

H2@Scale Analysis

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Project ID # sa171

Overview

Timeline and Budget

- Project start date: 10/1/18
 - Follow-on project after completing H2@Scale lab call
- FY19 planned DOE funding: \$350,000
- Total DOE funds received to date: \$350,000

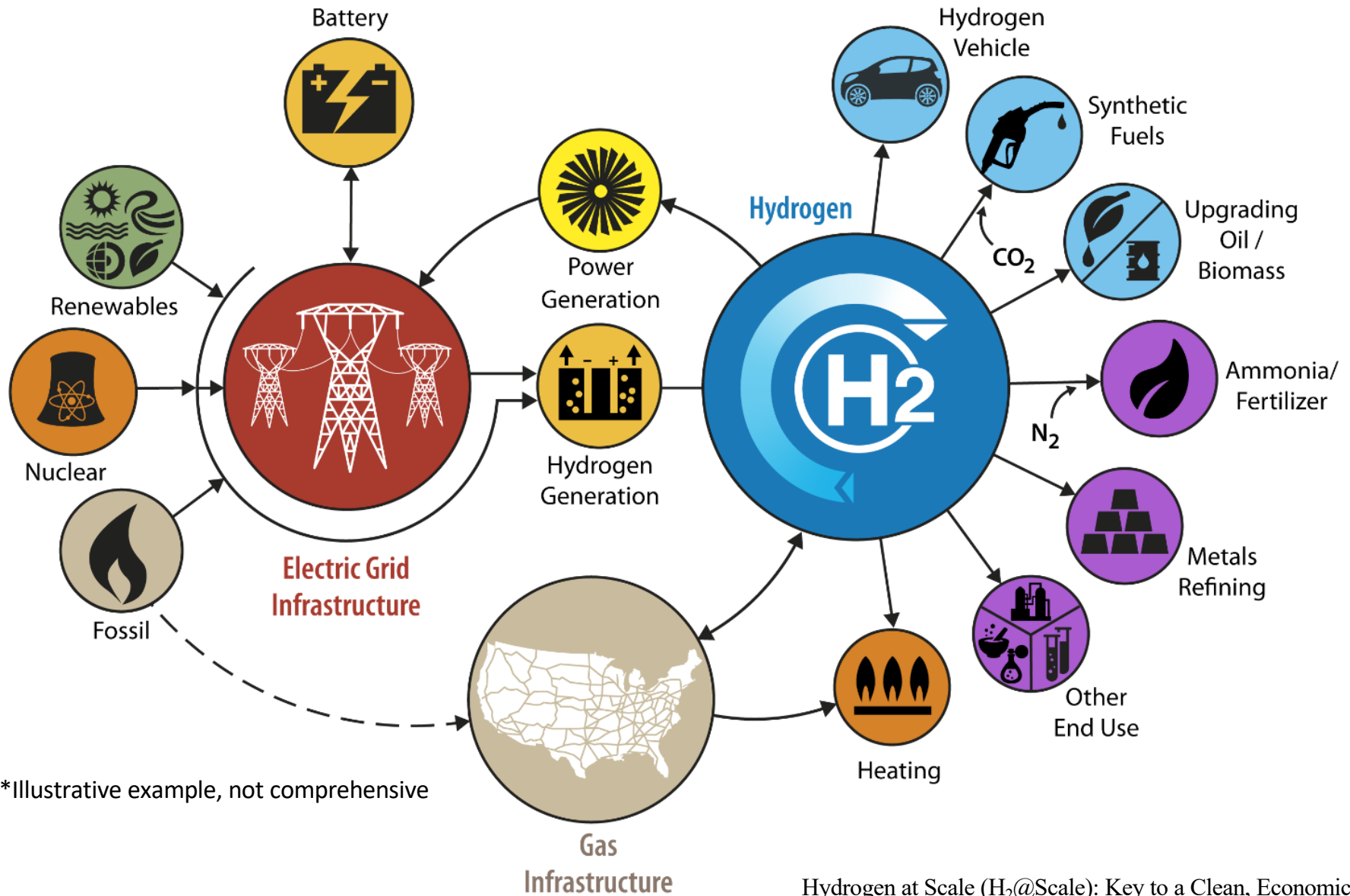
Partners

- Project lead: NREL
- Lab Partners: ANL, LBNL, PNNL, INL, LLNL
- DOE Partners: Nuclear Energy
- Industrial and Academic Reviewers

Barriers (Systems Analysis)

- A: Future Market Behavior
 - Potential market for low value energy and potential hydrogen markets beyond transportation
- D: Insufficient Suite of Models & Tools
 - Tools integrating hydrogen as an energy carrier into the overall energy system and quantifying the value hydrogen provides
- E: Unplanned Studies and Analysis
 - H2@Scale is a new concept and requires analysis of its potential impacts for input in prioritizing research and development

Relevance: H₂@Scale Concept



*Illustrative example, not comprehensive

Hydrogen at Scale (H₂@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

Relevance: Objective

In support of Title VIII of the Energy Policy Act and feedback from the Hydrogen Technical Advisory Committee, the H2@Scale Analysis Objectives are to:

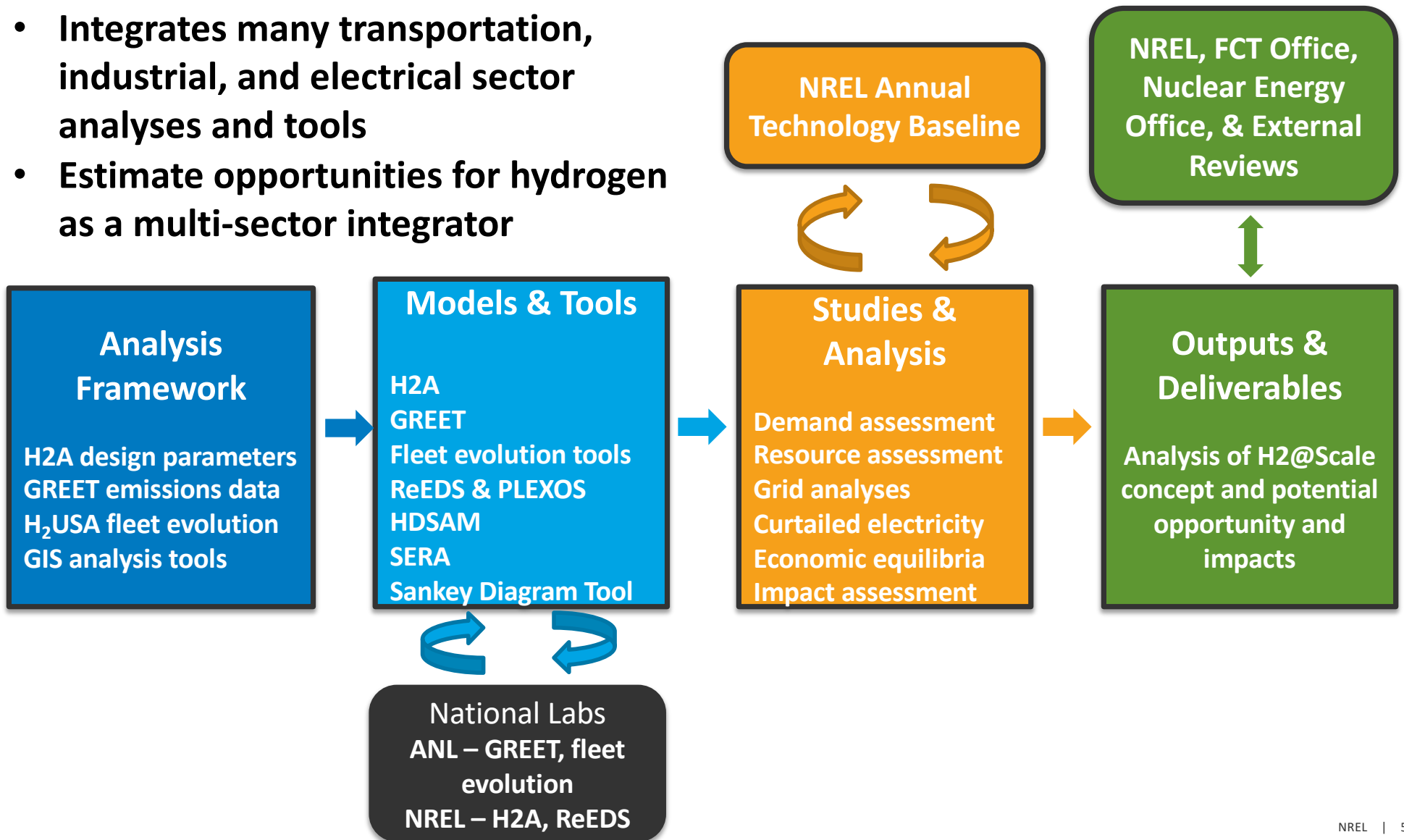
- **Quantify the potential of the H2@Scale vision** for the 48 contiguous states in the U.S.
- **Maximum Market Potential and Resource Technical Potential**
 - The maximum market potential is the estimated market size and resource availability constrained by the services for which society currently uses energy, real-world geography, and system performance, but not by economics
- **Economic Potential**
 - The quantity and price of hydrogen at which suppliers are willing to sell and consumers are willing to buy, assuming various market and technology-advancement scenarios.

Analysis results will help prioritize the initiative's early-stage research & development

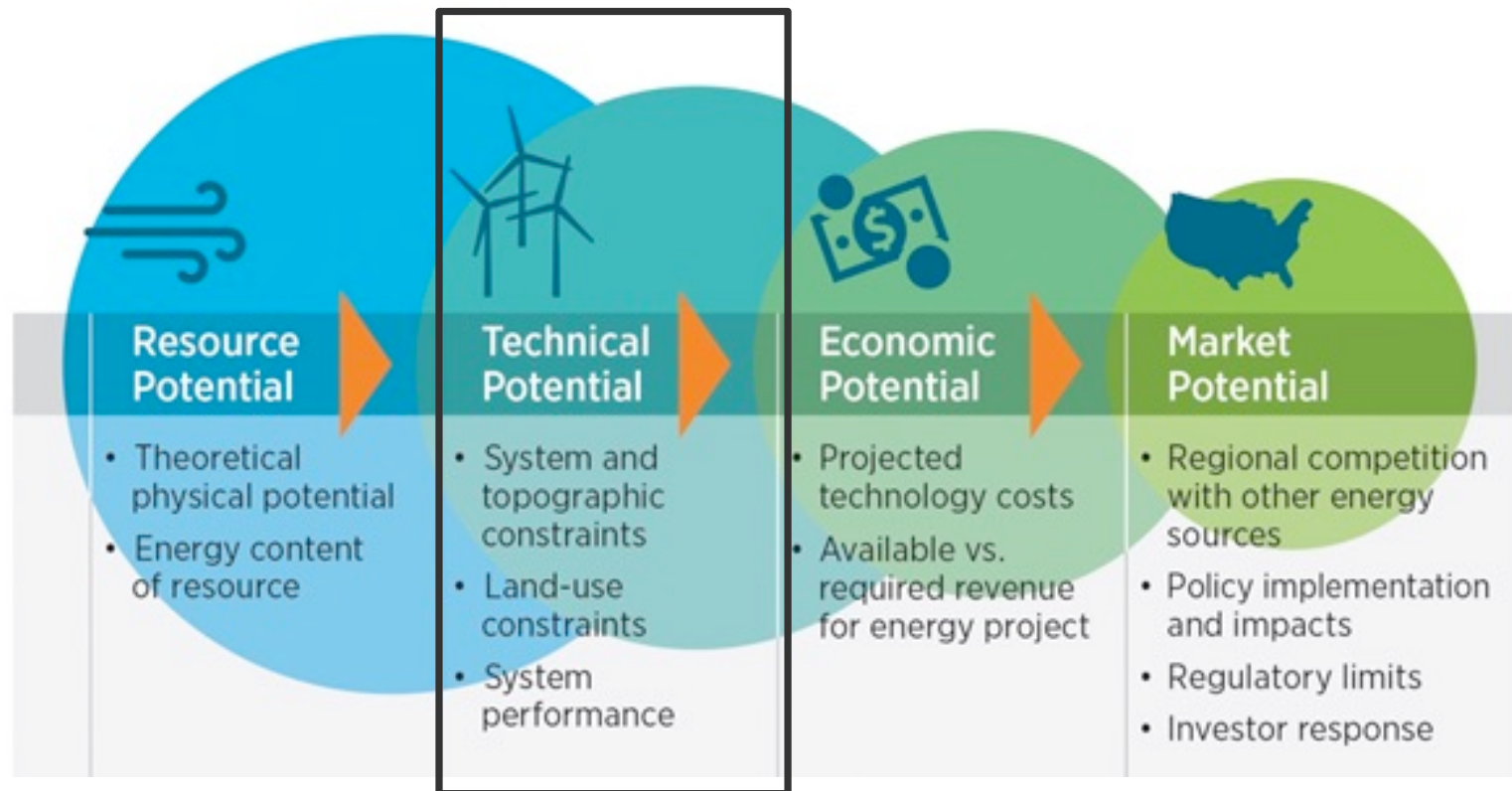
Approach: FCTO and Systems Analysis Framework

H2@Scale Analysis

- Integrates many transportation, industrial, and electrical sector analyses and tools
- Estimate opportunities for hydrogen as a multi-sector integrator



Approach: Maximum Market Potential & Resource Technical Potential

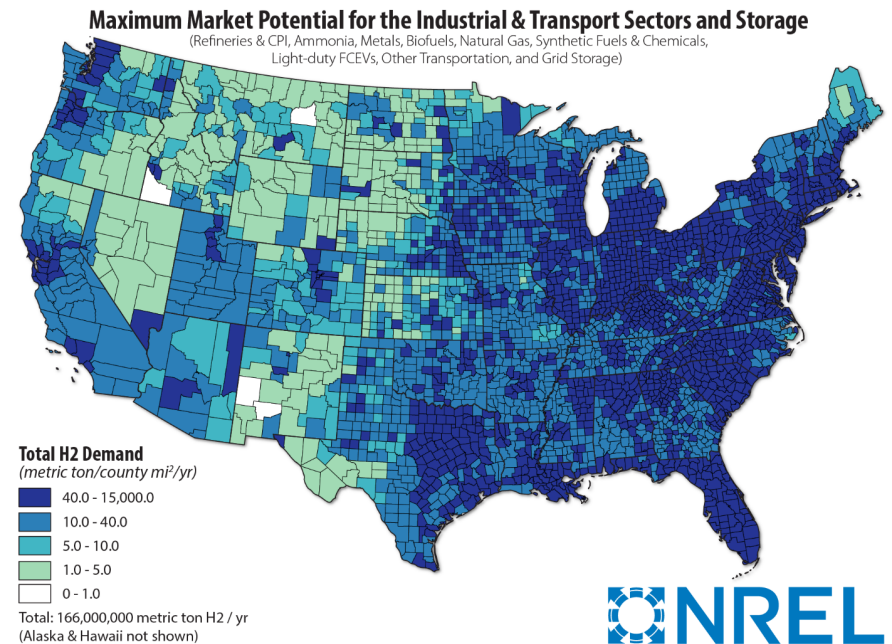


Maximum Market Potential – For possible hydrogen markets, estimate the quantity of hydrogen necessary to provide all the services within the market (i.e., without competing options)

Resource Technical potential – Constrained by existing end-uses, real-world geography, and system performance. *Not by economics.*

Accomplishments: Improved Estimates of Maximum Market Potential

Application	Maximum Market Potential (MMT/yr)
Refineries and the chemical processing industry (CPI) ^a	8
Metals	12
Ammonia	4
Biofuels	4
Synthetic Fuels and Chemicals	14
Natural Gas Supplementation	10
Light-duty Fuel Cell Electric Vehicles (FCEVs)	57
Other Transportation (Medium- & Heavy-Duty)	29
Seasonal Energy Storage for the Electricity Grid	28
Total	166

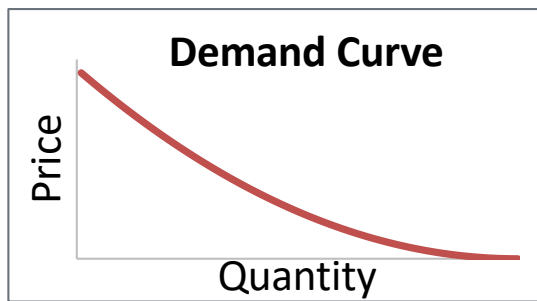


Maximum growth potential of hydrogen market by 2050 is 16X.

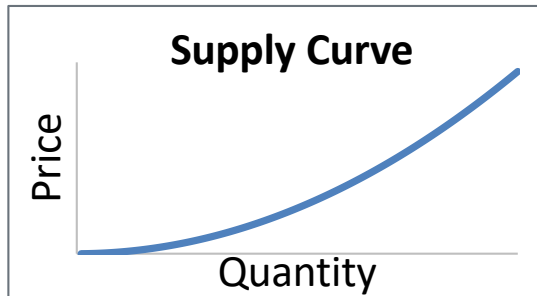
Definition: The maximum market potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, and system performance, but not by economics.

Approach: Economic Potential

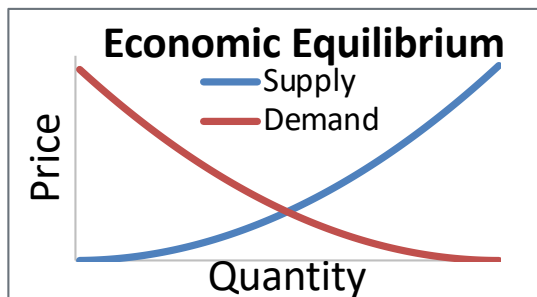
Develop national supply and demand curves for hydrogen and use them to estimate market size and composition



Demand Curve: The quantity that users will purchase across a range of threshold prices.



Supply Curve: The quantity that producers will produce across a range of production costs.



Economic Equilibrium: Quantity where demand price is equal to the supply price.

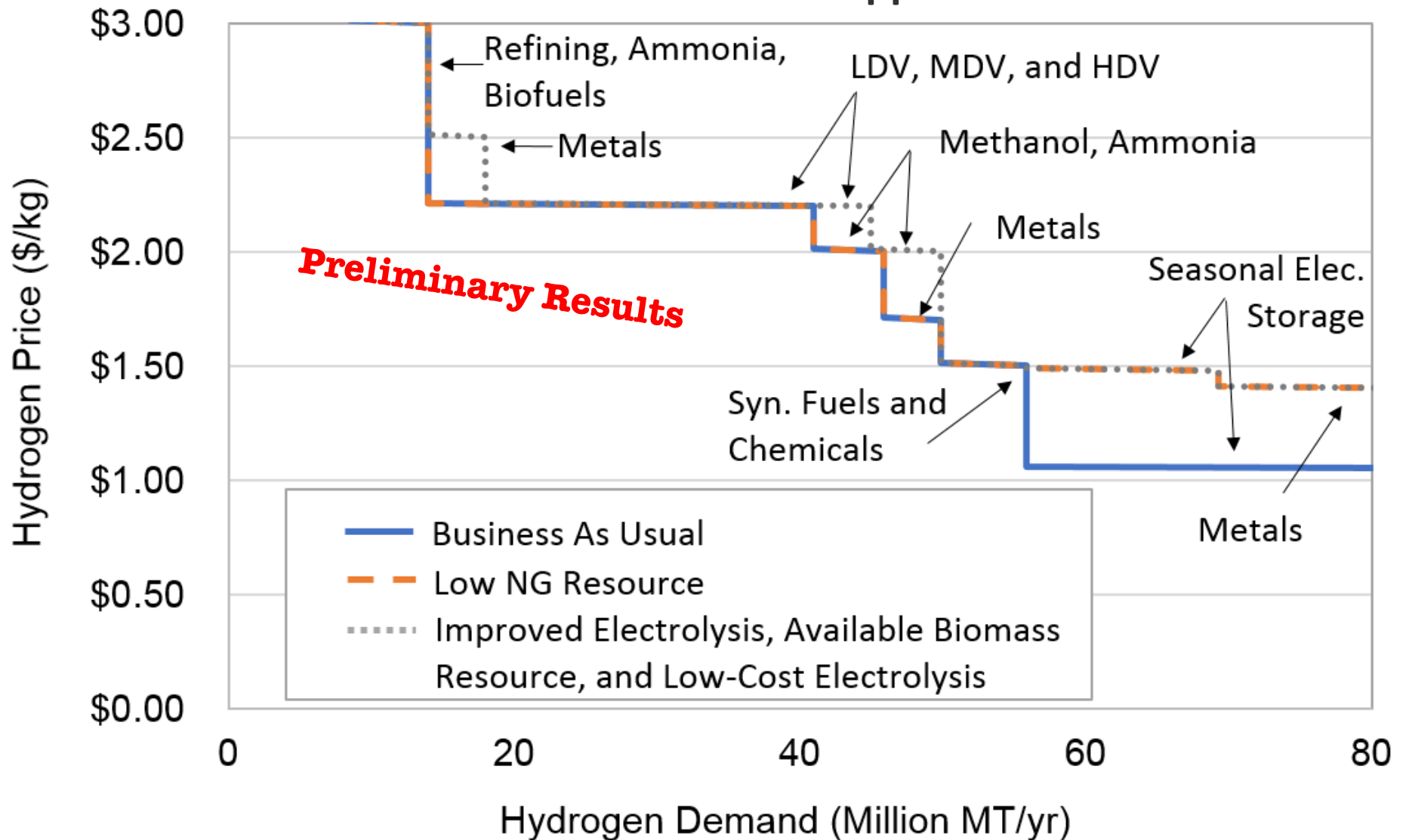
- No excess supply or demand.
- Market pushes price and quantity to equilibrium.

Approach for Economic Potential: Five National Scenarios

Scenario Name	Business as Usual	Low NG Resource	Improved Electrolysis	Available Biomass Resource	Low-Cost Electrolysis
Natural gas price assumption	AEO 2017 Reference scenario	AEO 2017 Low Oil and Gas Resource and Technology scenario			
Availability of Steam Methane Reforming facilities	Hydrogen generation from SMRs for non-ammonia production is capped at three times current levels (23 MMT/yr)				
Nuclear hydrogen	Hydrogen generation from SMRs estimated for future ammonia production is capped at 5 MMT hydrogen/yr				
Low-Temp. Electrolysis capital costs	20% of current nuclear fleet available at \$25/MWh _e equivalent				
Otherwise-curtailed electricity market assumption	\$400/kW		\$200/kW		\$100/kW
Biomass	Available at retail price		Between retail and wholesale		Wholesale price
Metals demand	Not available		Available		Not Available
	Must compete with existing technologies		Markets are willing to pay a premium for metals refined using hydrogen		

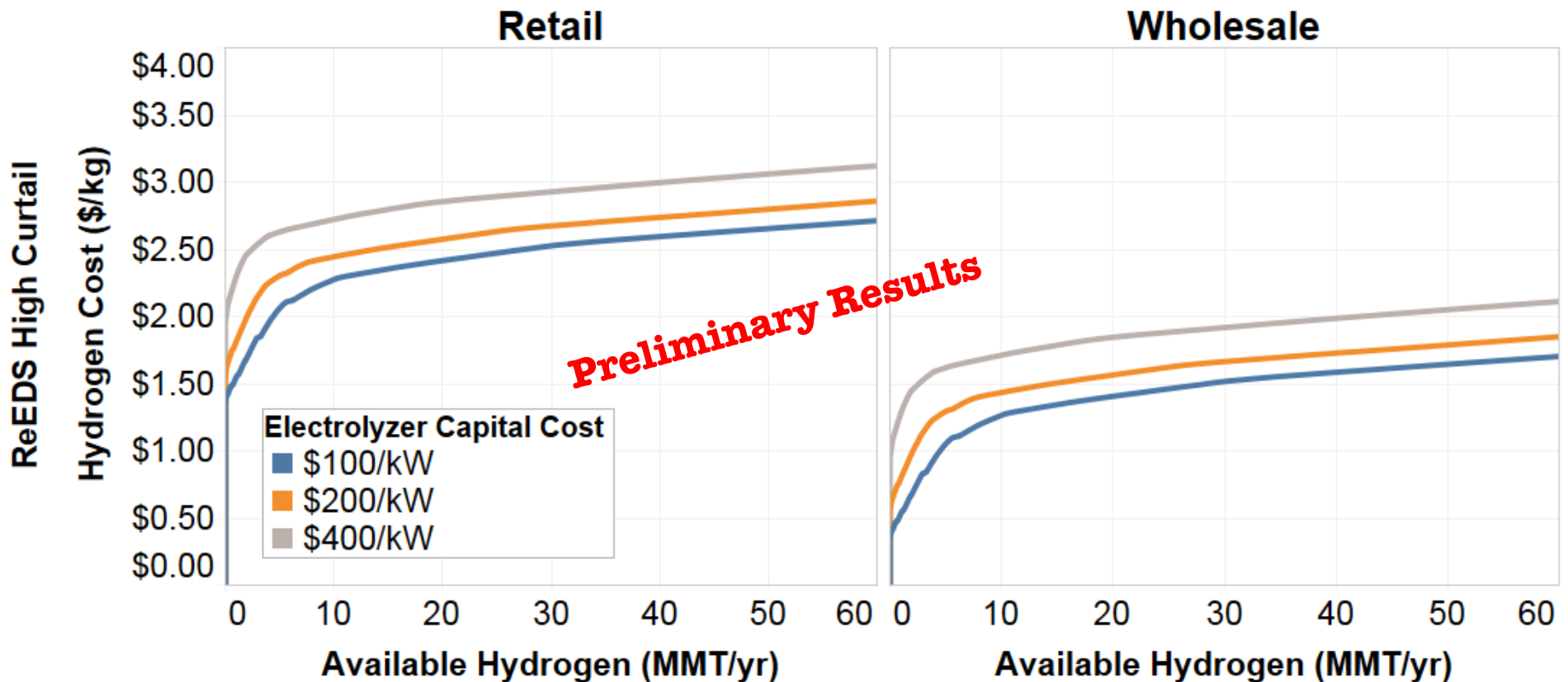
Accomplishment: Aggregated Demand Curves Across End Uses

- Validated and improved estimates of threshold price / market size combinations for each application



Accomplishment: Supply Curves Using Otherwise Curtailed Electricity (OCE)

- Used ReEDS capacity expansion model to estimate generator fleet and generation mix at multiple OCE values
- Improved supply curves for low temperature electrolysis-generated hydrogen using the PLEXOS dispatch model to estimate price/availability combinations

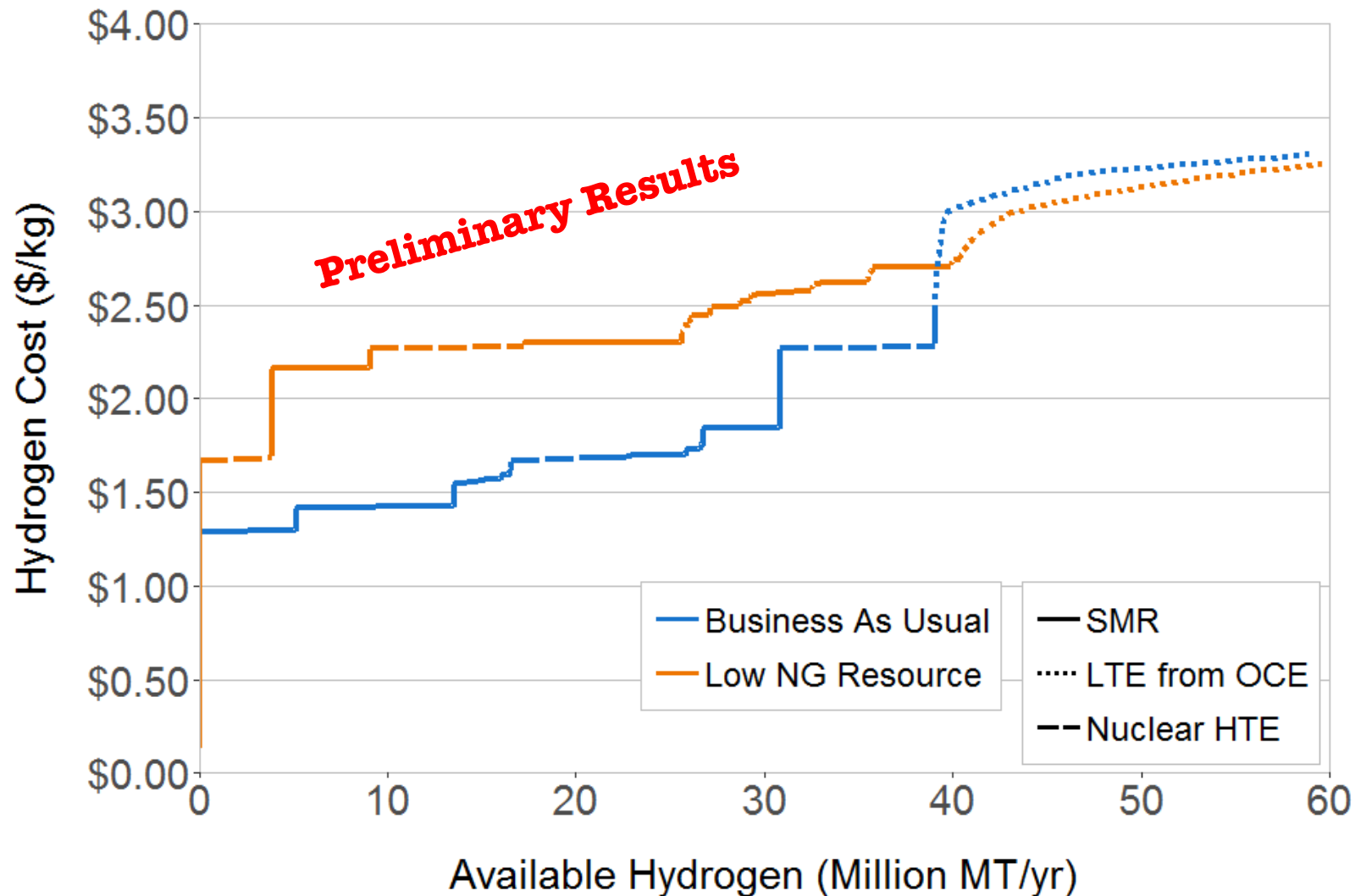


Transaction Cost Assumption: \$20/MWh

\$0/MWh

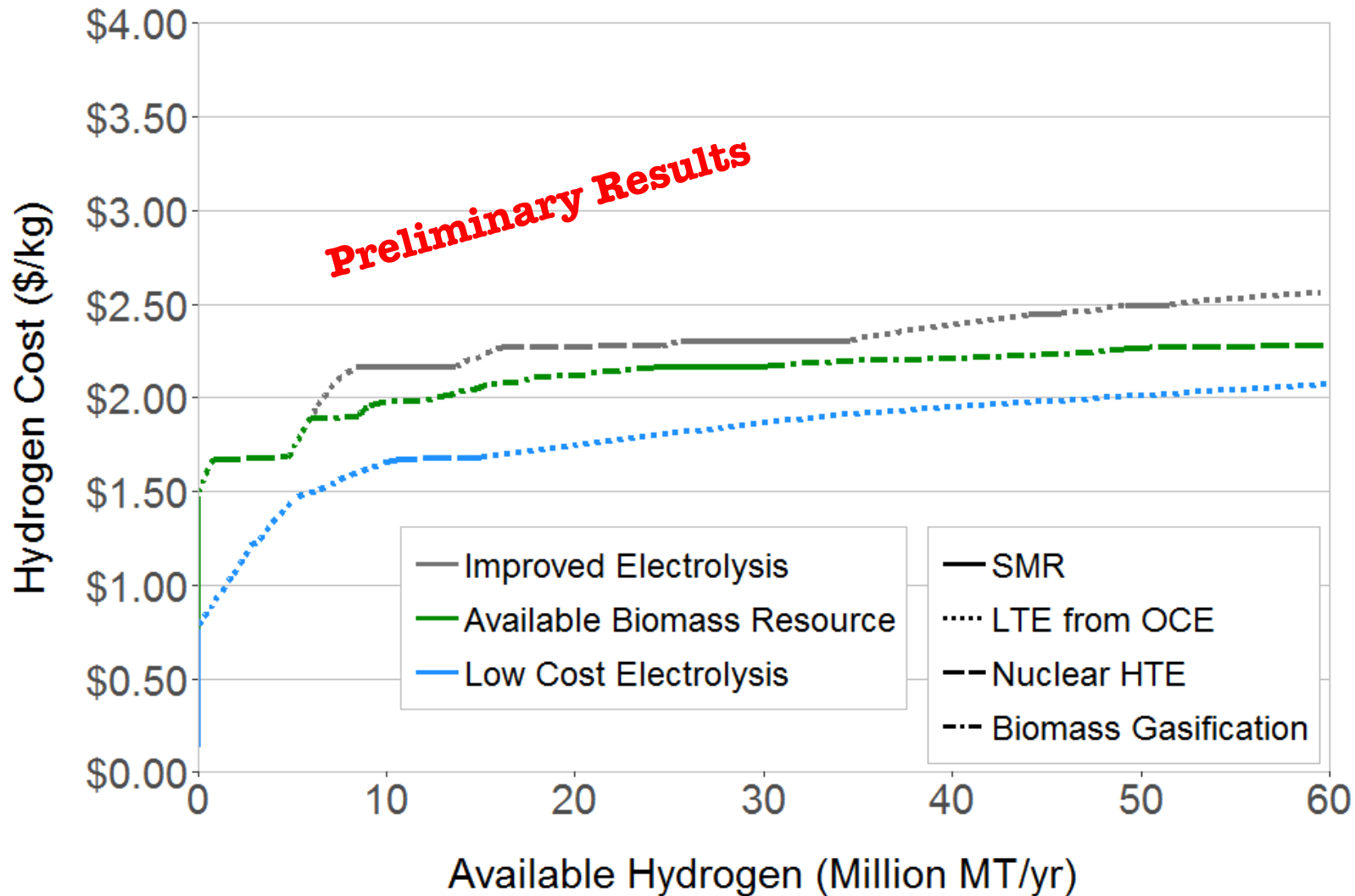
Accomplishment: Aggregated Supply Curves Across Production Options

Based on estimates of levelized production cost / supply availability combinations for each production option



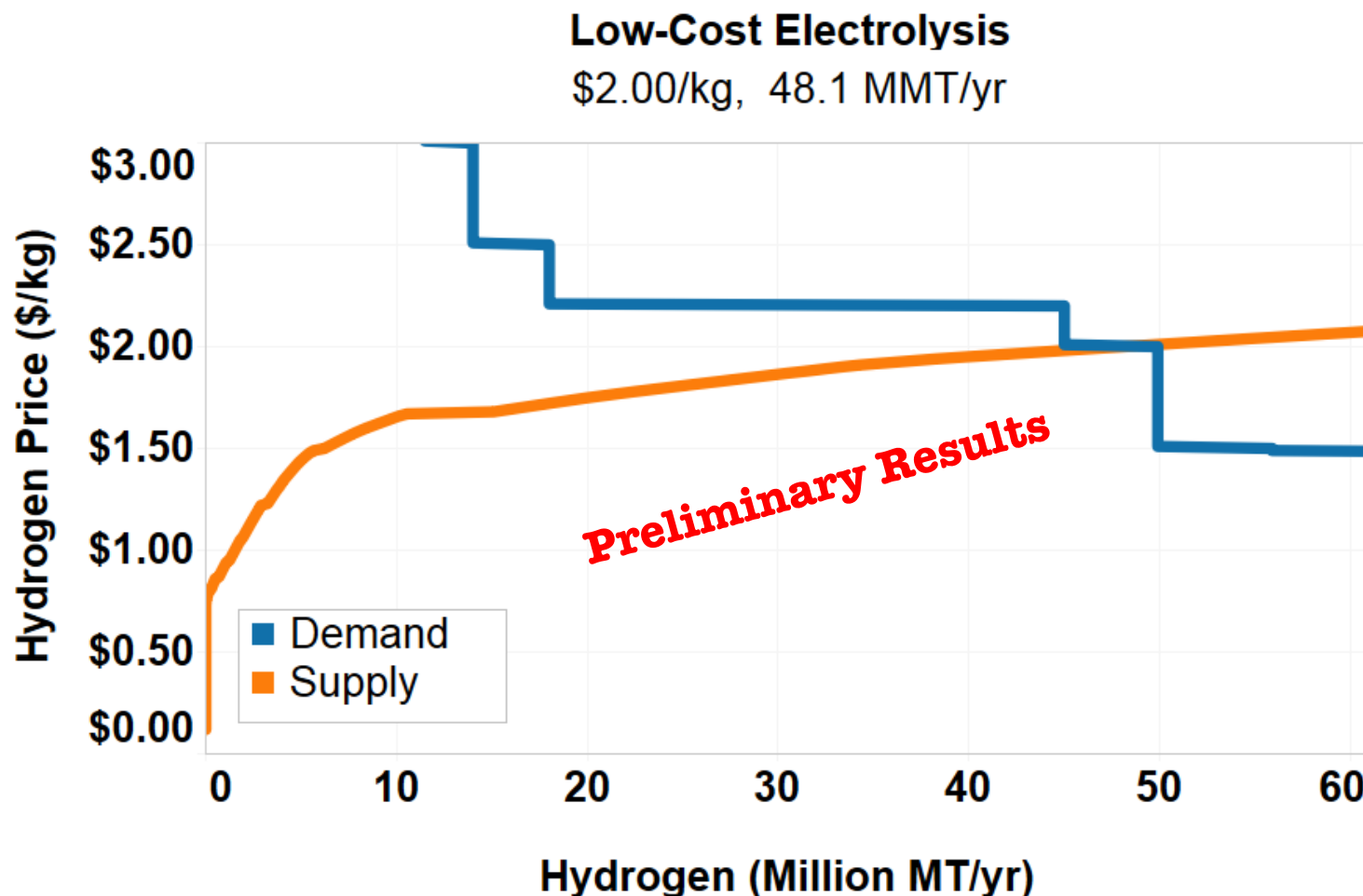
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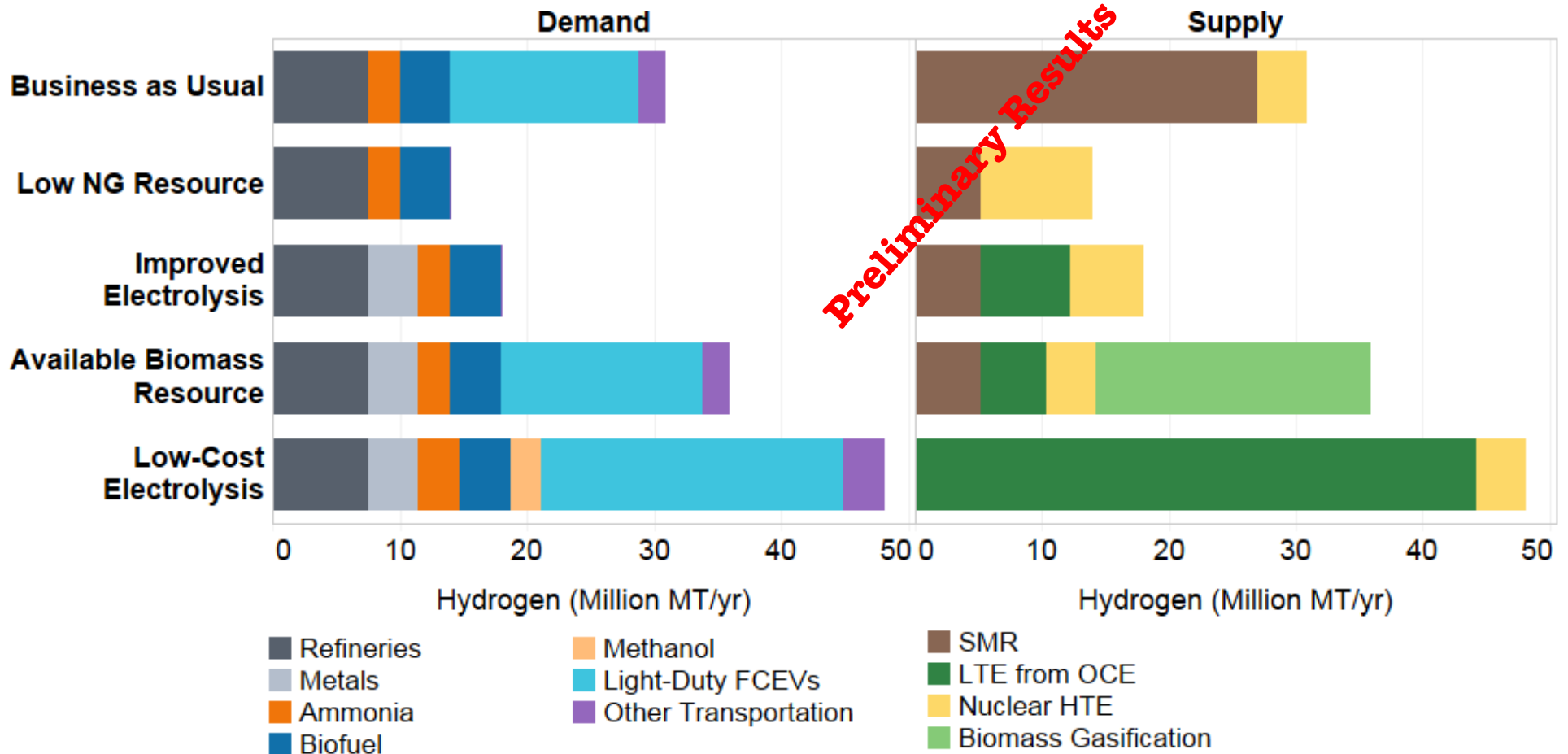


Accomplishment: Identified Market Prices and Equilibrium for Each Scenario

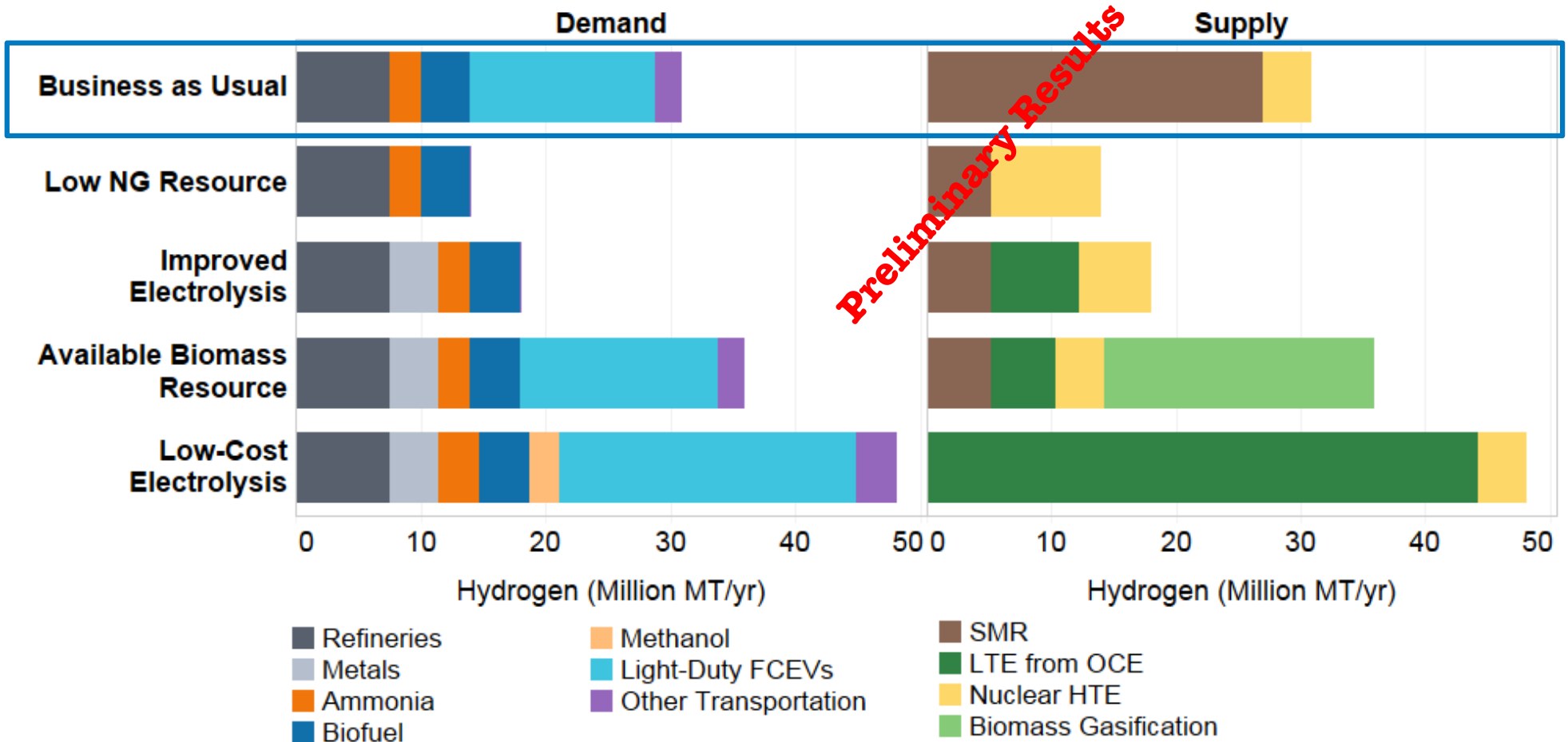
The intersection of the supply and demand curves indicate the market size and price at equilibrium. Low-cost electrolysis scenario shown



Accomplishment: Developed and Reviewed Economic Potential Results



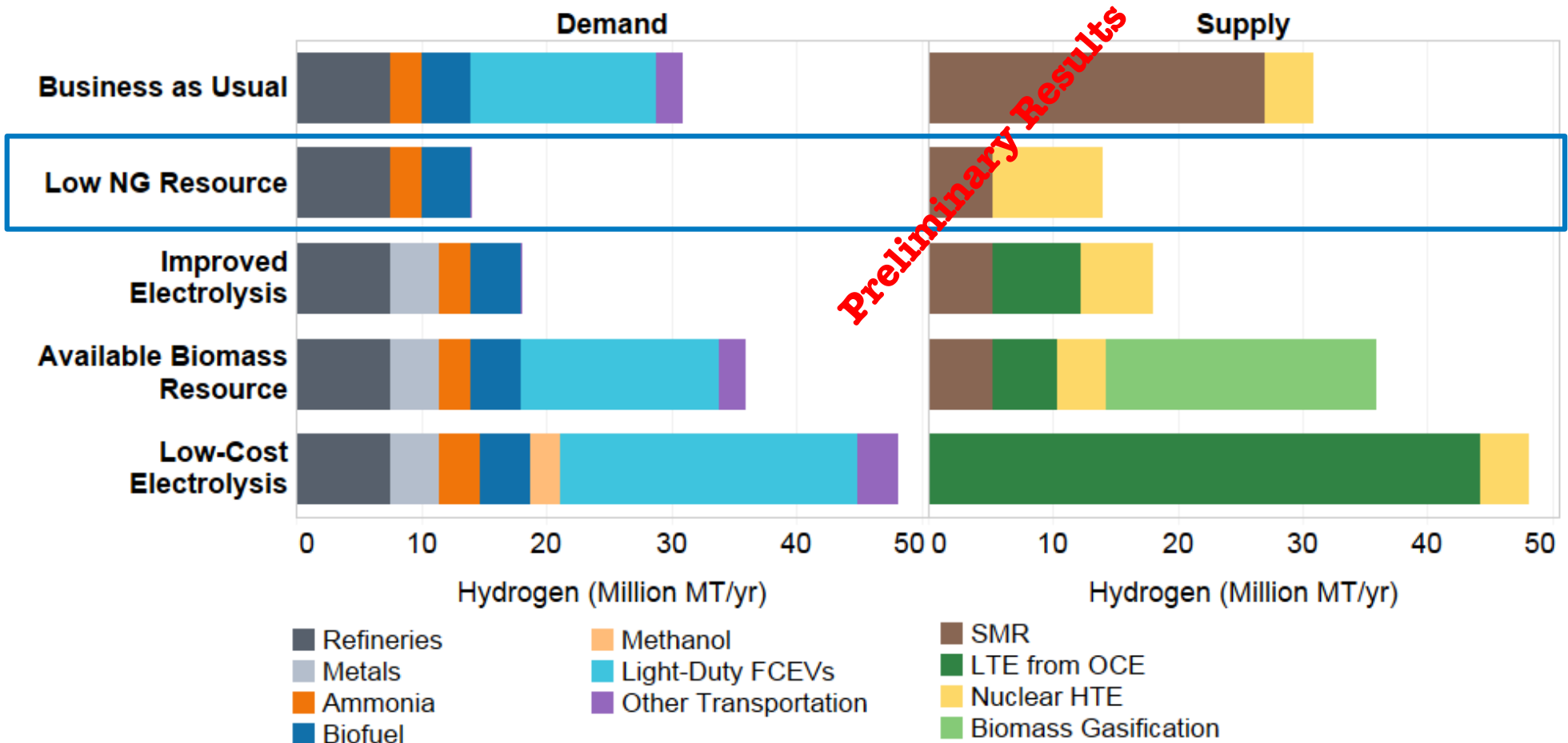
Accomplishment: Developed and Reviewed Economic Potential Results



Business as Usual Scenario

Low-cost natural gas drives growth in H₂ markets with some nuclear participation

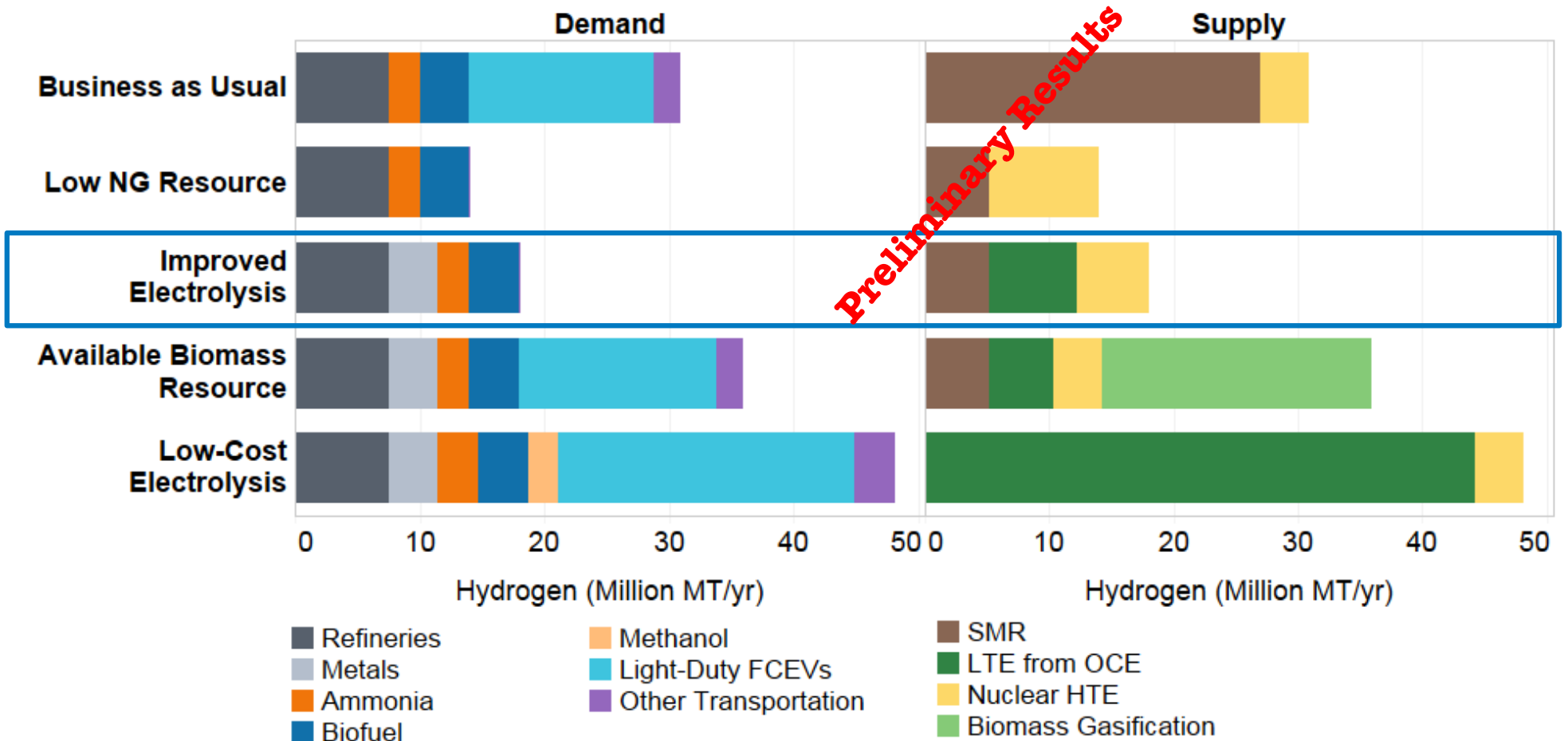
Accomplishment: Developed and Reviewed Economic Potential Results



Low NG Resources Scenario

Higher cost natural gas results in minimal growth in hydrogen applications

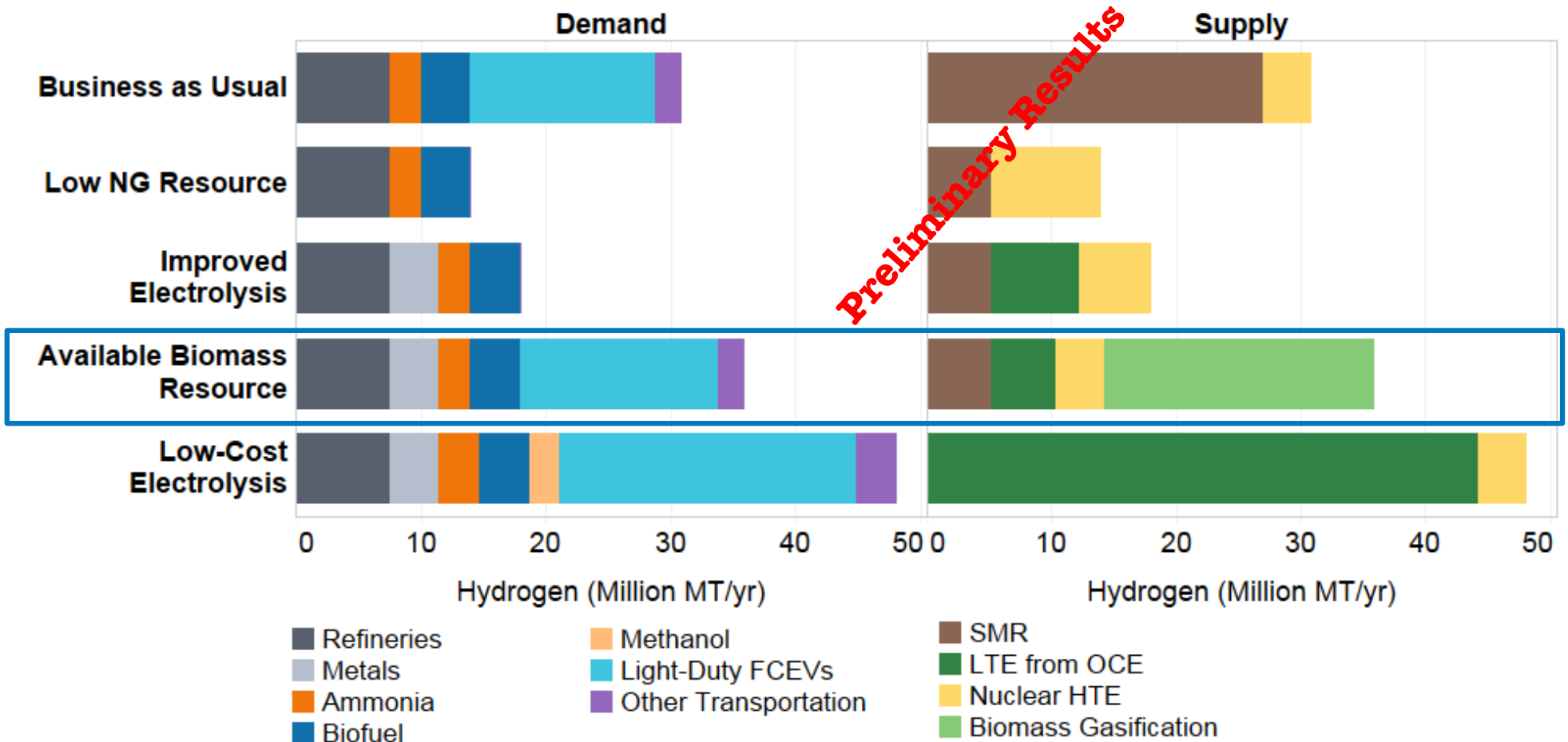
Accomplishment: Developed and Reviewed Economic Potential Results



Improved Electrolysis Scenario

Drivers for metals applications increase market. Some LTE penetration at \$200/kW capital cost with grid value

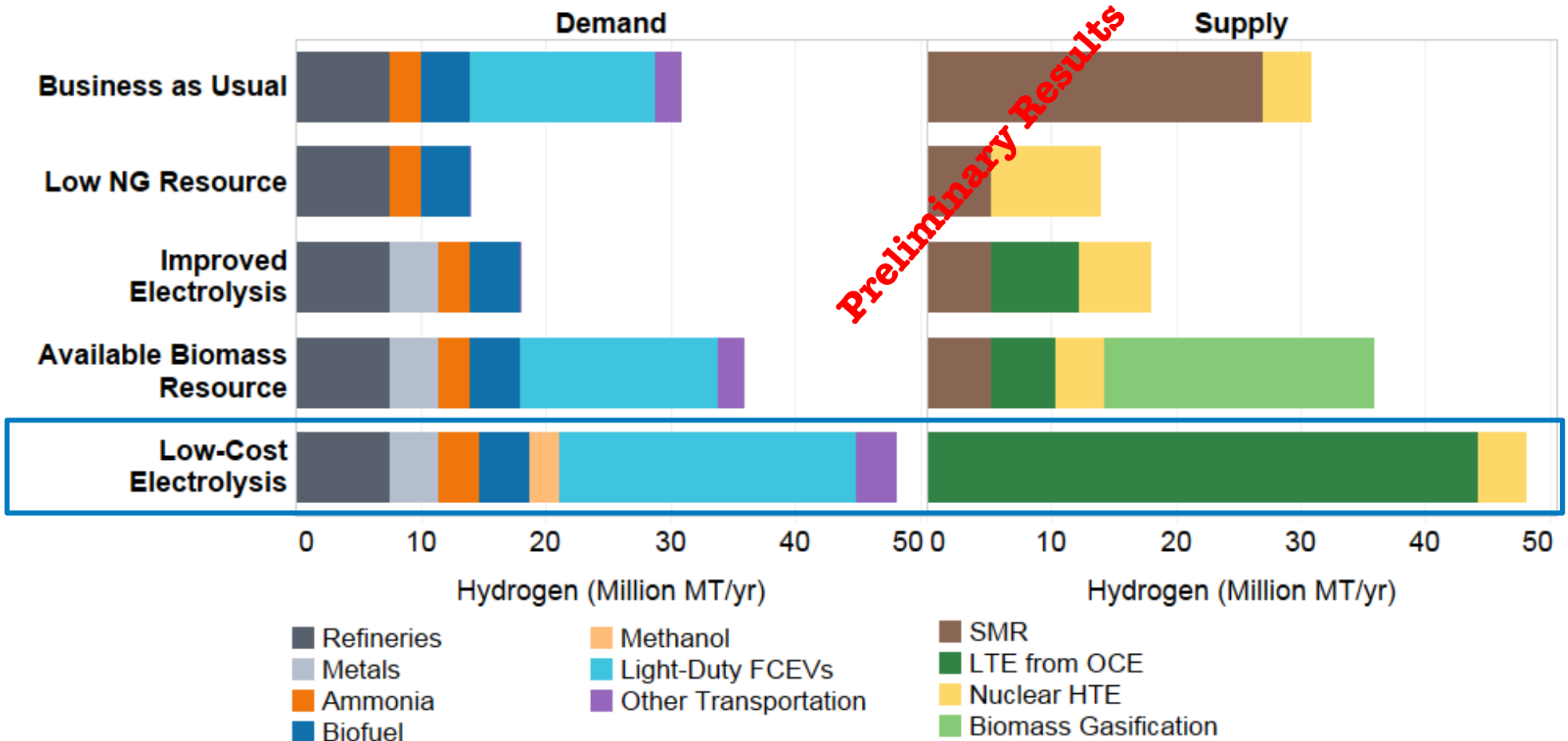
Accomplishment: Developed and Reviewed Economic Potential Results



Available Biomass Resources Scenario

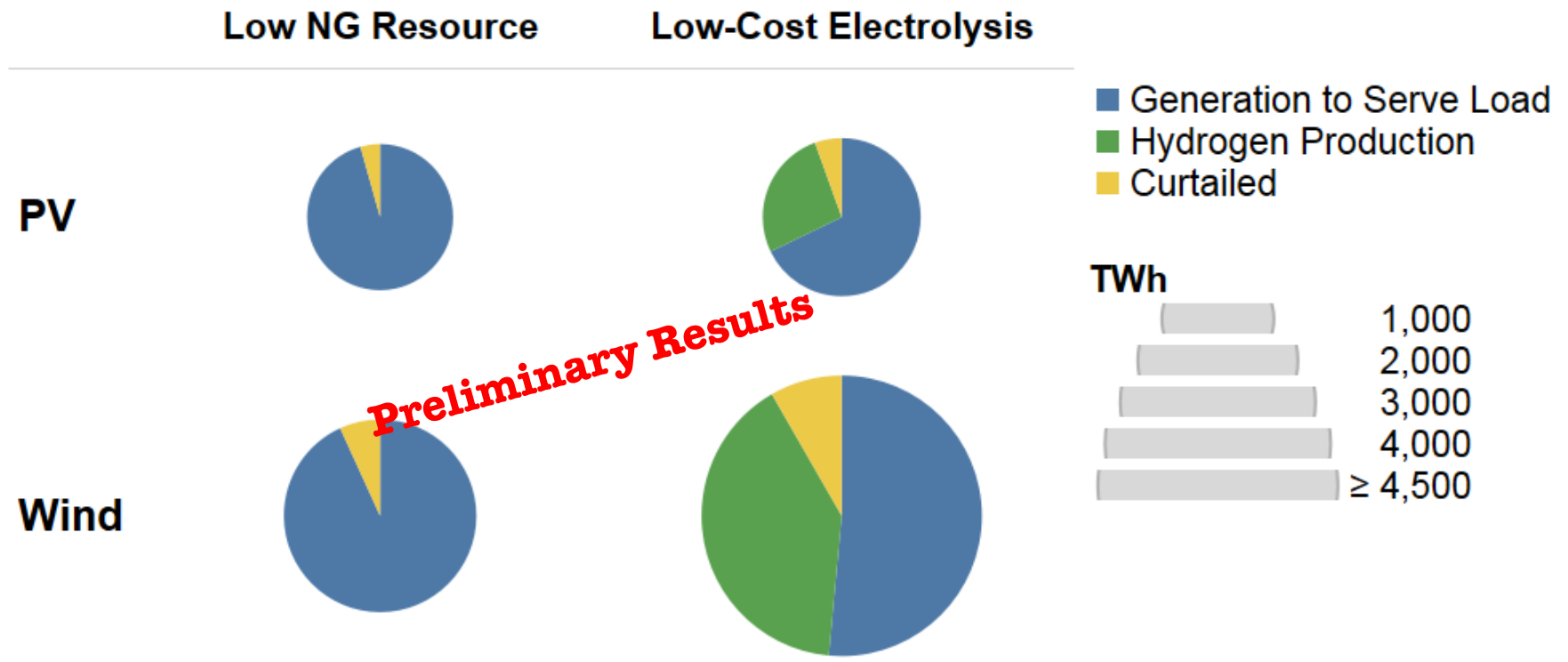
If the biomass is not used for higher value purposes, it could be a key resource

Accomplishment: Developed and Reviewed Economic Potential Results



Accomplishment: Estimated Potential Impact on Wind and Solar PV Markets

H2@Scale has the potential to increase the total market size of wind and solar photovoltaic (PV) generation



Estimates are based on national scenarios with minimal resolution into regional constraints. Increased resolution will likely impact the most competitive source of energy supply

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- **Comment:** The supply and demand curves should point out which industries and applications would be able to deliver hydrogen at the equilibrium price and which ones would be willing to pay that price.
 - *Response:* This year's presentation is more clear regarding the mix of hydrogen supply and applications at equilibrium in each scenario.
- **Comment:** The project just needs a scenario for utopia.
 - *Response:* The maximum market size scenario is a maximum without considering other opportunities. One could consider it a utopia that is not met by the economic potential scenarios. Additional opportunities to exceed the economic equilibria could be considered.
- **Comment:** The project needs a sensitivity analysis.
 - *Response:* Many sensitivity analyses have been performed and are included in our draft report. Some are provided in the supporting slides but, due to limitations in presentation length, could not be provided in the body of the presentation.

Collaboration and Coordination

This project involves multiple labs performing analysis and industry providing insights and feedback.

	Role	Organizations Providing Input and Review
NREL	Lead; production cost estimates, supply-demand scenarios, impact assessments, spatial and temporal analysis, case studies	EPRI SoCal Gas California Air Resources Board Exelon
ANL	Deputy lead; hydrogen demand analysis, emission and water use impact analysis	Shell ExxonMobil
LBNL	Support scenario development	General Motors
PNNL	Support scenario development	NH3 Energy Association Nexceris
INL	Nuclear and metals characterization	DOE Office of Nuclear Energy
LLNL	Visualizations including Sankey diagrams	DOE EERE Offices (Fuel Cell Technologies Office, Solar Energy Technologies Office, Wind Energy Office, Bioenergy Technologies Office)
Office of Nuclear Energy	Identify synergies between H2@Scale and nuclear energy	NREL ANL PNNL Sandia

Remaining Challenges and Barriers

Economic Potential Estimates

- Additional markets
- National analysis does not represent regional opportunities and challenges
- Transportation and storage requirements and costs are overly simplified

Transition

- Strategies for achieving economic potential are not available

Business Cases

- Opportunities for individual businesses have yet to be identified

R&D Targets

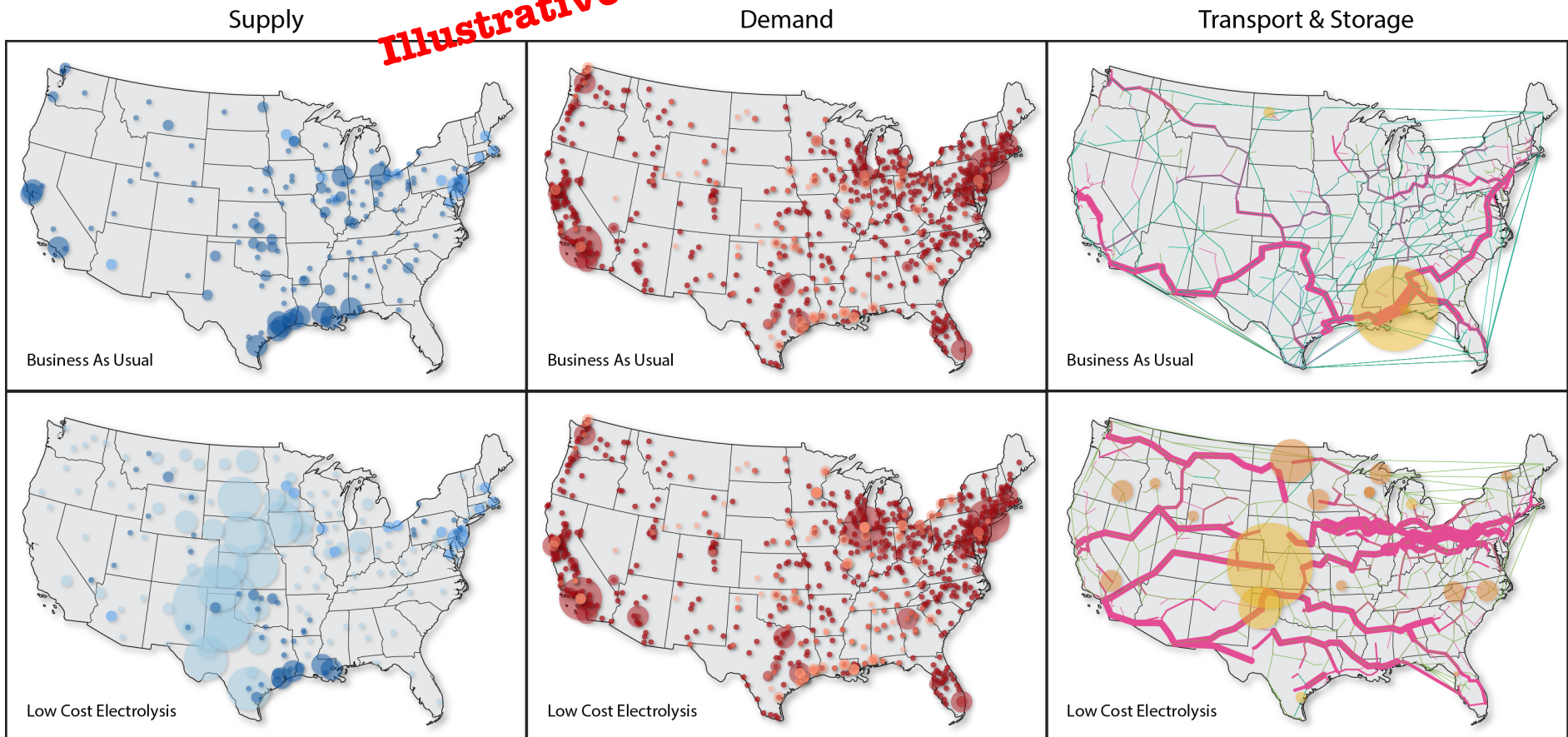
- Technologies roadmaps to meet R&D targets have not been developed

Proposed Future Work: Estimate Hydrogen Transport and Storage Costs

We are using the Scenario Evaluation and Regionalization Analysis (SERA) Model estimate optimal transport and storage infrastructure



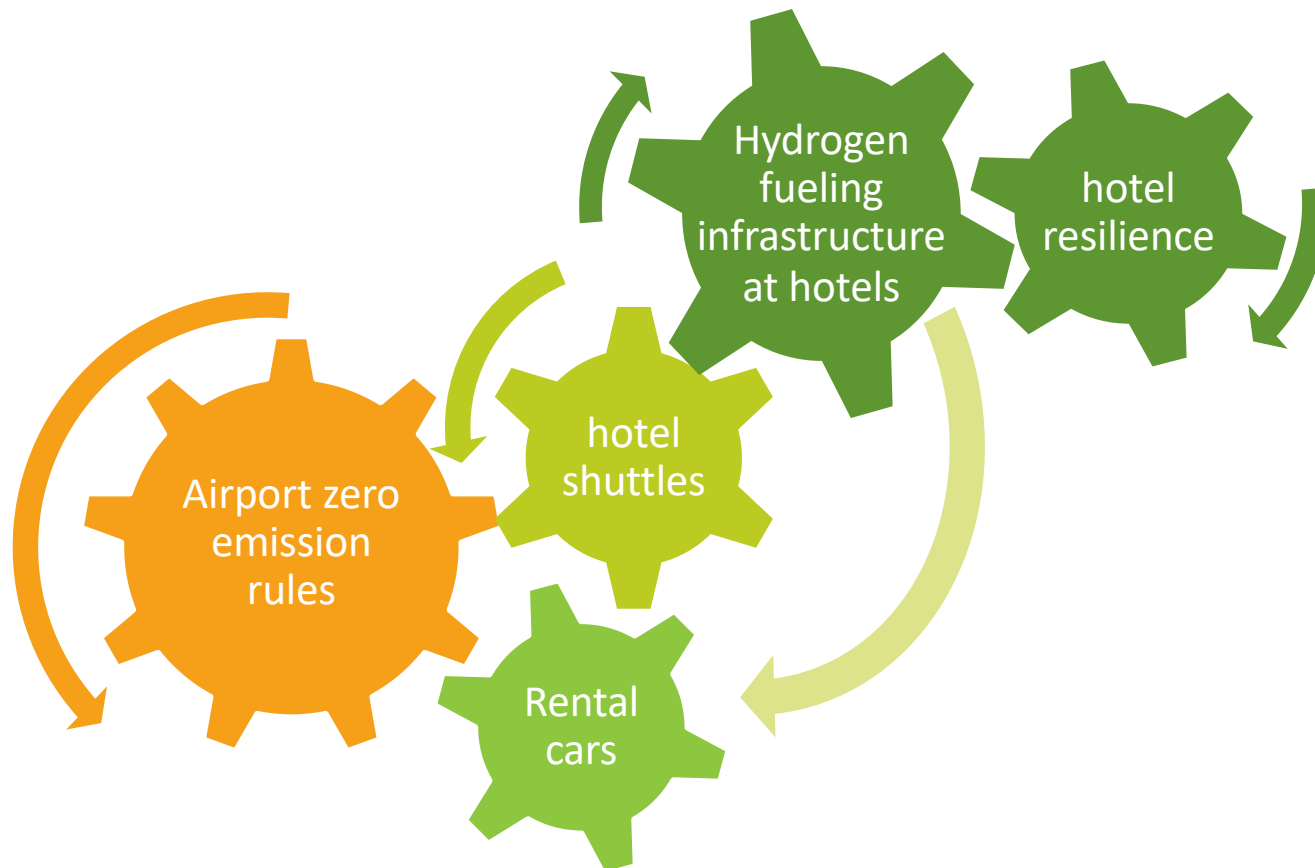
Illustrative Results



Any proposed future work is subject to change based on funding levels

Proposed Future Work: Regional Transition Analysis

We are identifying and developing a potential transition scenario from today's market in Texas to the "Low Cost Electrolysis" Scenario results.



Identifying possible order and interactions within and across application sectors and using SERA to identify transition of production technologies.

Any proposed future work is subject to change based on funding levels

Technology Transfer Activities

Planned: Provide hydrogen supply and demand data and projections to help companies identify business opportunities. Key niche: grid interactions

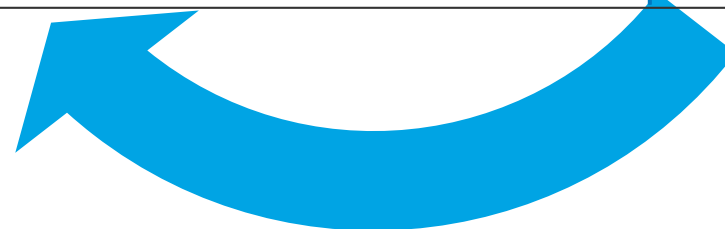


Current: Provide information about potential production options and market opportunities to businesses looking to invest

Lab Team

Industry

Current: Receive input and feedback on technical and economic potential through extensive reviews and workshops



Planned: Receive extensive input for regional roadmaps to ensure the opportunities, implementation order, and synergies are reasonable

Summary

H2@Scale can transform our energy system by

- economically benefitting nuclear and renewable hydrogen production technologies
- providing energy for transportation, feedstock for industry, and seasonal electricity storage

- **Technical potential:** *166 MMT H₂/ yr*
- **Economic potential:** *14 - 48 MMT H₂/ yr*
- **Use of low-cost, low-availability electricity could increase wind & solar PV markets**

Report is in final review

Further analysis is needed to understand the spatial and temporal aspects of H2@Scale, possible transition options, and quantify research and development targets.

H₂

@Scale:

Energy system-wide benefits of increased H₂ implementation

Major Assumptions

Category	Assumption
Markets	Markets are at equilibrium – projected 2050 economic conditions
PV & Wind CAPEX	Based on 2017 Annual Technology Baseline Low Prices. Land-based wind CAPEX in 2050: \$1174/kW; Commercial solar in 2050: \$972/kW
Coal with CCS	Hydrogen levelized production cost: \$1.94/kg. Adding storage and delivery cost would be \$2.33/kg on the supply curve
Delivery and Storage Costs	Supply curves include storage and delivery cost assumptions of ~\$0.10/kg for steam methane reforming (SMR) and ~\$0.40/kg for other technologies (cost for pipeline transport of 200,000 MT/yr 250 miles with geologic storage)
Demand Price Thresholds	At demand centers -- delivery & dispensing costs for vehicles added separately in vehicle market models (i.e., \$5.00/kg at pump)
Carbon Dioxide	100 MMT/yr of concentrated carbon dioxide available from ethanol production
Vehicle Fleet	In 2050: 163 million cars, 163 million light trucks, 14 million medium duty trucks, 6.7 million heavy duty trucks

Key scenario assumptions are reported on Slide 5

Thank You

www.nrel.gov

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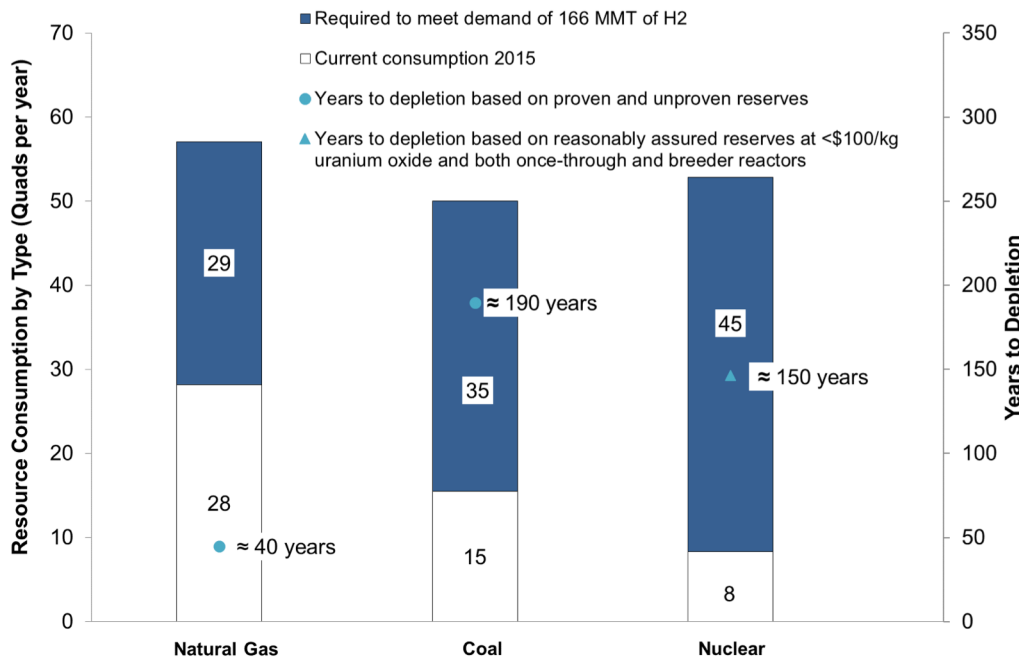
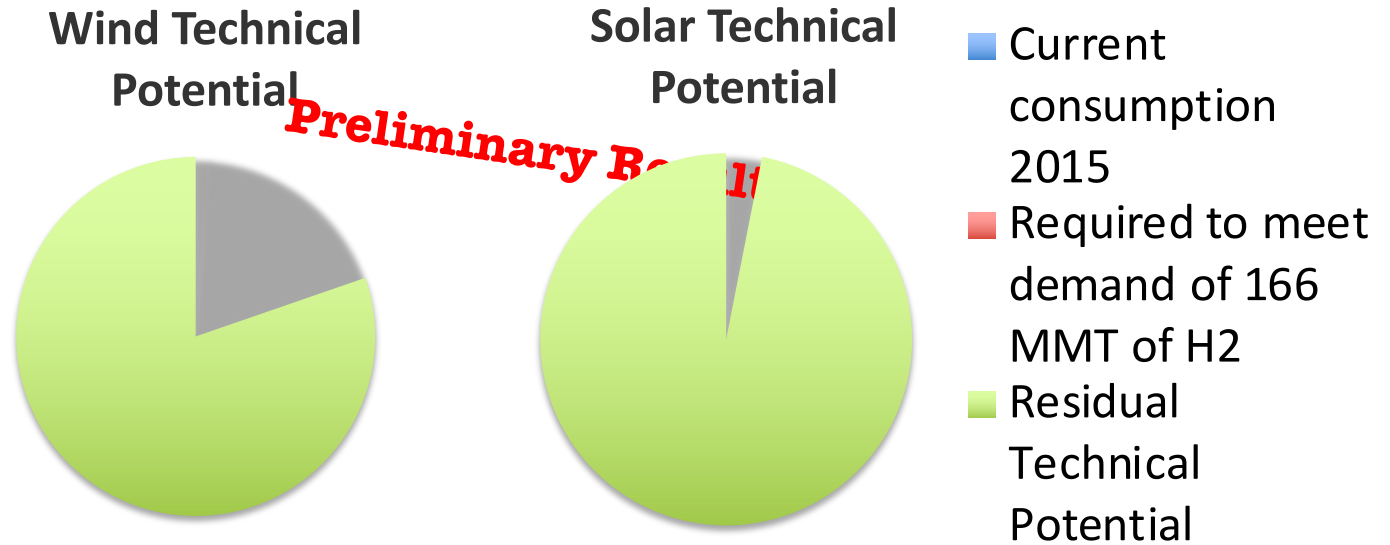
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Technical Backup Slides

Technical Potential Supply from Renewable, Fossil, and Nuclear Resources

Total demand including hydrogen is satisfied by $\approx 20\%$ of wind, 3% of solar, and $\approx 200\%$ of biomass technical potential



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

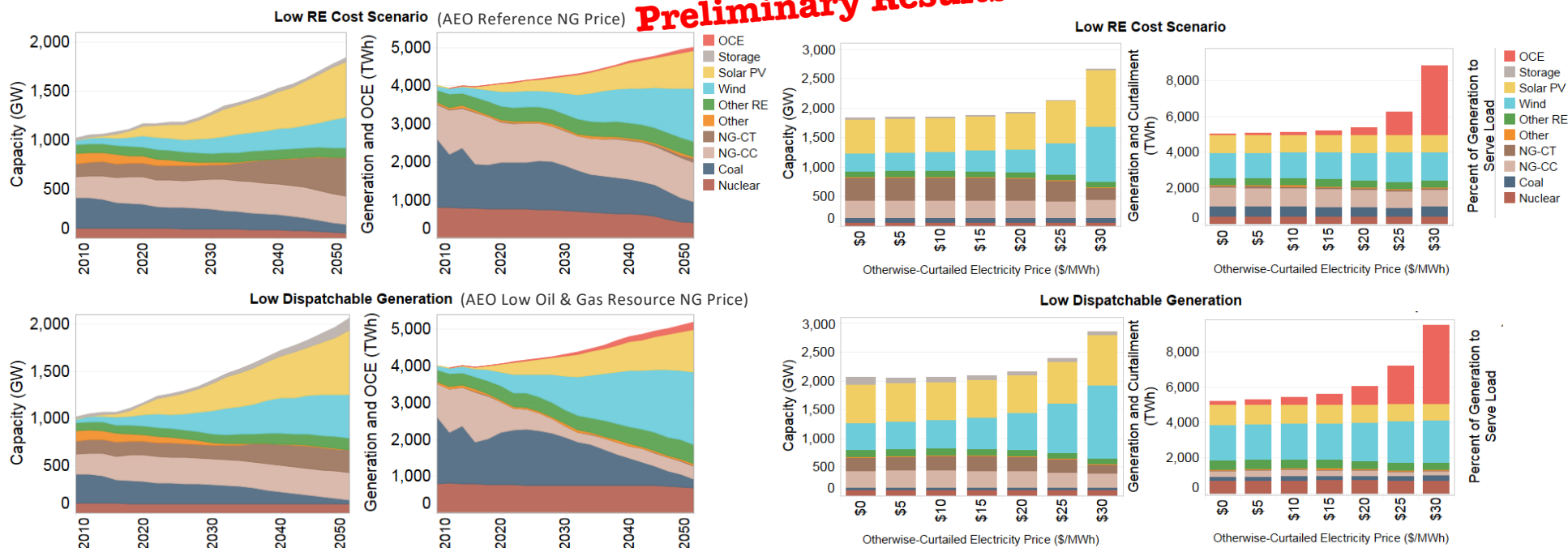
ReEDS Results

Used ReEDS to estimate generator fleet and generation mix at multiple OCE values

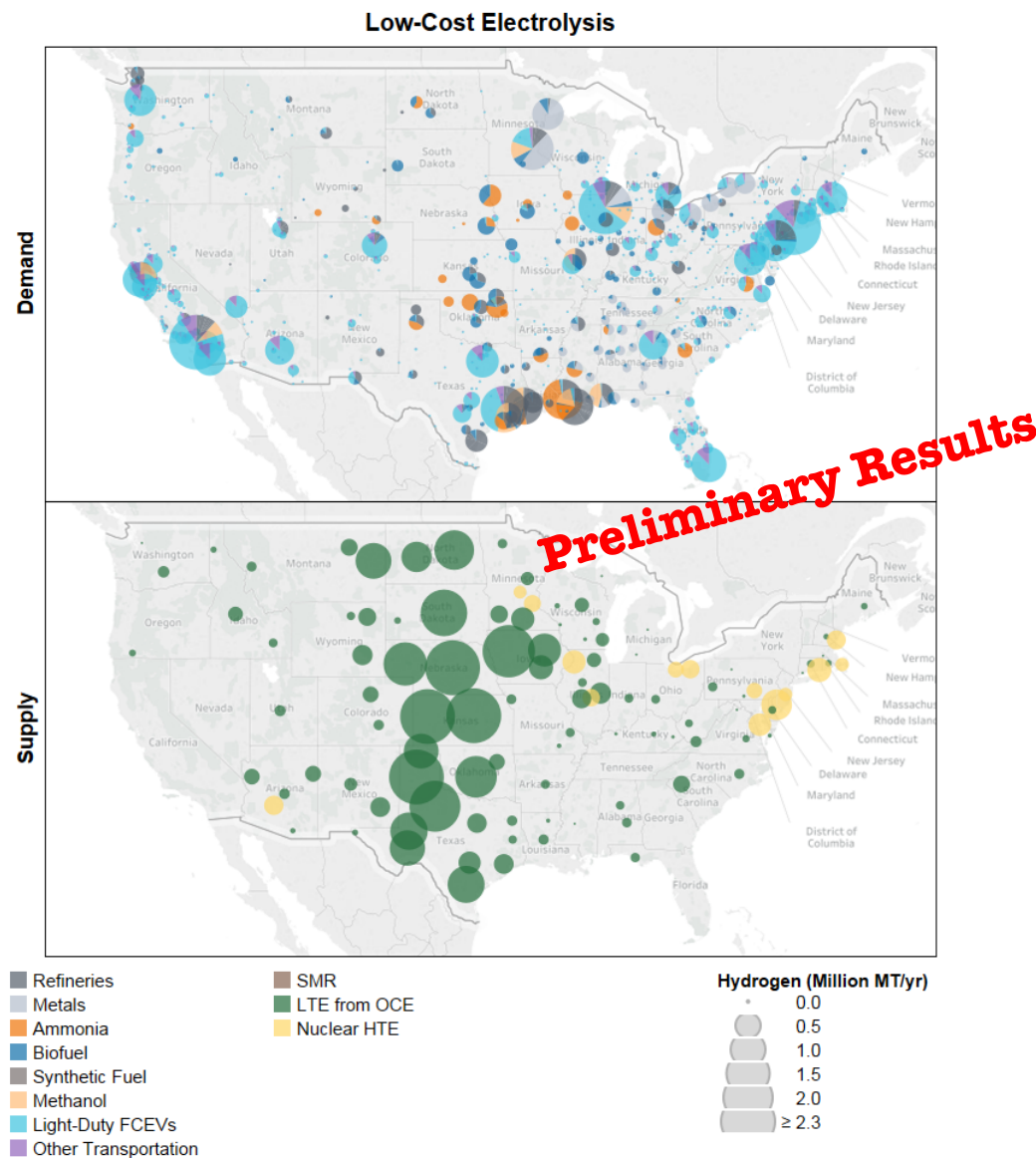
Buildout with \$0/MWh OCE

2050 Results at Various OCE Values

Preliminary Results



Accomplishment: Identified Spatial Aspects of Economic Potential Scenarios



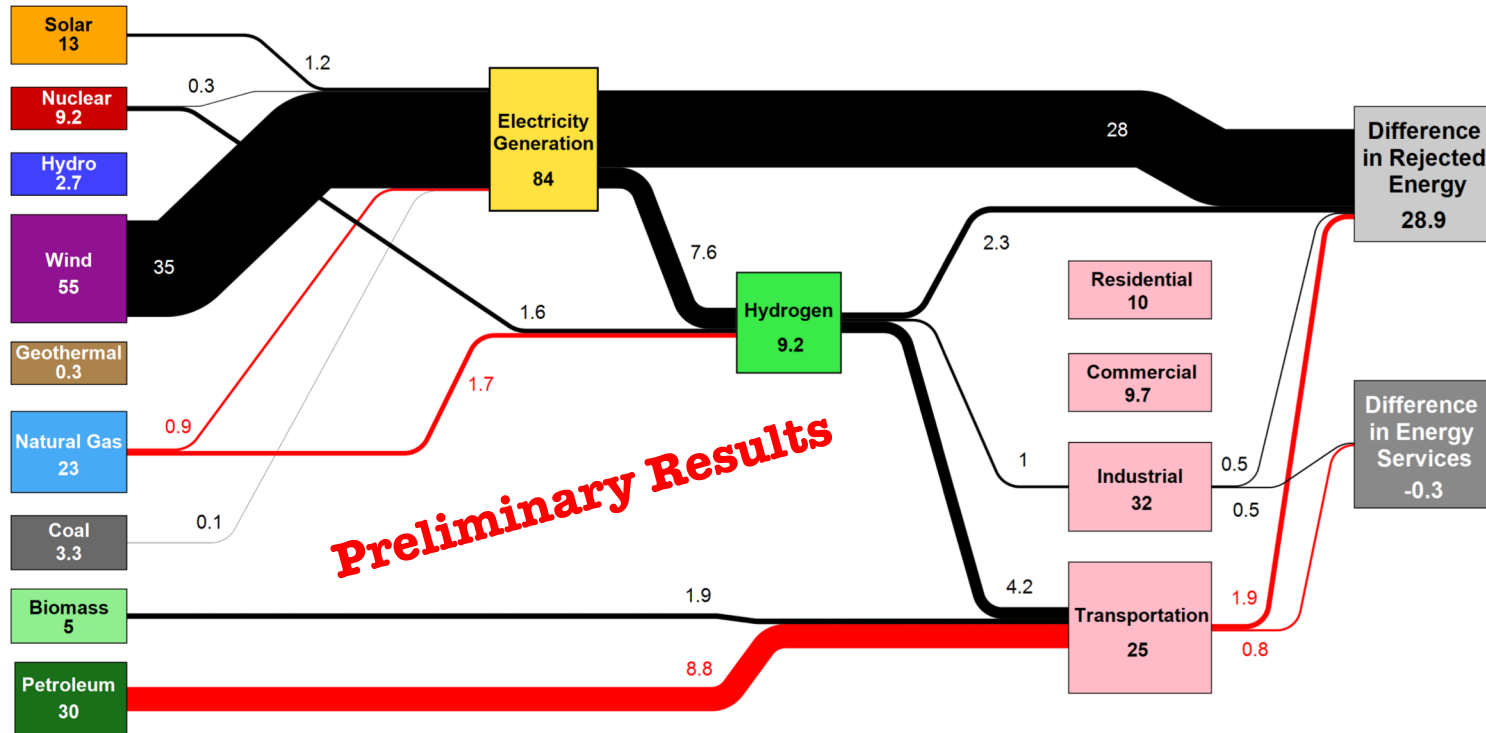
- In the Low-Cost Electrolysis Scenario, the majority of the hydrogen is generated in the central U.S.
- Demands are primarily near urban centers
- Large delivery infrastructure investments could be necessary

Accomplishment: Estimated Impacts on U.S. Energy System

2050 Energy Use Difference between Low Cost Electrolysis and High Curtail Baseline
(Quadrillion BTUs)

Note: Boxes represent Low Cost Electrolysis values

Black Flows indicate Low Cost Electrolysis uses more energy than High Curtail Baseline
Red Flows indicate High Curtail Baseline uses more energy than Low Cost Electrolysis



Source: LLNL February 2019. 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. Renewable resources for electricity in BTU-equivalent values assumes 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, 24% for the transportation sector, and 49% for the industrial sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

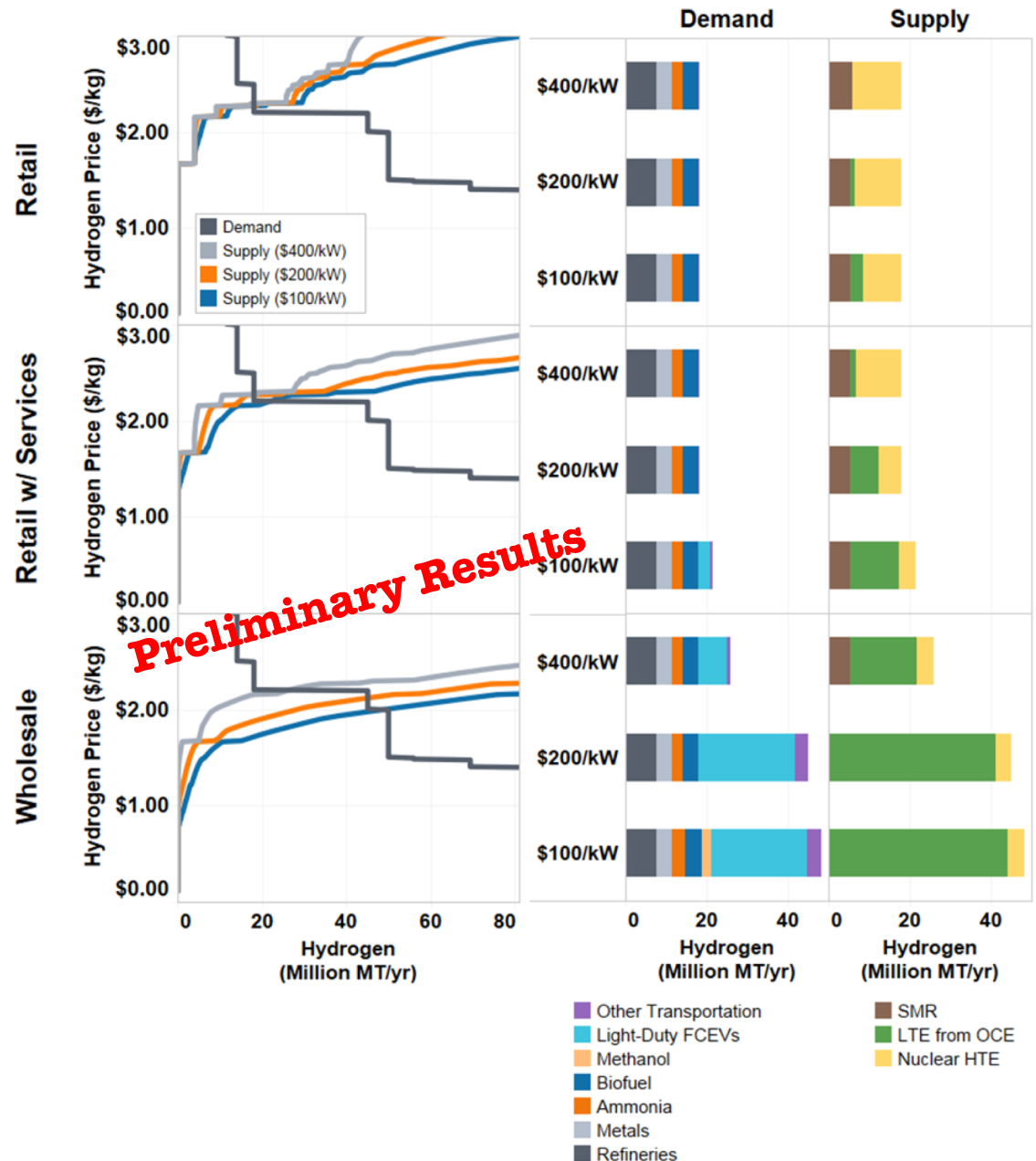
The Low-Cost Electrolysis Scenario primarily offsets oil for transportation with hydrogen from wind. It also reduces natural gas for electricity and hydrogen production.

Sensitivities

We have performed sensitivities on a number of parameters:

- Natural gas prices
- Natural gas SMR availability
- Low temperature electrolysis cost and electricity price availability
- Nuclear high temperature electrolysis availability
- Biomass resource availability
- Metals refining support and
- Increased support for other demands.

The figure on the right shows results from the low temperature electrolysis cost and electricity price availability sensitivity. It indicates electricity price has a stronger impact on market size than the electrolyzer capital cost.



Acronyms

Acronym	Definition
AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
CAPEX	Capital Expenditure
CCS	Carbon Capture and Sequestration
CPI	Chemical Processing Industry
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
FCEV	Fuel Cell Electric Vehicle
FY	Fiscal Year
H ₂	Hydrogen
HDV	Heavy Duty Vehicle
HTE	High Temperature Electrolysis
INL	Idaho National Laboratory
LBNL	Lawrence Berkeley National Laboratory
LDV	Light Duty Vehicle

Acronym	Definition
LLNL	Lawrence Livermore National Laboratory
LTE	Low Temperature Electrolysis
MDV	Medium Duty Vehicle
MMT	Million Metric Tonnes
NH ₃	Ammonia
NG	Natural Gas
NREL	National Renewable Energy Laboratory
OCE	Otherwise Curtailed Electricity
PNNL	Pacific Northwest National Laboratory
PV	Photovoltaic
SERA	Scenario Evaluation and Regionalization Analysis
SMR	Steam methane reforming
Syn.	Synthetic
yr	Year