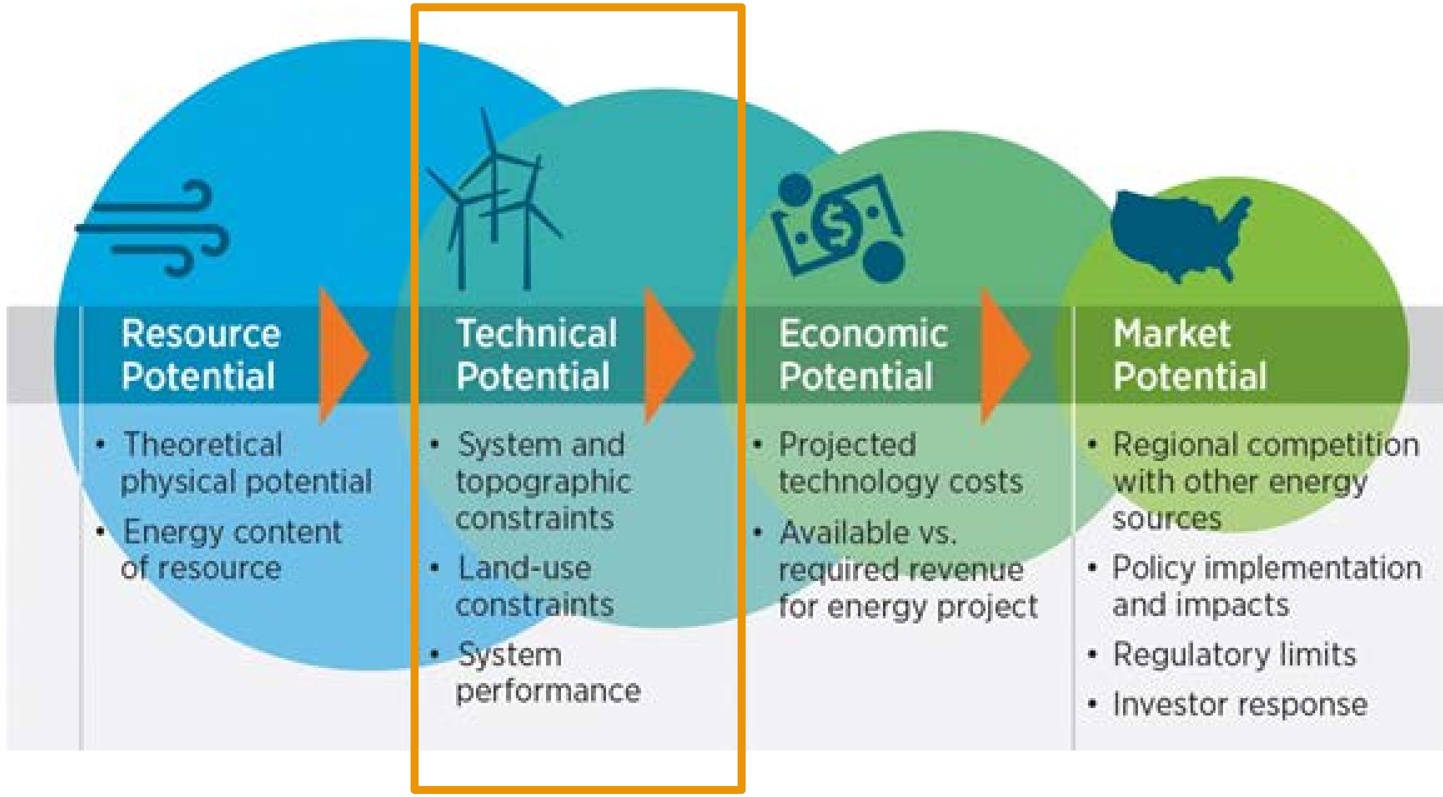


Illustrative example, not comprehensive

Presentation Topics

- Technical potential of demand for hydrogen
- National-scale economic potential
- Spatial / temporal analysis initiated

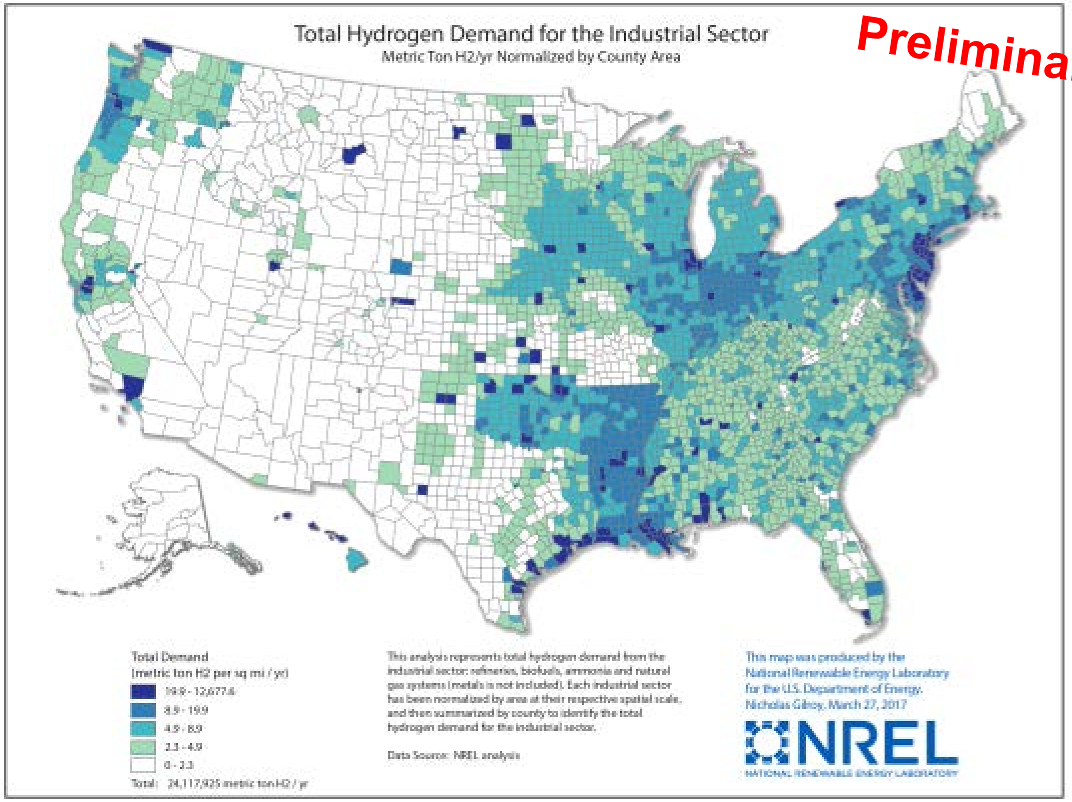
Technical Potential: Definition



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



Use	Technical 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 demand potential:

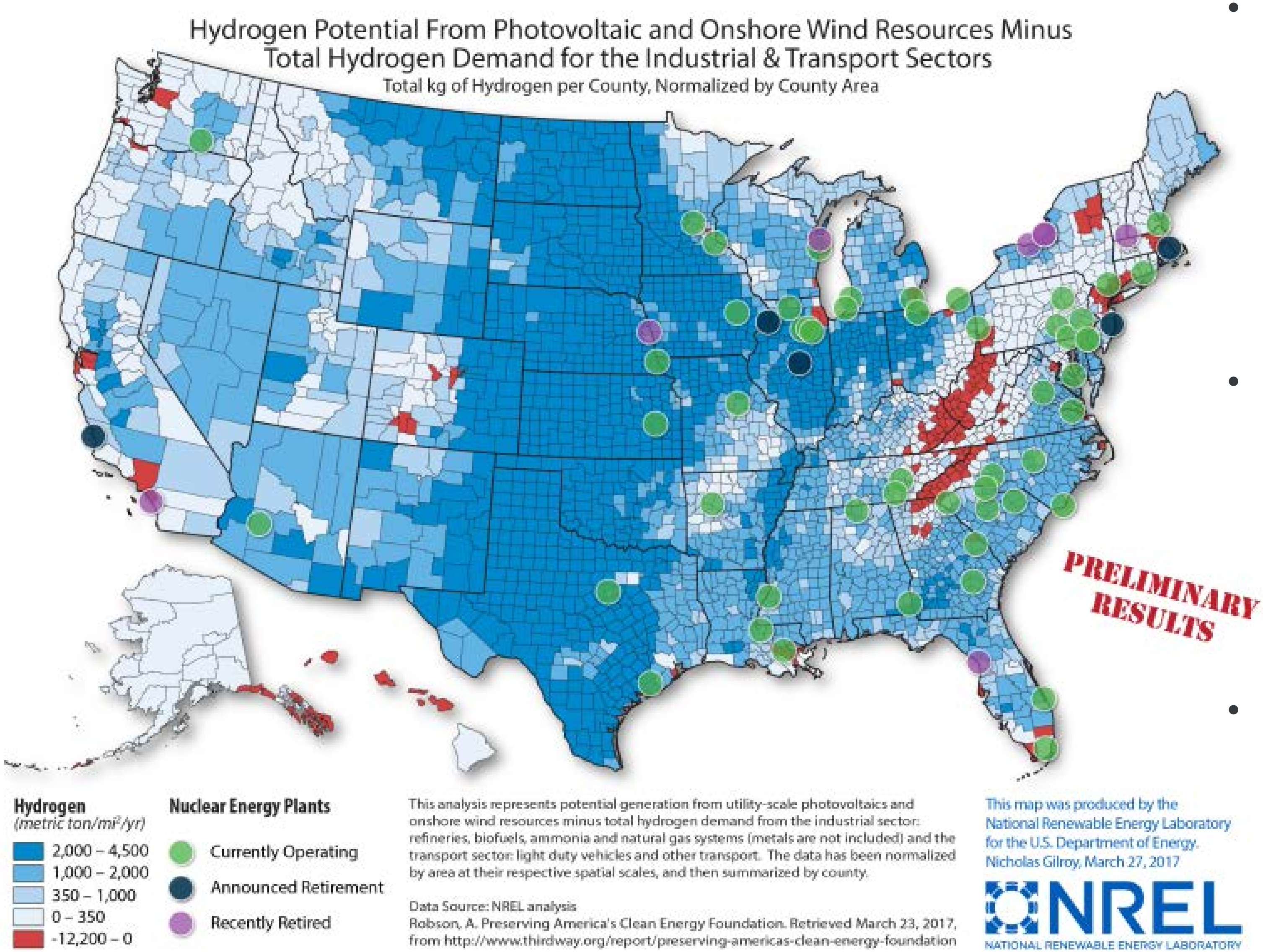
60 MMT/yr

Current U.S. market: ≈ 10 MMT/yr

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

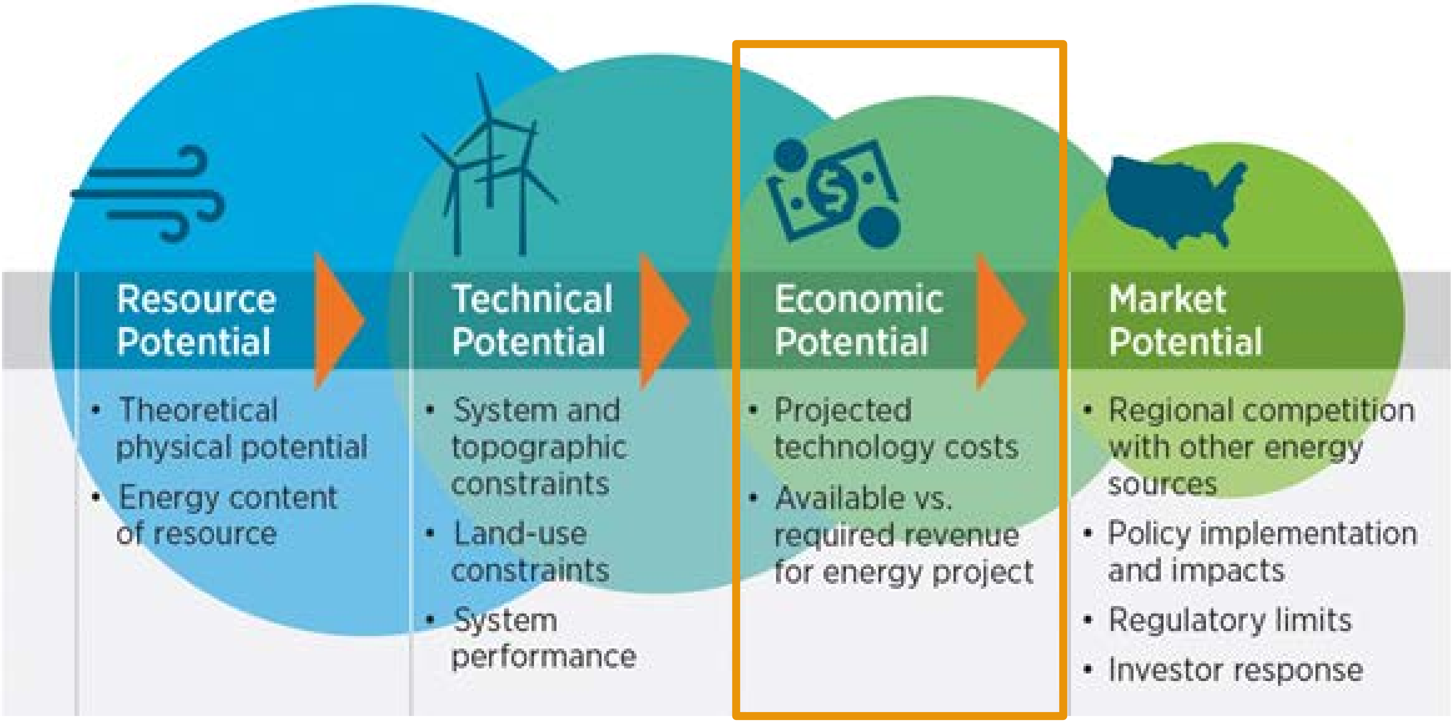
§ CPI: Chemical Processing Industry not including metals, biofuels, or ammonia
* Current potential used due to lack of consistent future projections
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels
1. Global hydrogen Generation Market by Merchant & Captive Type, Distributed & Centralized Generation, Application & Technology- Trends & Forecasts (2011-2016)

Initial Analysis: Where Resources are Sufficient



- PV and wind resources exceed industrial + transportation demand (not including metals) in **counties colored blue**
- Industrial + transportation demand is greater than resources **only in counties colored red**
- Nuclear production could provide the necessary additional generation

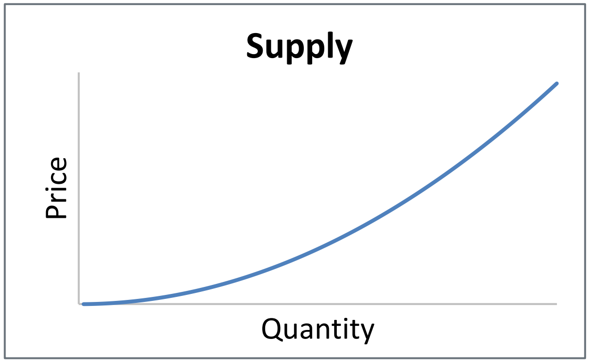
Economic Potential: Definition



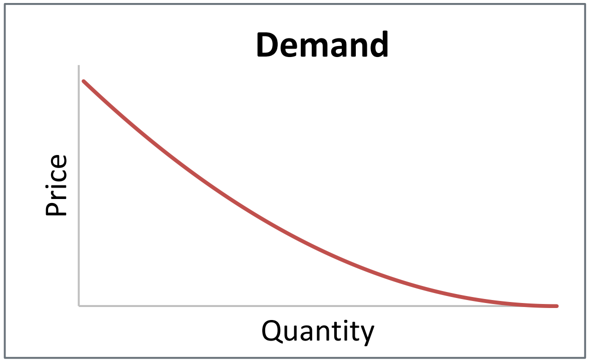
Economic potential is the **subset of the technical potential** where the **cost required** to produce hydrogen **is below** the **revenue available**

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

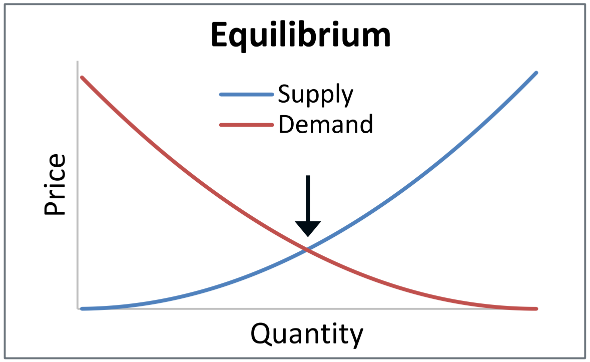
Using National Demand and Supply Curves to Estimate Potential



The relationship between the price of an economic good and the quantity that is **produced**: how much are producers willing and able to produce at a given set of prices?



The relationship between the price of an economic good and the quantity that is **demanded**: how much consumers are willing and able to purchase at a given set of prices?



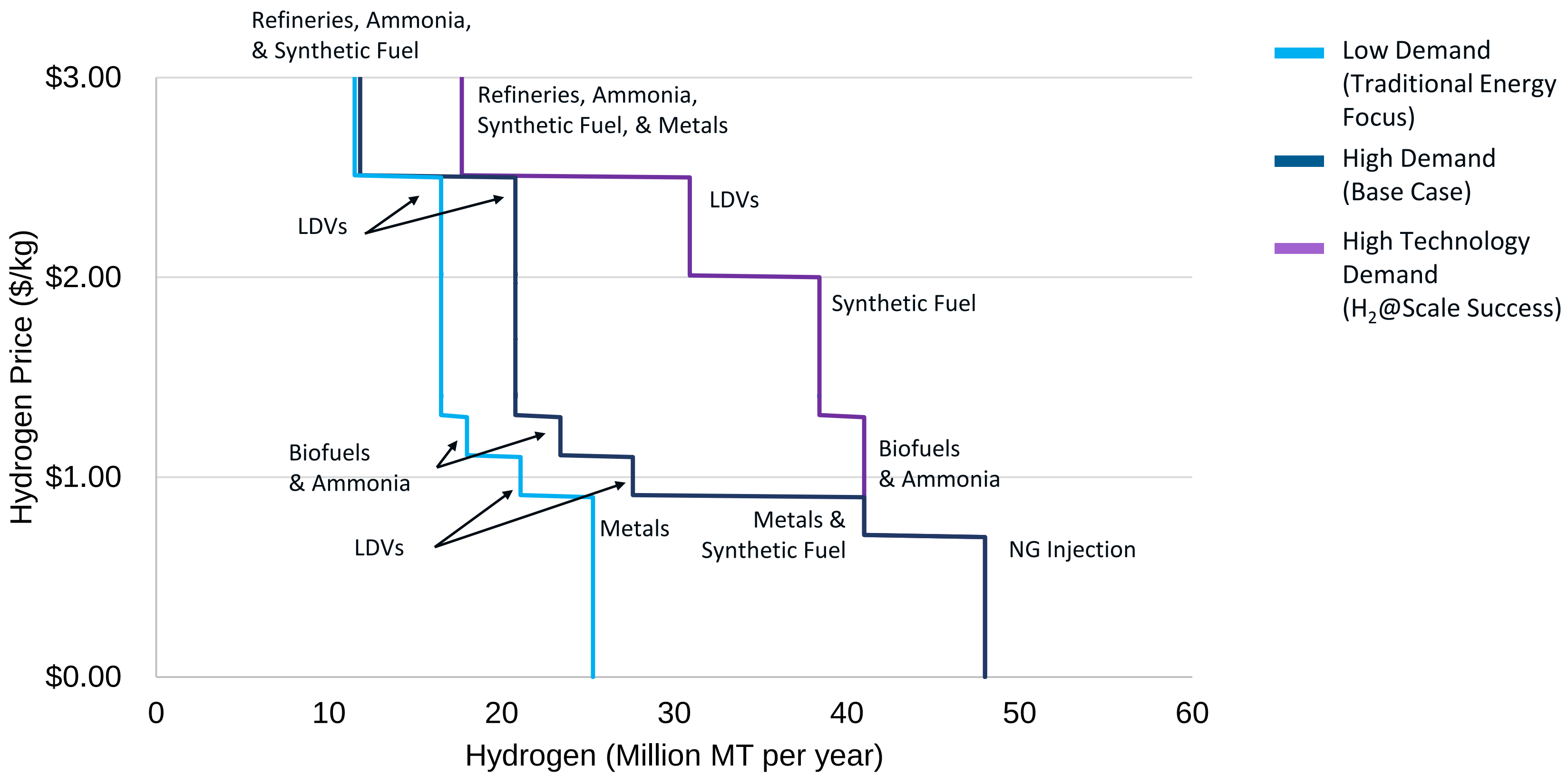
The quantity where the **demand price is equal to the supply price**, which requires that there is no excess supply or demand. The market will push price and quantity to these values.

Schwartz, Robert A. *Micro Markets A Market Structure Approach to Microeconomic Analysis*. Wiley Finance. Chichester: Wiley, 2010.

H_2@Scale Economic Potential Approach

- Develop hydrogen **demand curves** for seven markets
  - Refineries
  - Ammonia
  - Synthetic fuel
  - Light-duty vehicles (LDV)
  - Biofuels
  - Metals
  - Natural gas injection
- Develop hydrogen **supply curves** for three production processes:
  - Low-temperature electrolysis using otherwise-curtailed electricity (OCE)
  - Natural gas steam methane reforming (SMR)
  - Nuclear plants with high-temperature electrolysis (HTE)
- Develop **scenarios** using different combinations of supply and demand curves

Scenario Demand Curves



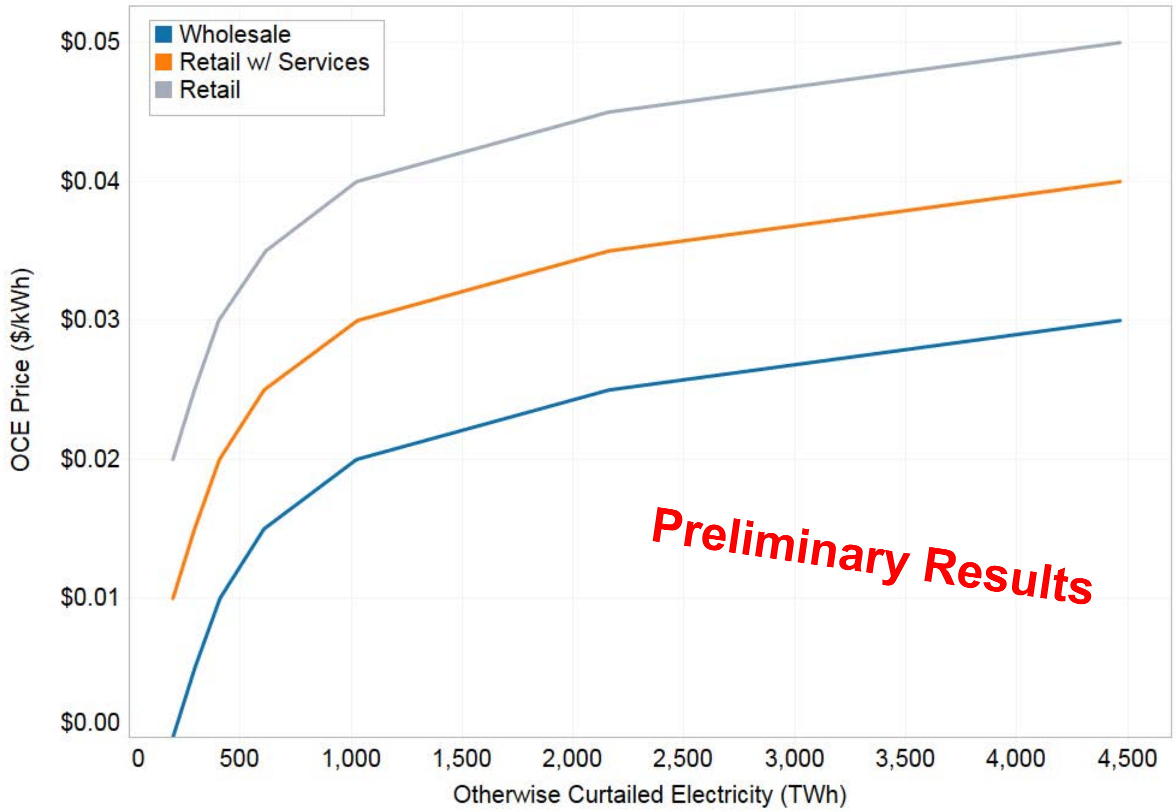
Demand Curve Scenario Assumptions

Demand	Base Case (High)	H_2@Scale Success (High Tech.)	Traditional Energy Focus (Low)
Metals Reshoring	Economically competitive	Willingness to pay for H_2 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

OCE Supply Curve Calculation Methodology

ReEDS Model

- U.S. capacity expansion model
- Competes conventional, renewable, and storage technologies
- Projects capacity, generation, and transmission across 136 balancing areas out to 2050



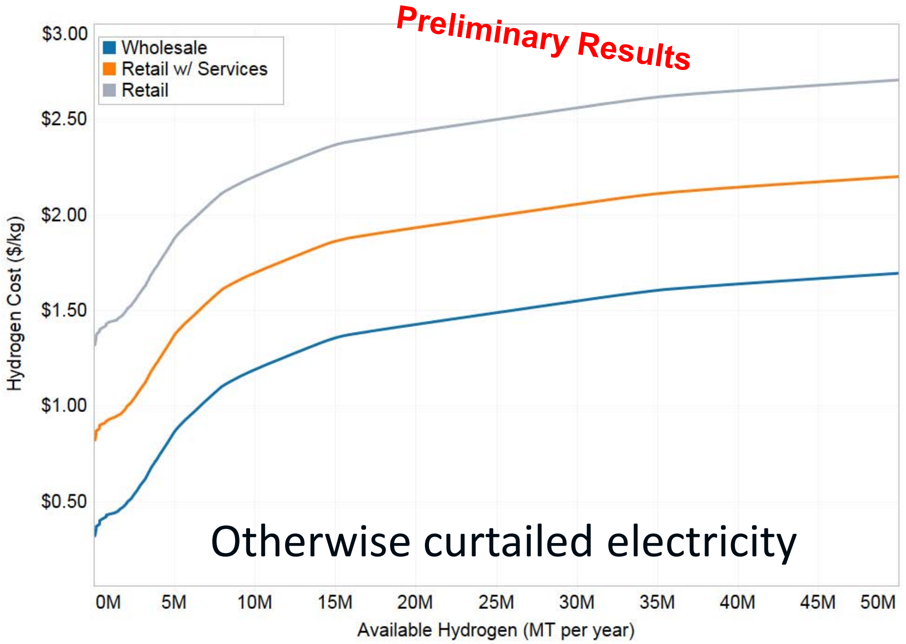
Assumptions

- ReEDS input parameters to achieve high renewable energy penetration
- Higher natural gas prices
- Lower renewable energy technology costs

Supply Curve

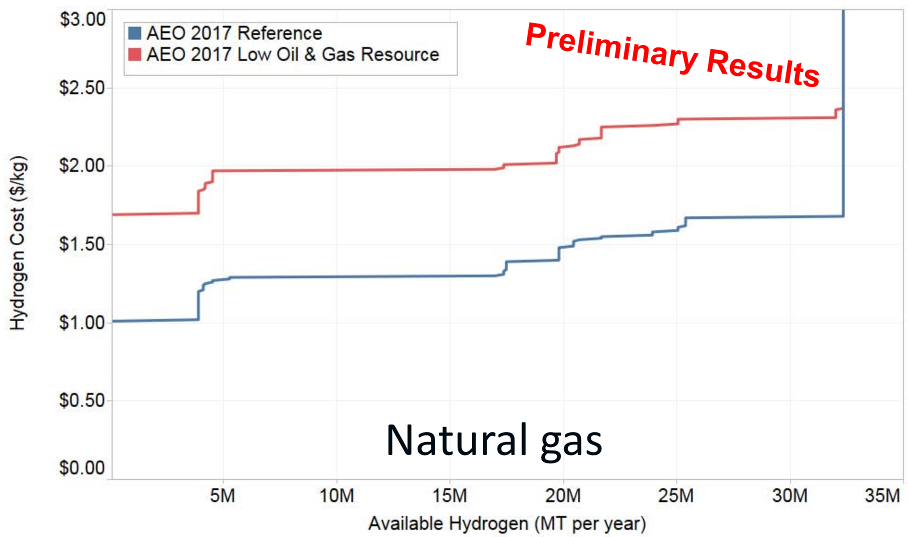
- Curtailed electricity from ReEDS vs. value of otherwise curtailed electricity (OCE)
- H2A model is used to convert this to a low-temperature electrolysis hydrogen supply curve

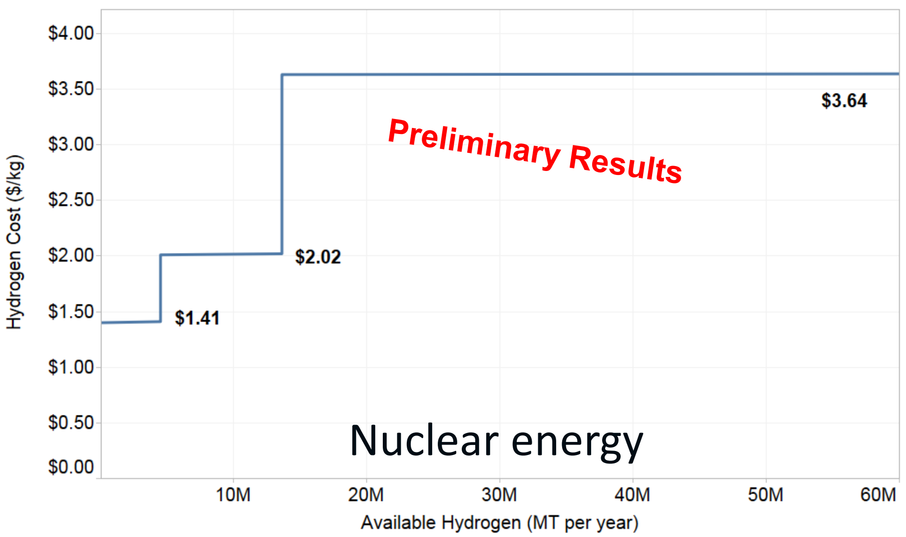
Hydrogen Supply Curves for Three Production Options



Generated supply curves for hydrogen from three sources:

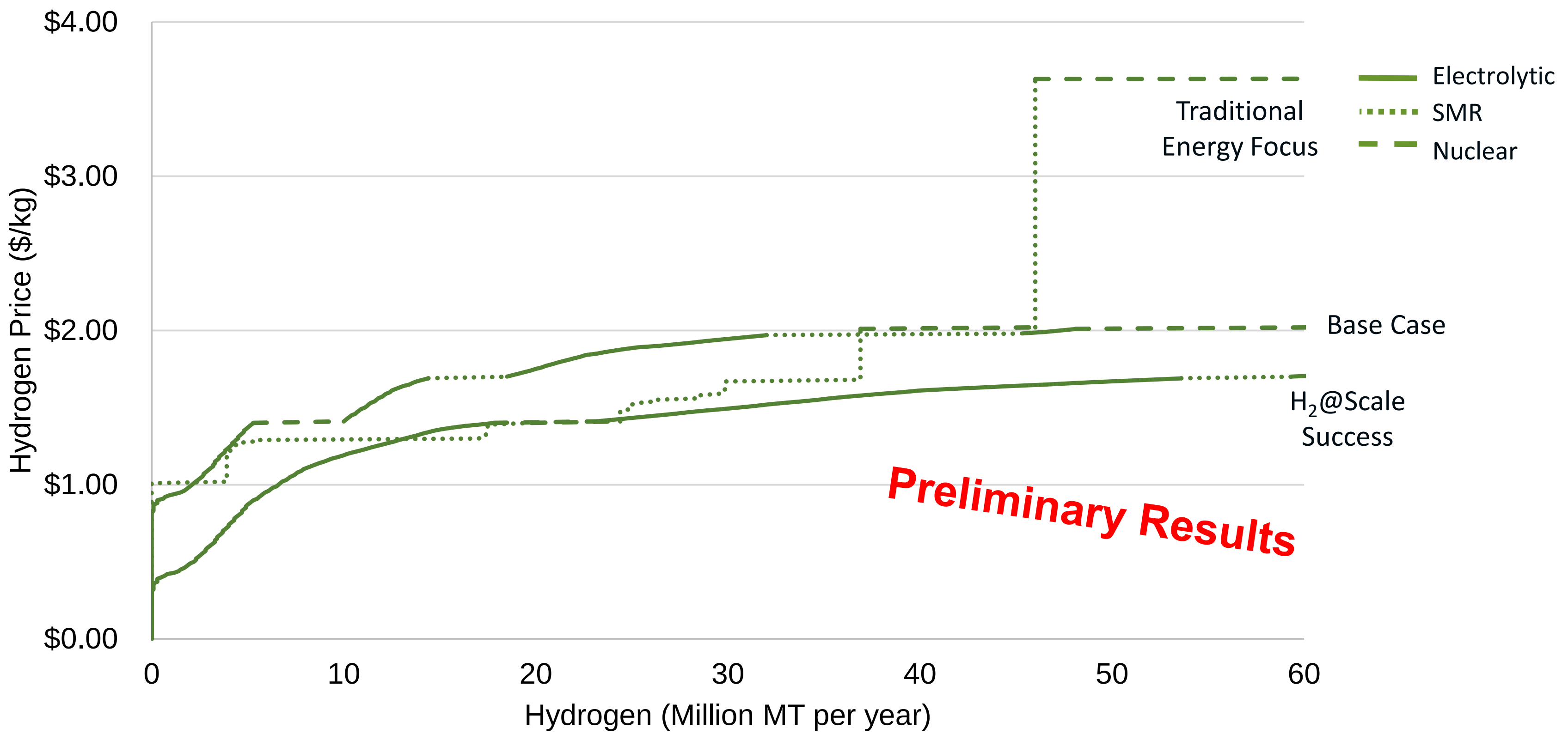
- Otherwise curtailed electricity from ReEDS results
- Natural gas based on current production and future potential (including a capital cost)
- Nuclear energy based on converting 20%-60% of the current nuclear power fleet to hydrogen production





Aggregated Supply Curves

Independent supply curves combined to create three aggregate supply curves

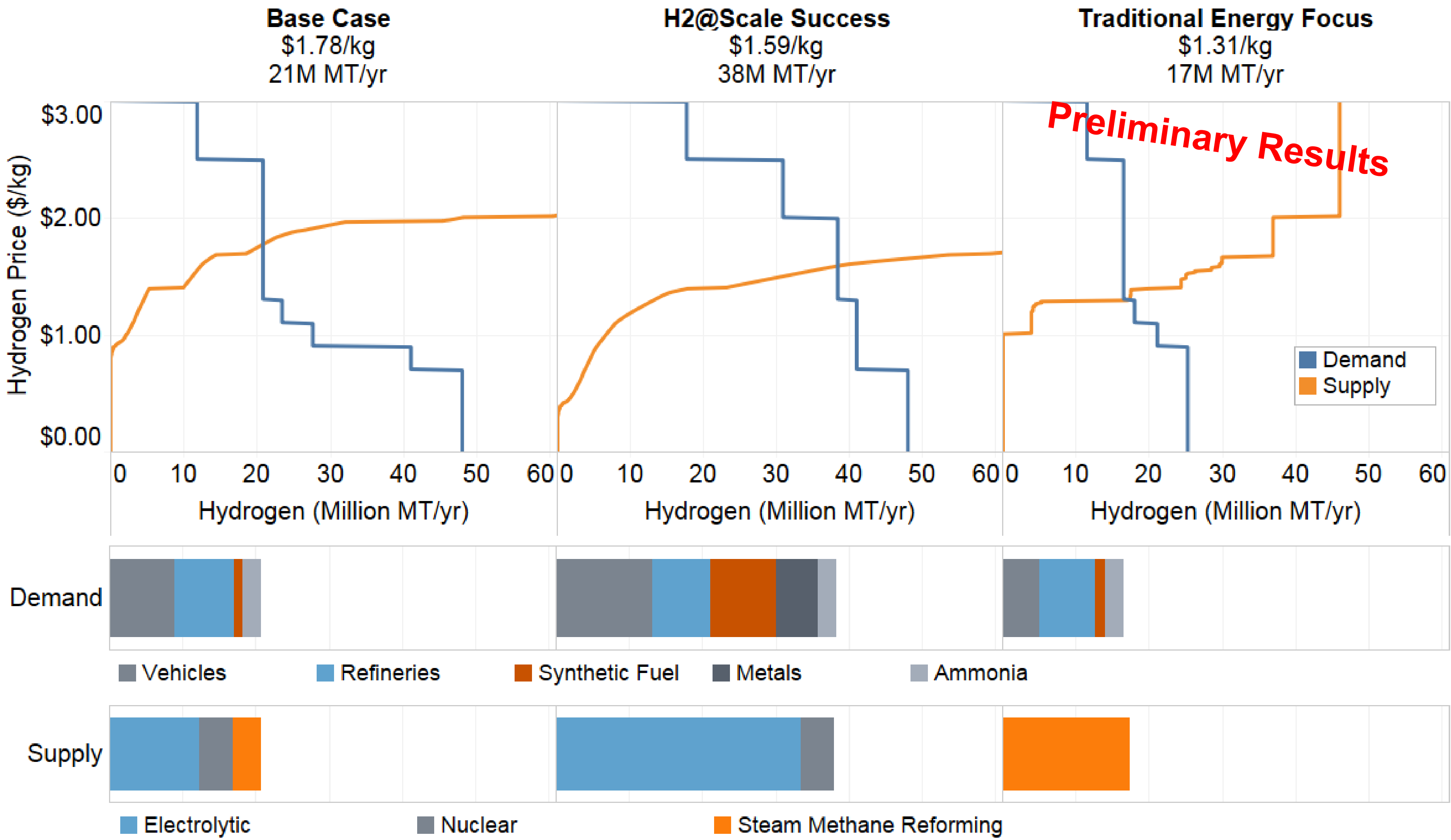


Key Assumptions for Each Case

Generator	Base Case	H_2@Scale Success	Traditional Energy Focus
Electrolytic	Retail w/ services elec. price	Low cost/high availability (Wholesale)	High cost/low availability
Nuclear	20% available at low cost	20% available at low cost	20% available at low cost
SMR	2017 AEO Low Oil & Gas Resource NG prices	2017 AEO Low Oil & Gas Resource NG prices	2017 AEO Reference NG prices

Scenario Summary Chart

Equilibria between supply and demand used to estimate market sizes and prices



Economic Potential: Scenario Summary

Preliminary Results

	Base Case	H_2@Scale Success	Traditional Energy Focus
H_2 Use	21 MMT/yr	38 MMT/yr	17 MMT/yr
H_2 Price	$1.78/kg	$1.59/kg	$1.31/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 (12), • Existing nuclear plants (5), • Existing NG reforming (4)	• Low-temperature electrolysis (33), • Existing nuclear plants (5)	• NG reforming (6 MMT/yr from existing and 11 MMT/yr from new)
Electrolysis	16% curtailment, $18/MWh wholesale price	33% curtailment, $24/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 from Technical and Economic Potential Analysis

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

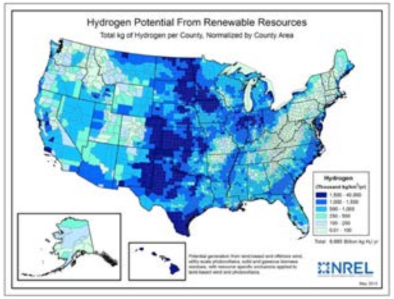
- **Technical potential:**
  60MMT H_2/ yr can reduce emissions by 15%

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

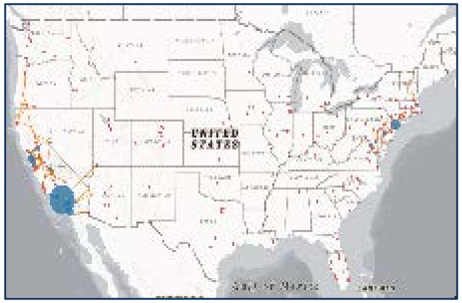
Spatial / Temporal Analysis Initiated

Using the Scenario Evaluation and Regionalization Analysis (SERA) to simulate least-cost hydrogen delivery & storage systems given supply curves, demand locations, and timing

Energy Resources → **Hydrogen Production** → **Storage & Delivery** → **Bulk Scale Demands**

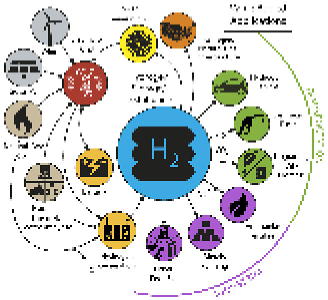


- Prices and availability of multiple resources
- Terrain, available use, etc.



- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs

- Truck delivery, rail, and pipeline with storage
- Tradeoffs (volume, distance) allow networked supply



- Located in 500+ metro areas
- Quantity set by economic potential scenarios

Acknowledgements

- DOE: Fred Joseck, Jason Marcinkoski, Neha Rustagi, Chris Ainscough (on detail)
- NREL: Wesley Cole, Elizabeth Connelly, Josh Eichman, Nicholas Gilroy, Brian Bush, Lori Bird, Bryan Pivovar, Keith Wipke
- ANL: Jeongwoo Han, Amgad Elgowainy
- LBNL: Max Wei
- PNNL: Karen Studarus

Questions

- Can you think of additional demand opportunities we should consider?
- Who might be involved in developing infrastructure necessary for hydrogen to be a key energy carrier?
  - Policy-makers
  - Regulators
  - Supply / demand
  - Project developers
  - Others?
- What are the next steps to implementing H2@Scale?

Supporting Slides

www.nrel.gov

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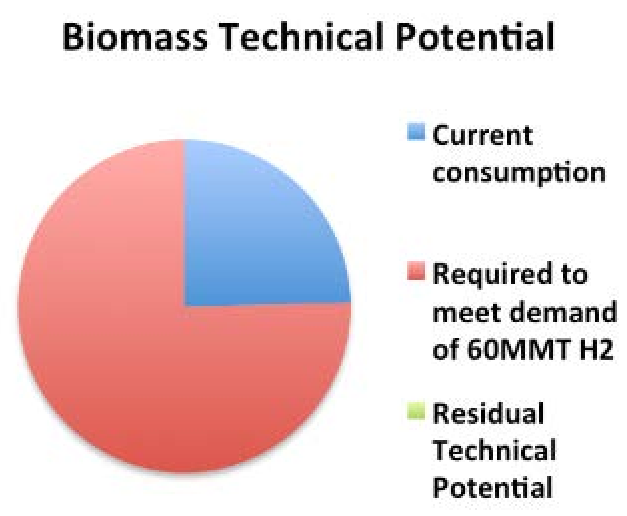
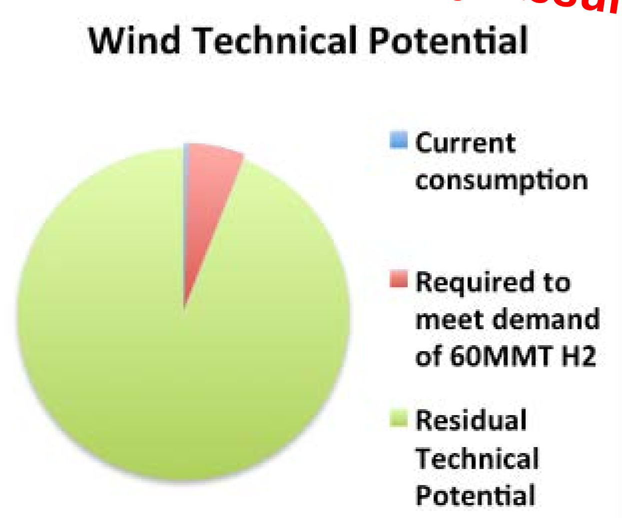
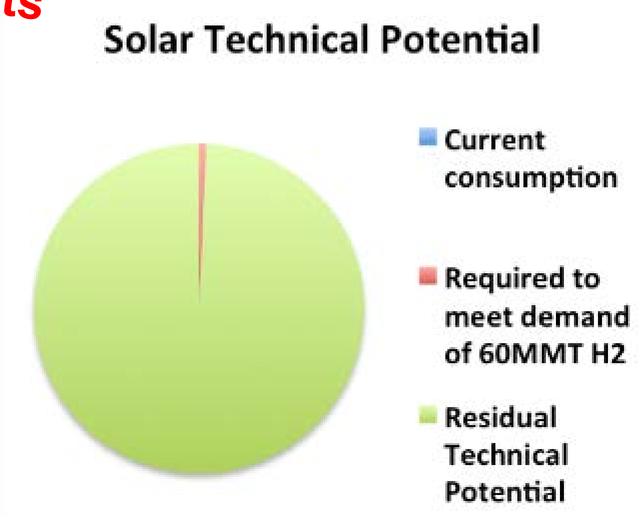
Technical Potential: Impact on Renewable Resources

	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

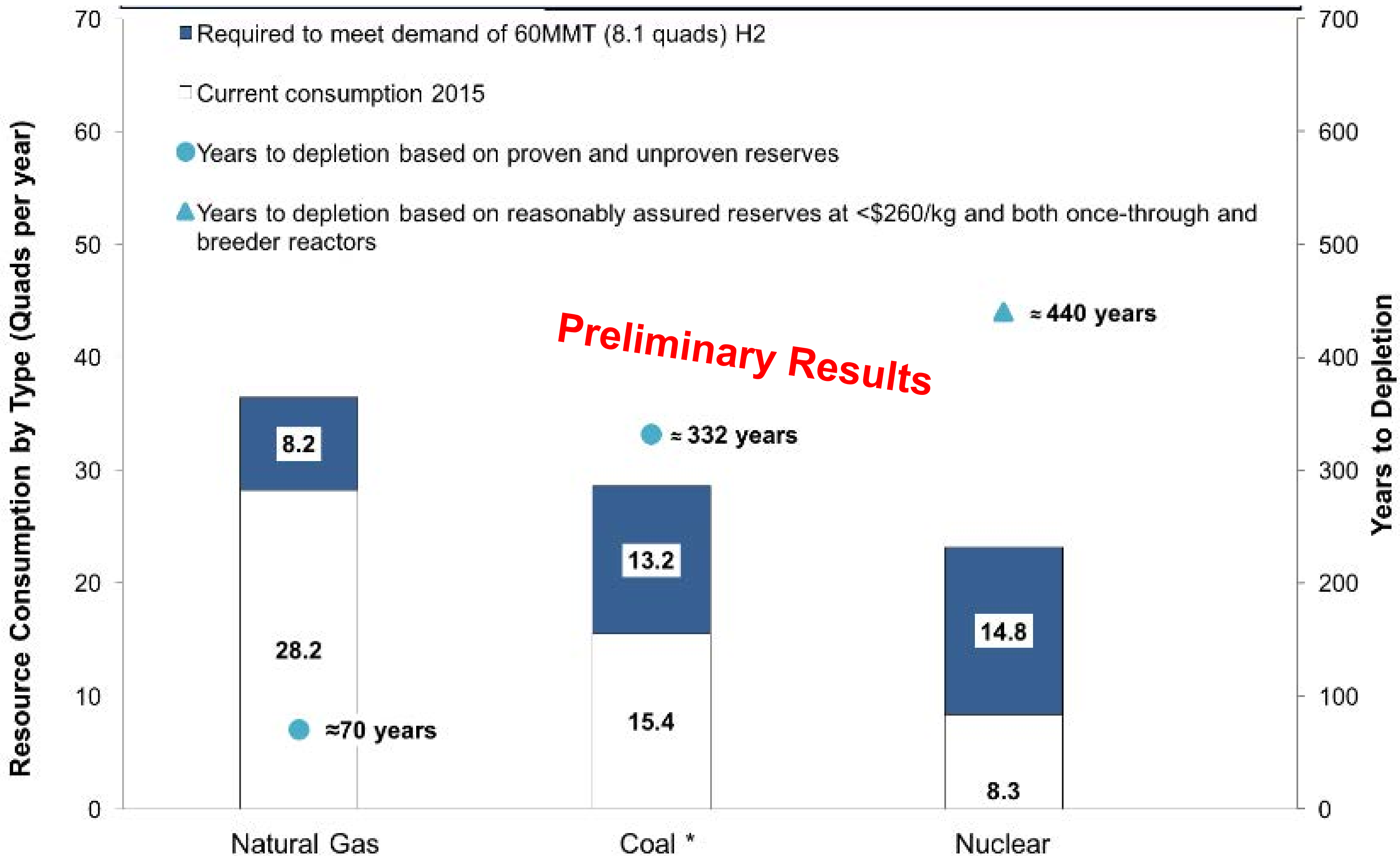






Total demand including hydrogen is satisfied by ≈6% of wind, <1% of solar, and ≈100% of biomass technical potential

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

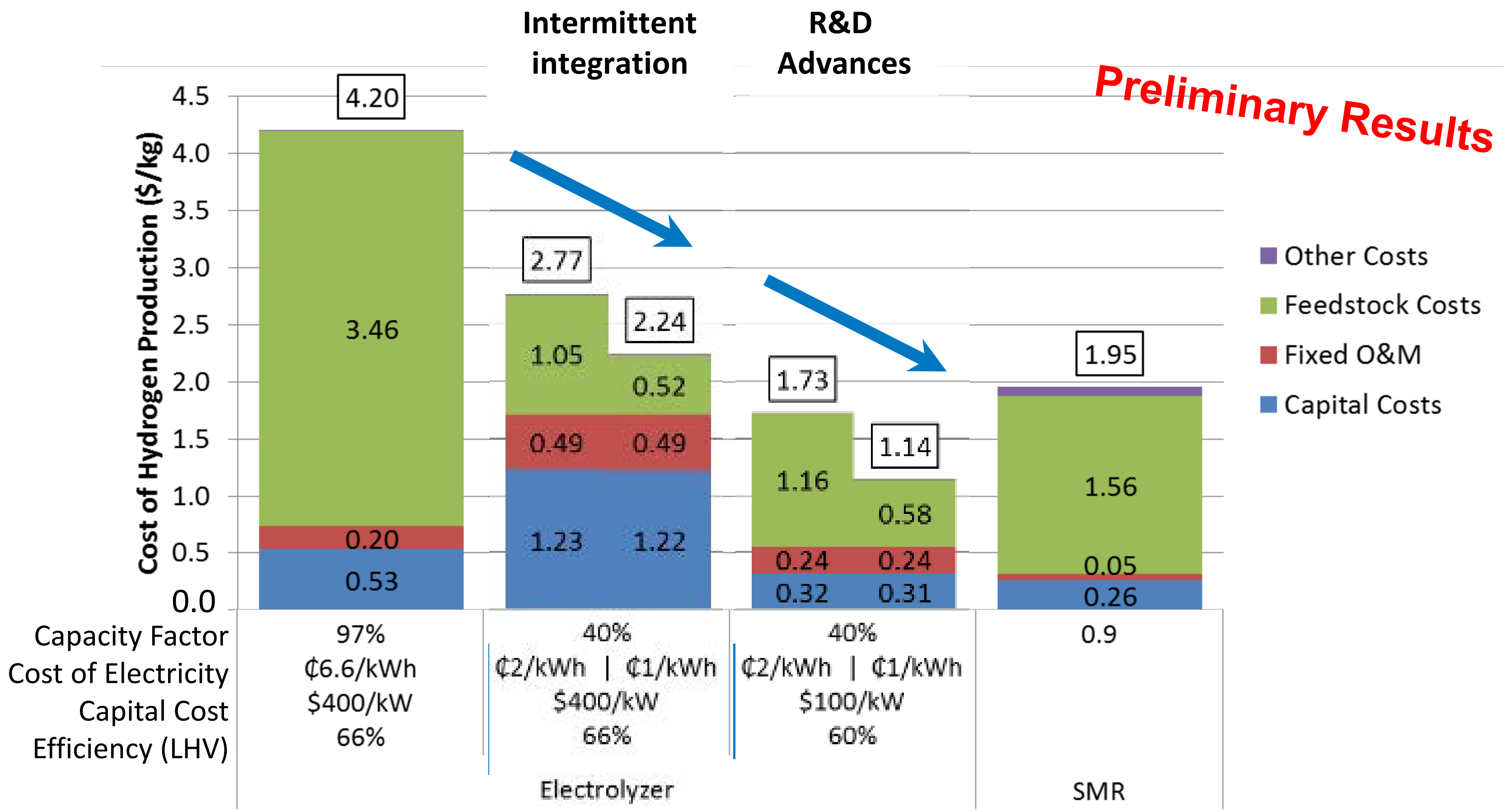
~16% of U.S. energy-related emissions in 2016

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

Improvements Enabling Use of Low-Cost Electricity



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

Remaining Analysis Challenges and Barriers

Technical Potential

- Potential demand
- Supply resources
- Impact potential (limited)
- Infrastructure Issues

Economic Potential

- H_2 price requirements
- Supply options and costs
- Scenarios
- Impact potential

Additional analysis needs

- Spatial issues
- Additional scenarios
- Economic inertia
- Economic externalities

- Regional and spatial issues are being analyzed
- Impacts on economics, resources, and emissions at potential market sizes are not known with high fidelity
- Barriers to market entry and growth are poorly characterized

H2@Scale CRADA Call Selections

First round of Selections Include 25 Applications from:

- Air Liquide
- Aquahydrex
- California Energy Commission
- California Governor's Office of Business and Economic Development
- Connecticut Center for Advanced Technology
- C4-MCP, Inc.
- Electric Power Research Institute
- Exelon
- Frontier Energy
- GinerELX
- GTA, Inc.
- Honda
- HyET
- NanoSonic
- Nikola Motor
- Pacific Gas & Electric
- PDC Machines
- Quong & Asssociates, Inc.
- RIX
- Southern Company
- Tatsuno
- TerraPower

Selections and subsequent working group assignments are subject to negotiation.

H2@Scale Consortium: Structure

U.S. Department of Energy

R&D Priorities

- ***Modeling and analysis*** *to guide R&D;*
- ***Materials compatibility*** *R&D;*
- ***Grid*** *simulation and testing;*
- ***Safety*** *R&D;*
- *Materials and component* ***manufacturing*** *R&D;*
- *Development and use of* ***co-products****;*
- ***Performance verification & demonstration*** *to guide R&D*

Working Groups

1. Hydrogen Quantitative Performance Analysis and Operation R&D
2. Hydrogen Distribution Component Development R&D
3. Advanced Hydrogen Production Concepts R&D
4. Hydrogen Integration with Energy Generation R&D

Manufacturing and U.S. Supply Chain Strategy Development

Funding and Leadership *of CRADA projects* (U.S. Department of Energy → National Labs)

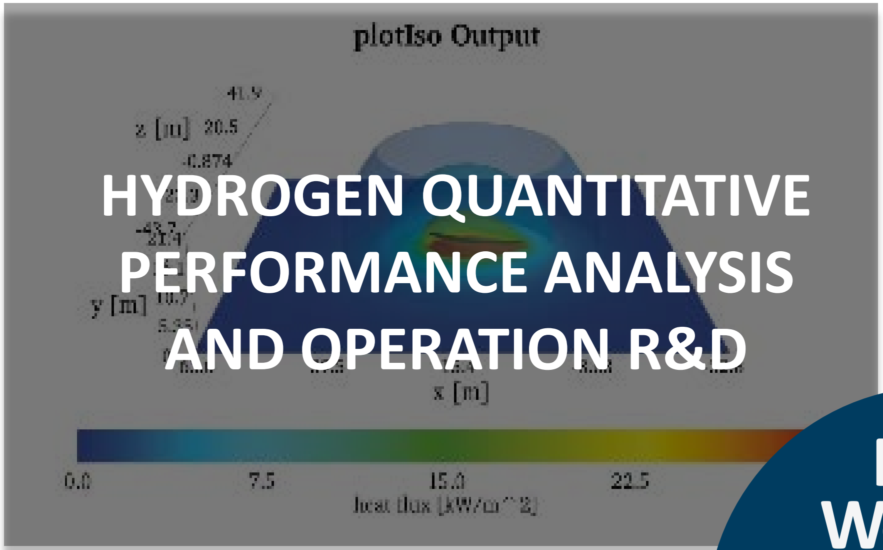
Stakeholders (e.g. industry, academia)

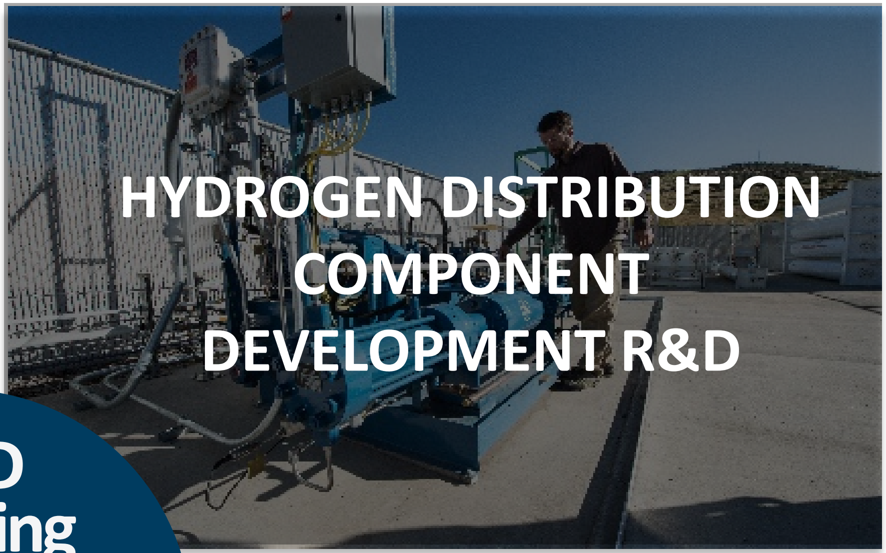
Funding and Leadership *of CRADA projects* (Stakeholders → National Labs)

Execution of CRADA scope of work (National Labs → Stakeholders)

National Labs

H2@Scale R&D Working Groups





R&D Working Groups