H2@Scale Analysis

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DOE Hydrogen and Fuel Cells Program
2019 Annual Merit Review and Peer Evaluation Meeting

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

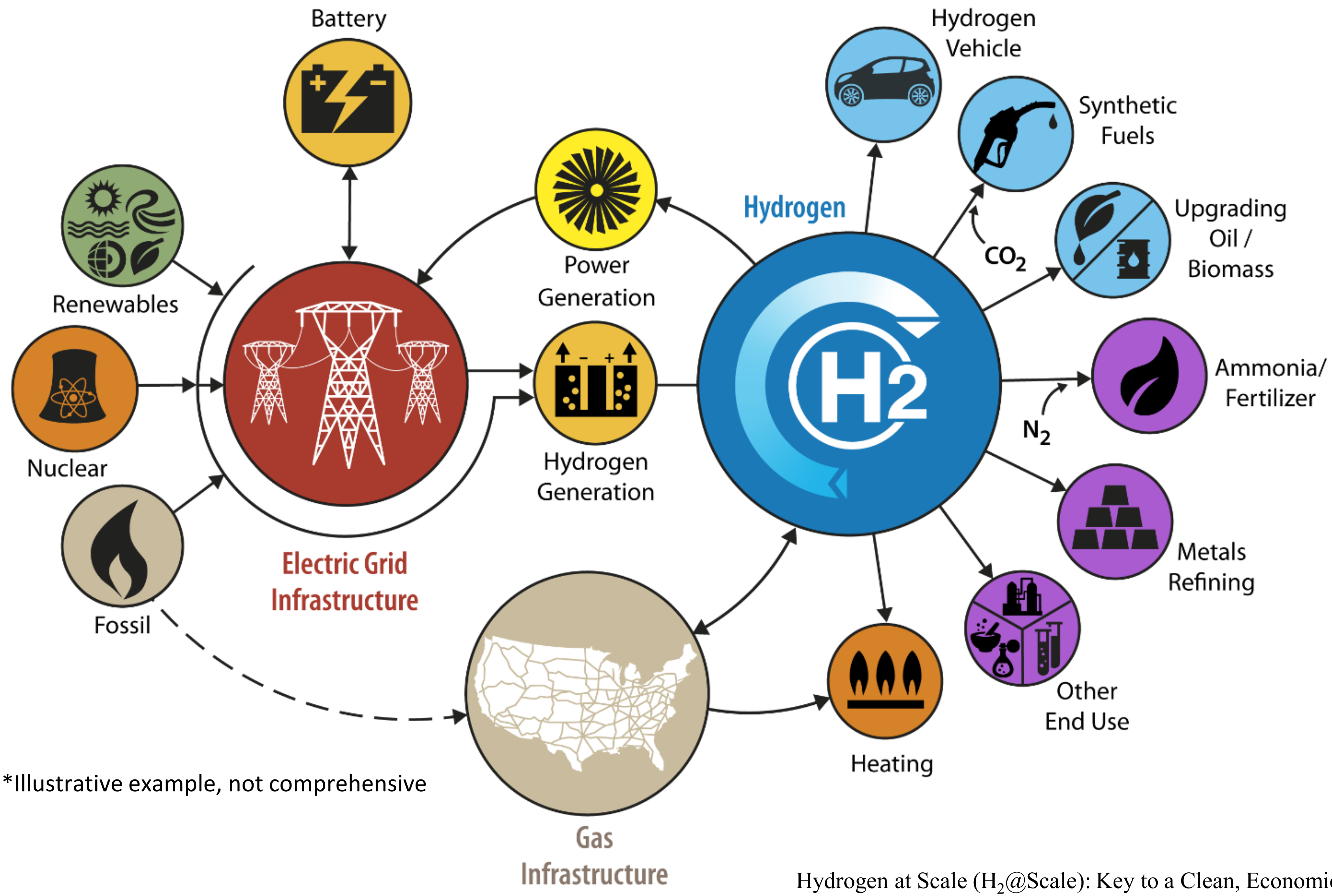
Partners

- 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 (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

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**

NREL Annual Technology Baseline

NREL, FCT Office, Nuclear Energy Office, & External Reviews

Analysis Framework

H2A design parameters
GREET emissions data
H_2USA fleet evolution
GIS analysis tools

Models & Tools

H2A
GREET
Fleet evolution tools
ReEDS & PLEXOS
HDSAM
SERA
Sankey Diagram Tool

Studies & Analysis

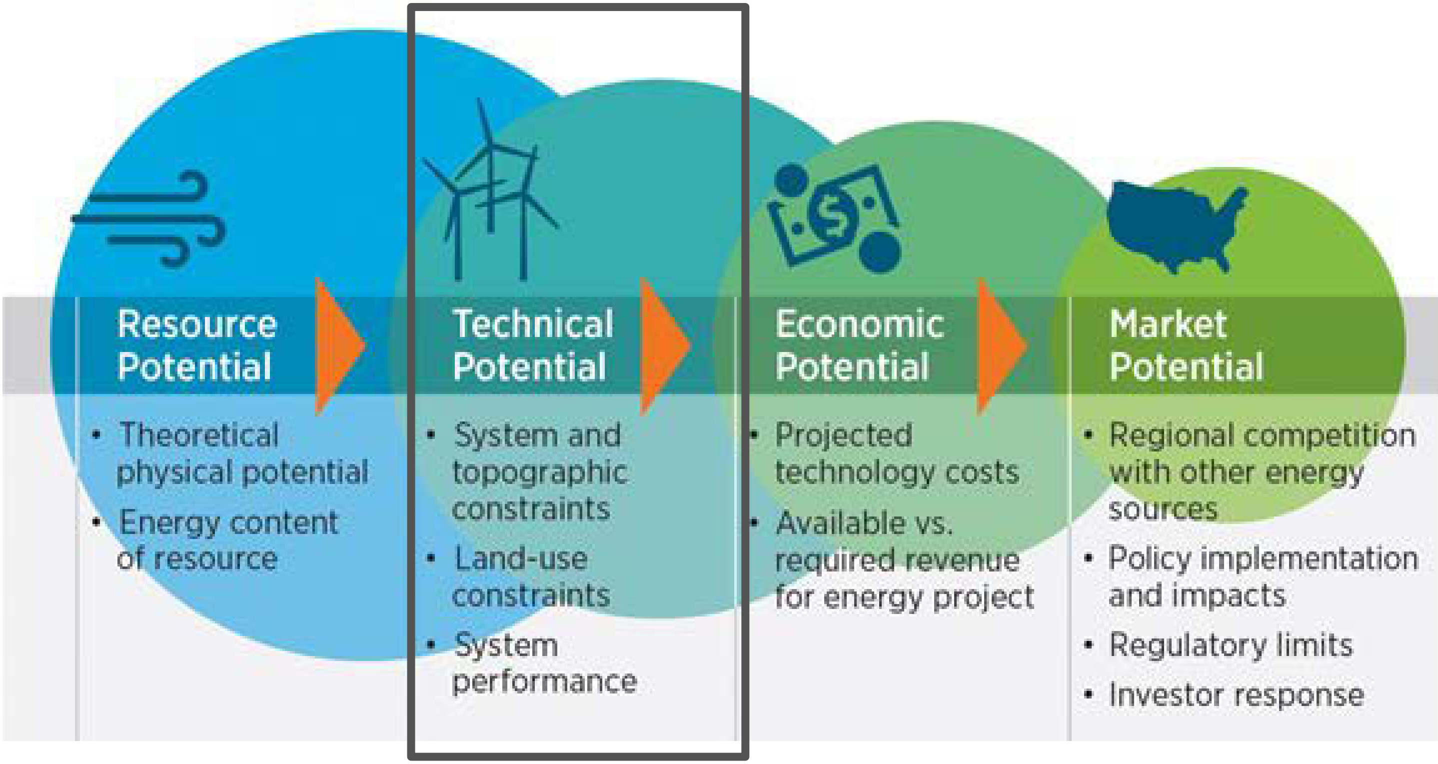
Demand assessment
Resource assessment
Grid analyses
Curtailed electricity
Economic equilibria
Impact assessment

Outputs & Deliverables

Analysis of H2@Scale concept and potential opportunity and impacts

National Labs
ANL – GREET, fleet evolution
NREL – H2A, ReEDS

Approach: Maximum Market Potential & Resource Technical Potential



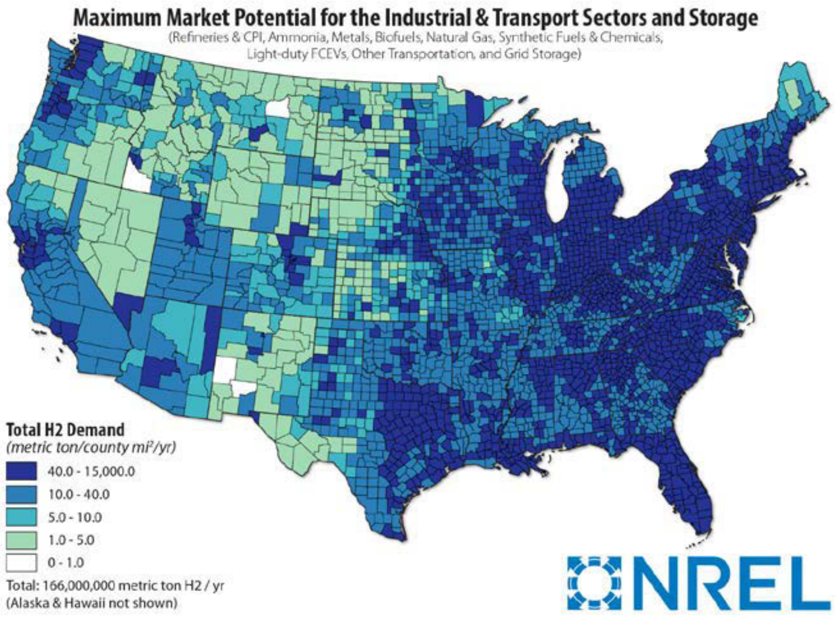
Maximum Market Potential – For possible hydrogen markets, estimate the quantity of hydrogen necessary to provide all the services within the market (i.e., without competing options)

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

Figure Source: 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

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**

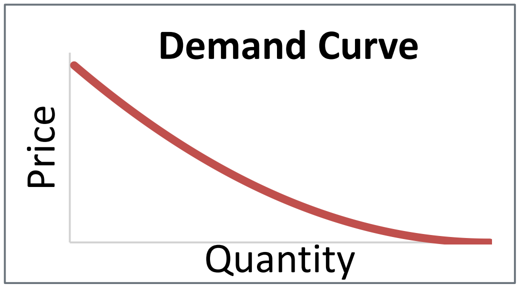


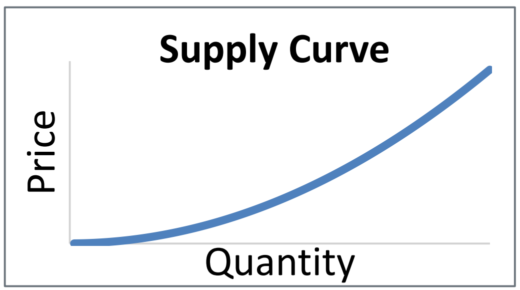
Maximum growth potential of hydrogen market by 2050 is 16X.

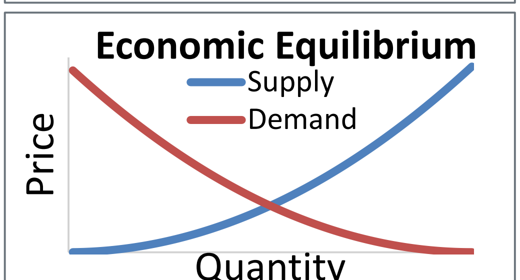
Definition: The maximum market potential is the estimated market size constrained by the services for which society currently uses energy, real-world geography, and system performance, but not by economics.

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.

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

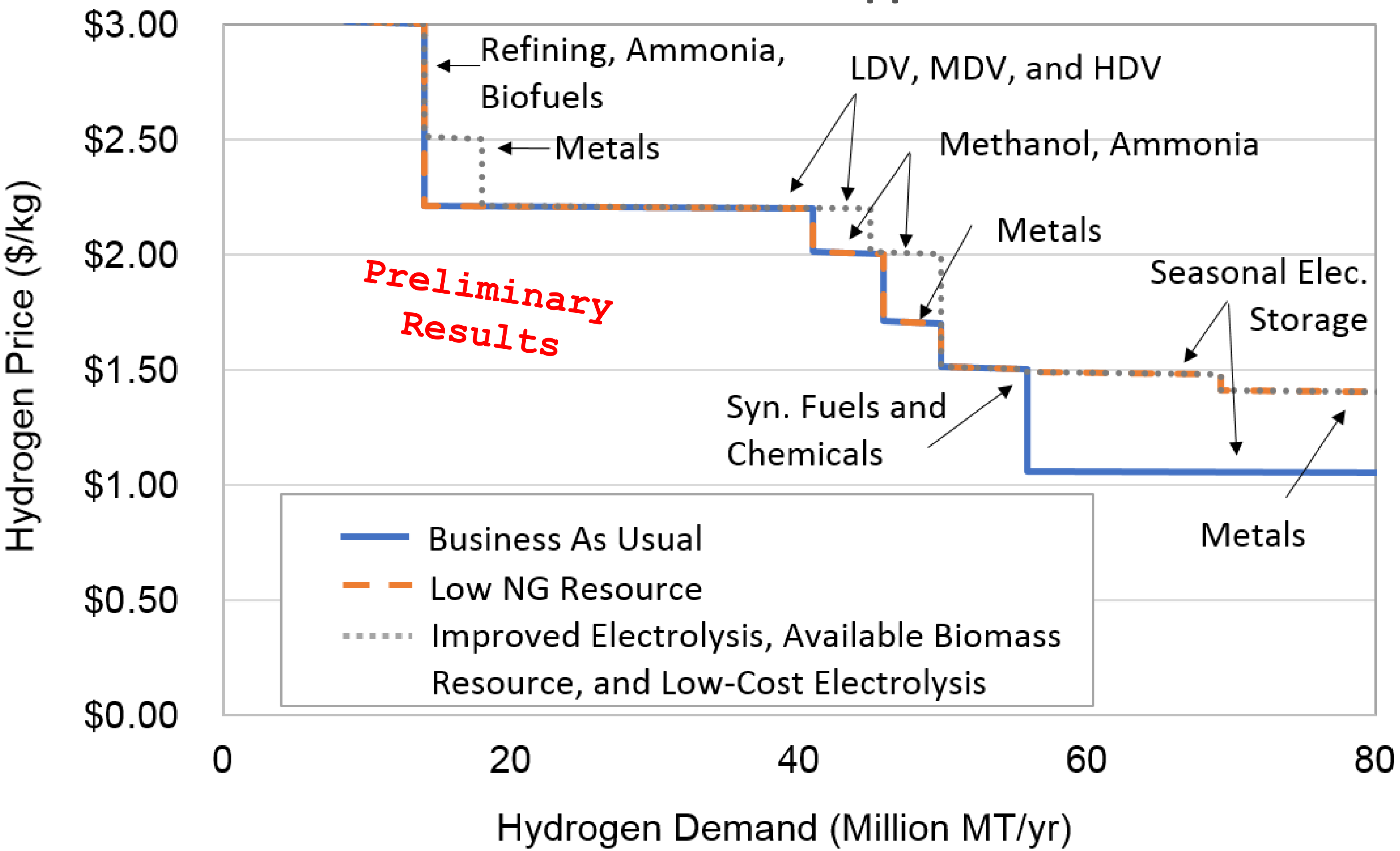
Approach for Economic Potential:
Five National Scenarios

<table>
<tr><th>Scenario Name</th><th>Business as Usual</th><th>Low NG Resource</th><th>Improved Electrolysis</th><th>Available Biomass Resource</th><th>Low-Cost Electrolysis</th></tr>
<tr><td>Natural gas price assumption</td><td>AEO 2017 Reference scenario</td><td colspan="4">AEO 2017 Low Oil and Gas Resource and Technology scenario</td></tr>
<tr><td>Availability of Steam Methane Reforming facilities</td><td colspan="5">Hydrogen generation from SMRs for non-ammonia production is capped at three times current levels (23 MMT/yr)

Hydrogen generation from SMRs estimated for future ammonia production is capped at 5 MMT hydrogen/yr</td></tr>
<tr><td>Nuclear hydrogen</td><td colspan="5">20% of current nuclear fleet available at $\$25/\text{MWh}_e$ equivalent</td></tr>
<tr><td>Low-Temp. Electrolysis capital costs</td><td colspan="2">$400/kW</td><td colspan="2">$200/kW</td><td>$100/kW</td></tr>
<tr><td>Otherwise-curtailed electricity market assumption</td><td colspan="2">Available at retail price</td><td colspan="2">Between retail and wholesale</td><td>Wholesale price</td></tr>
<tr><td>Biomass</td><td colspan="3">Not available</td><td>Available</td><td>Not Available</td></tr>
<tr><td>Metals demand</td><td colspan="2">Must compete with existing technologies</td><td colspan="3">Markets are willing to pay a premium for metals refined using hydrogen</td></tr>
</table>

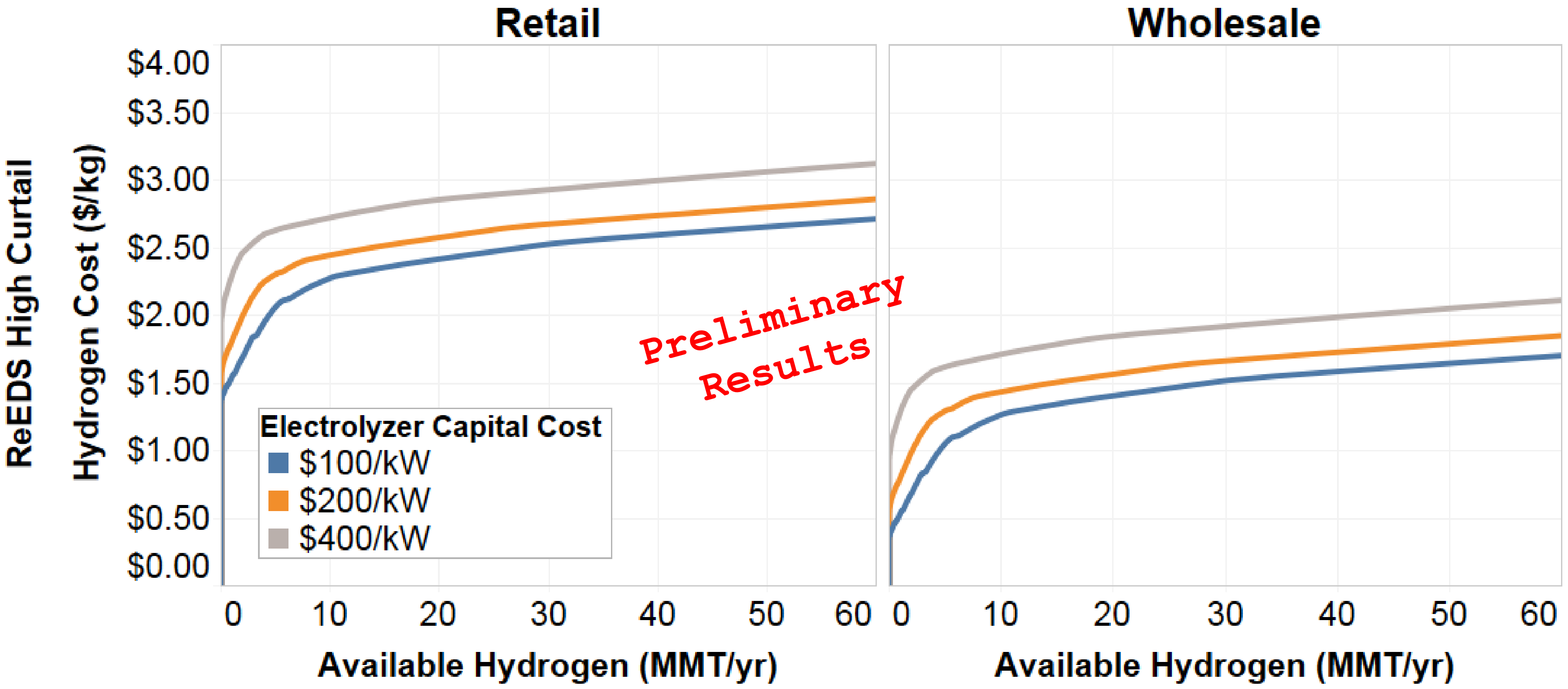
Accomplishment:
Aggregated Demand Curves Across End Uses

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



Accomplishment: Supply Curves Using Otherwise Curtailed Electricity (OCE)

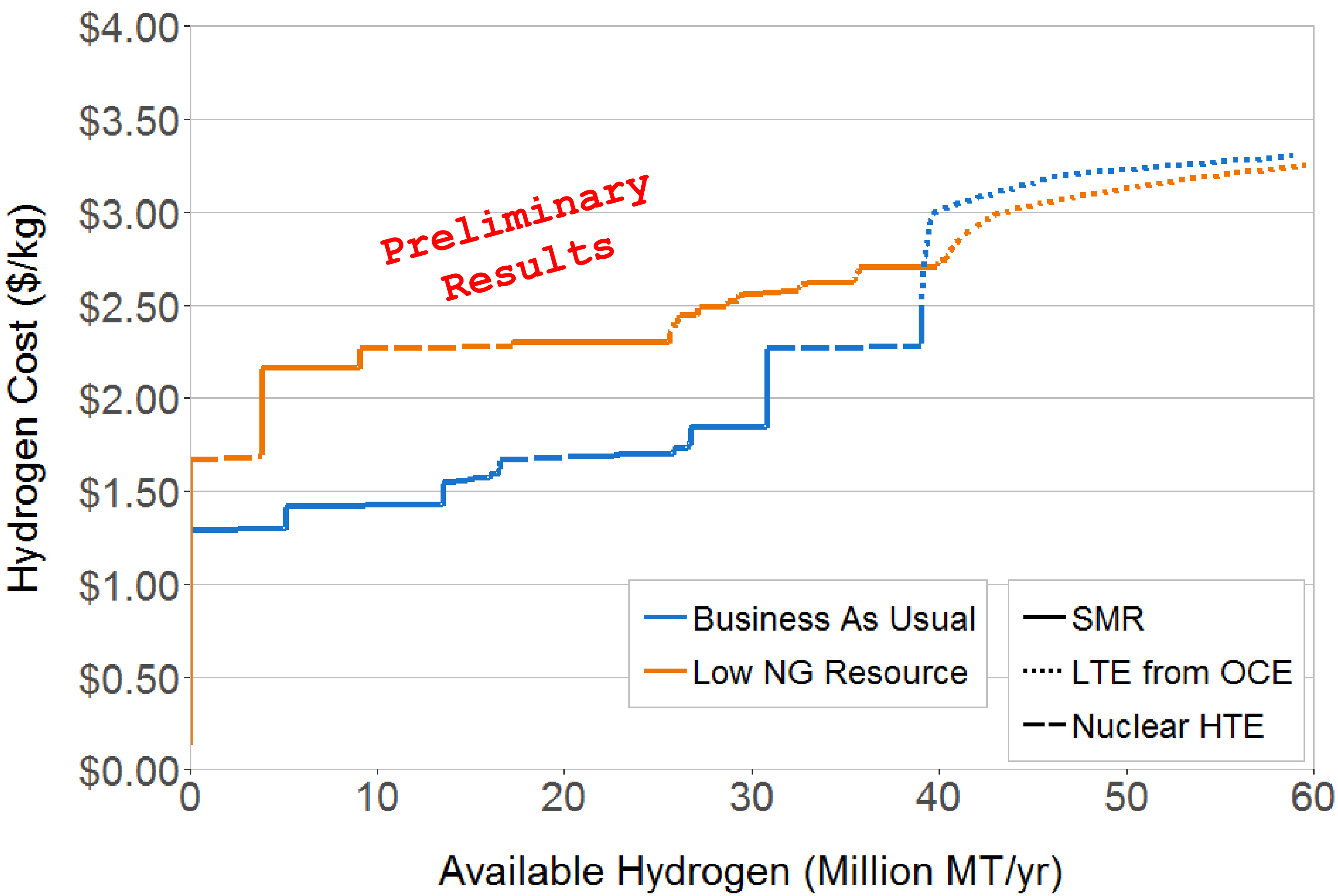
- **Used ReEDS capacity expansion model to estimate generator fleet and generation mix at multiple OCE values**
- **Improved supply curves for low temperature electrolysis-generated hydrogen using the PLEXOS dispatch model to estimate price/availability combinations**



Transaction Cost Assumption: **$20/MWh** **$0/MWh**

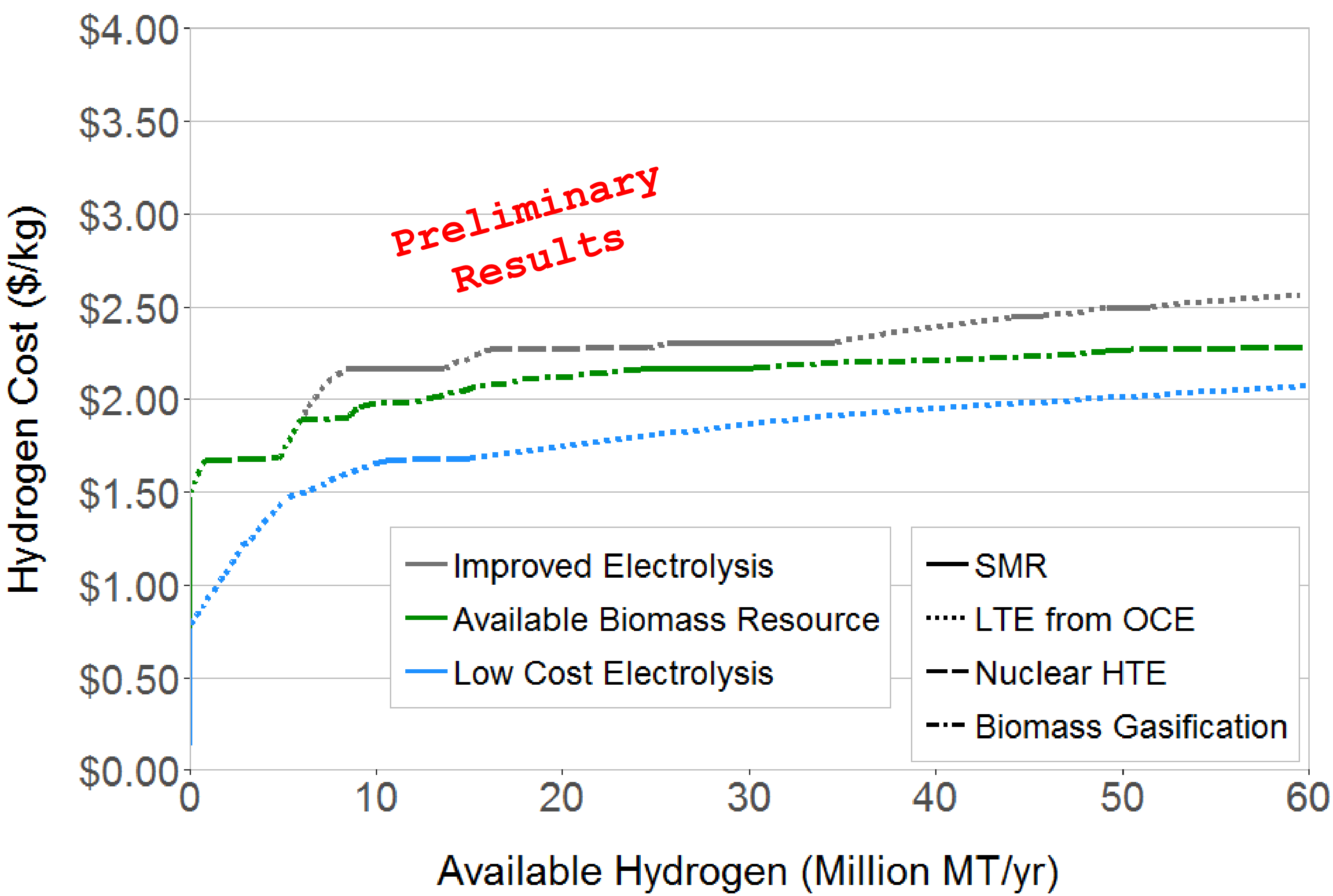
Accomplishment: Aggregated Supply Curves Across Production Options

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



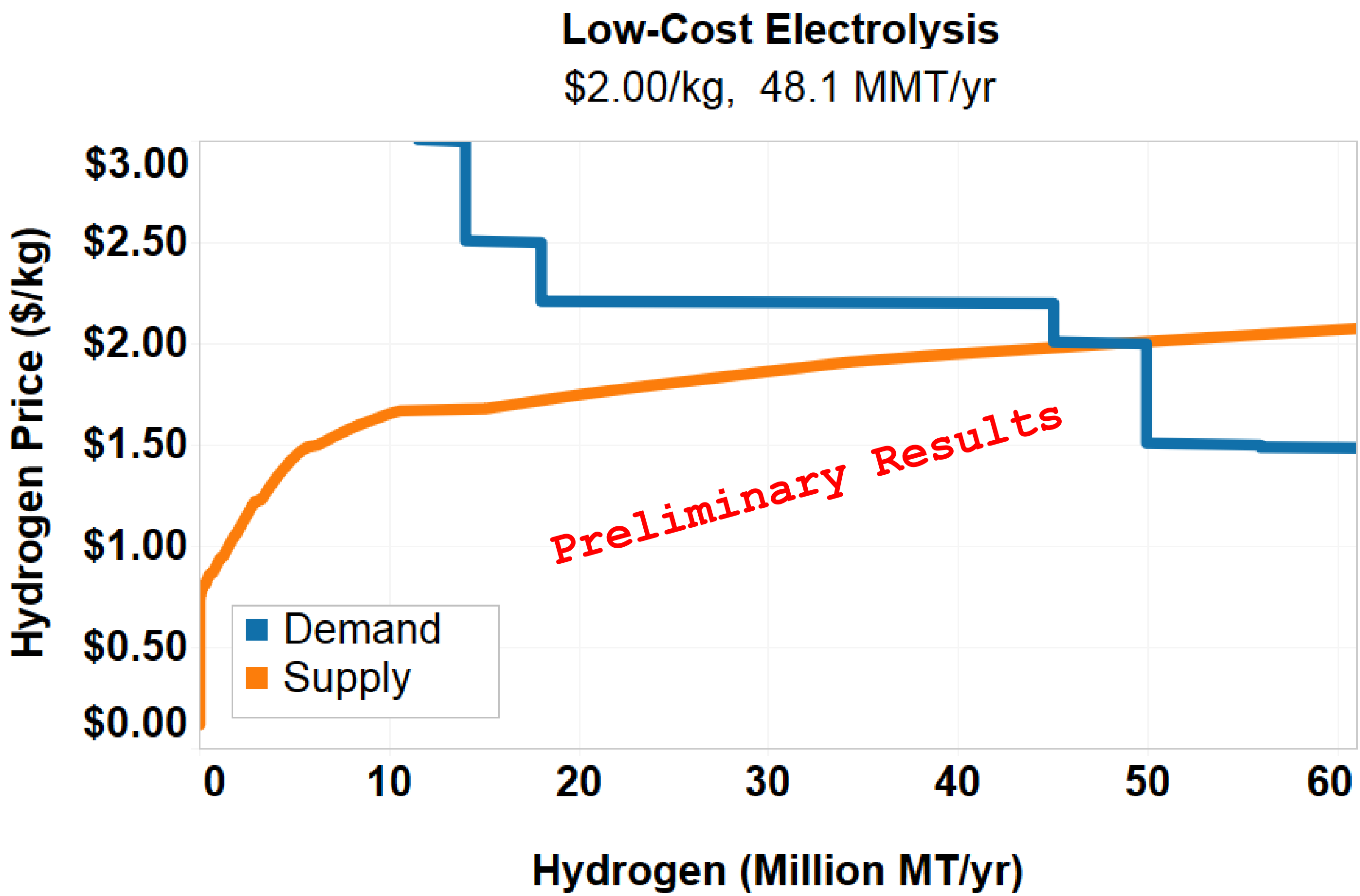
Accomplishment: Aggregated Supply Curves Across Production Options

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

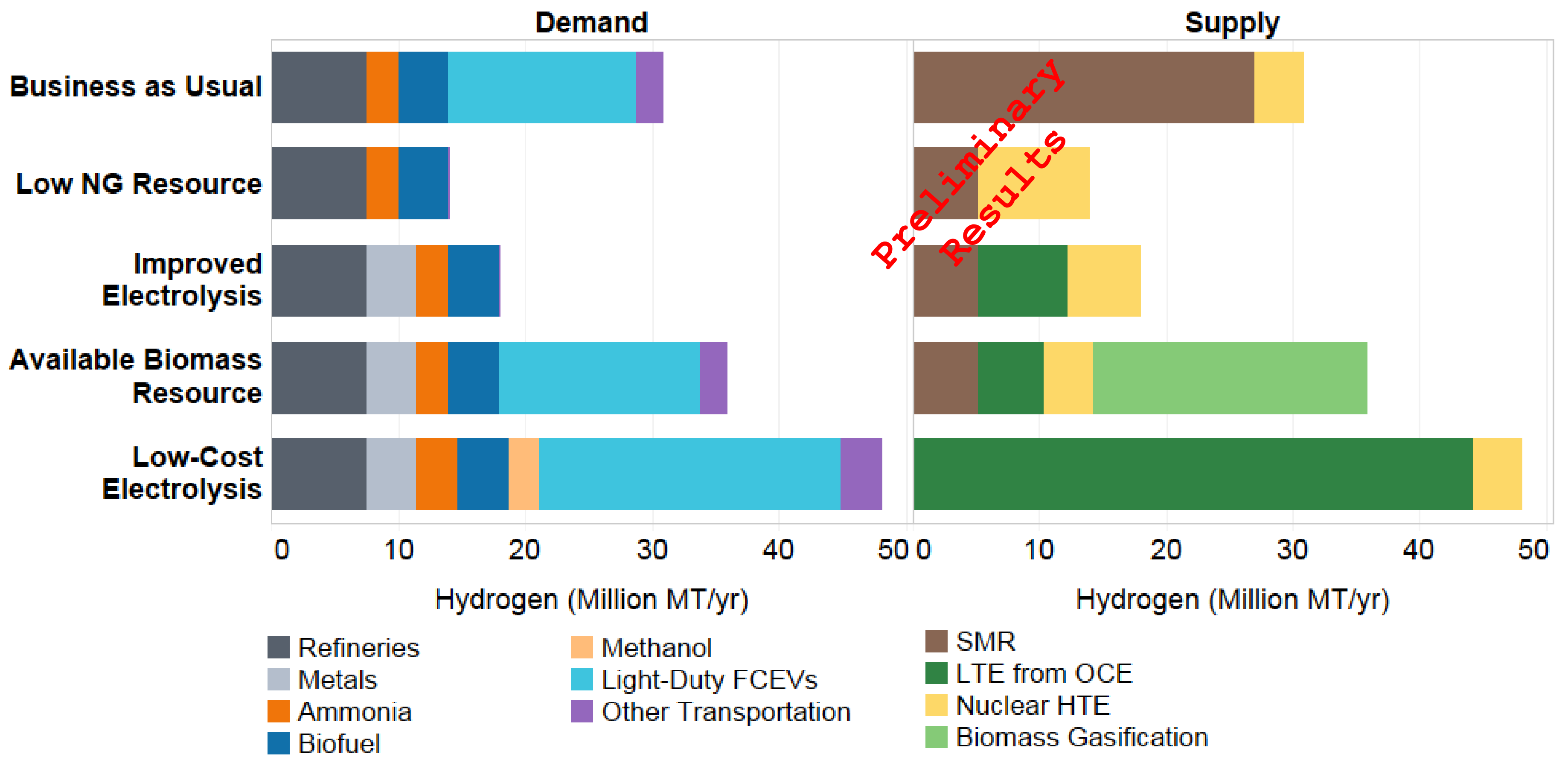


Accomplishment: Identified Market Prices and Equilibrium for Each Scenario

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



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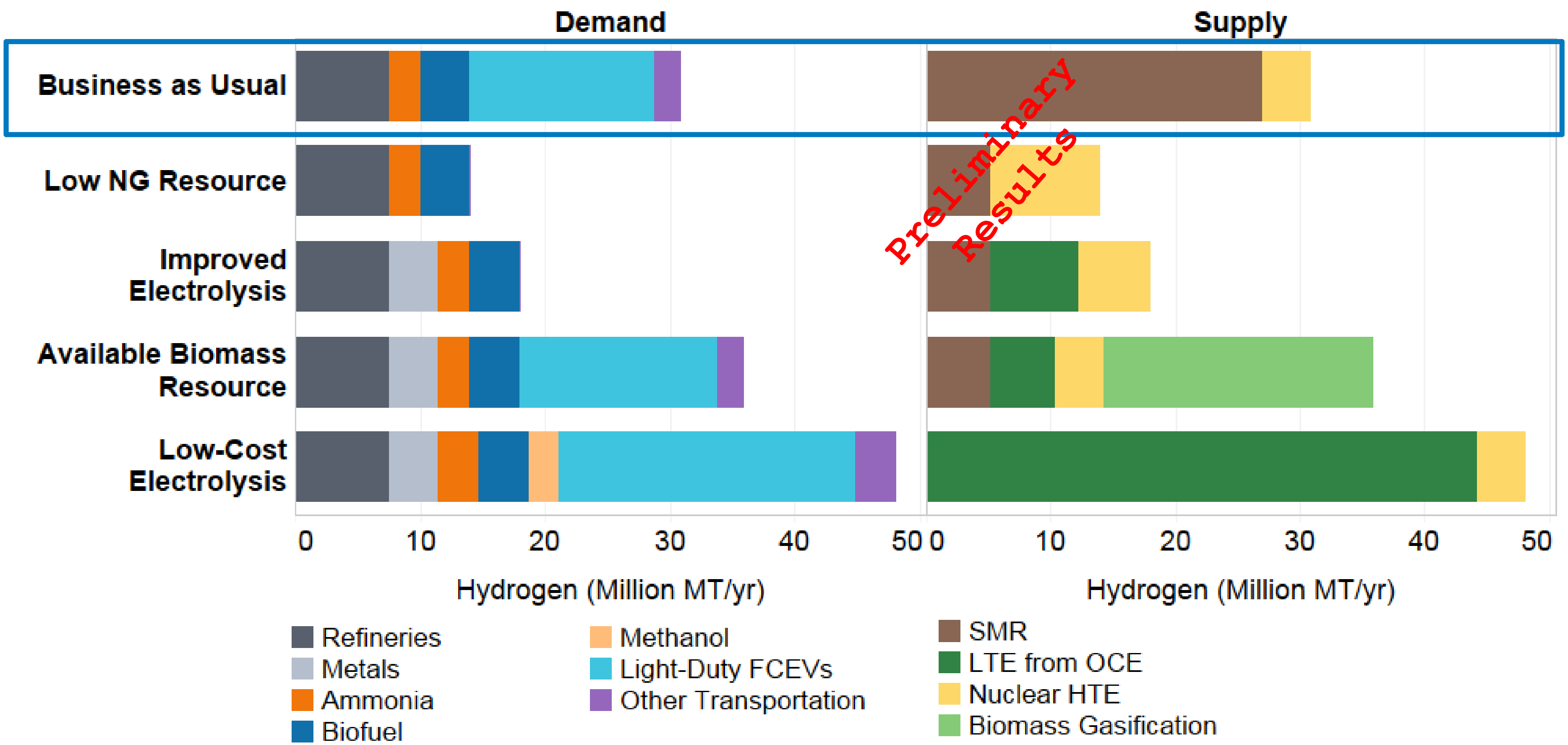
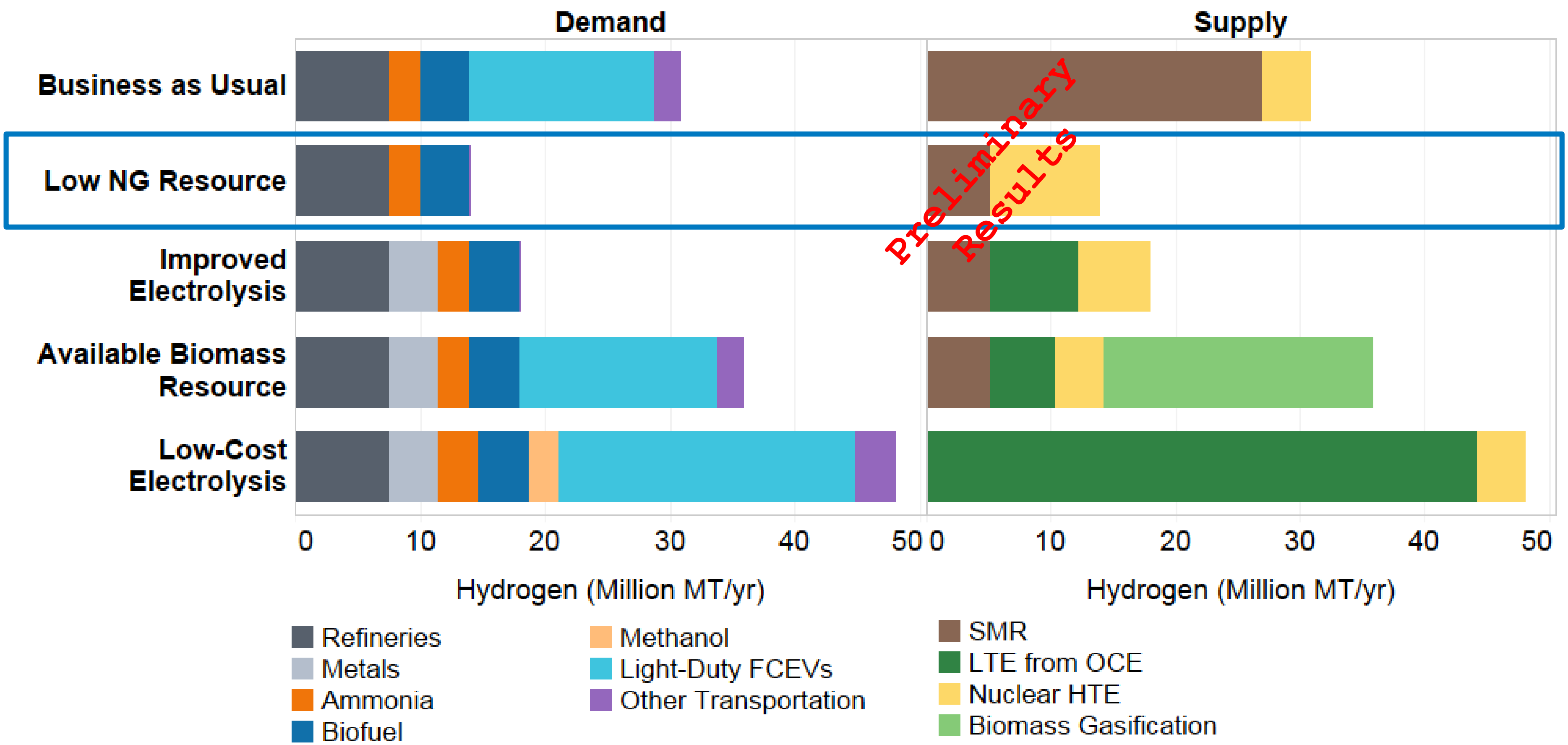


Business as Usual Scenario

Low-cost natural gas drives growth in H_2 markets with some nuclear participation

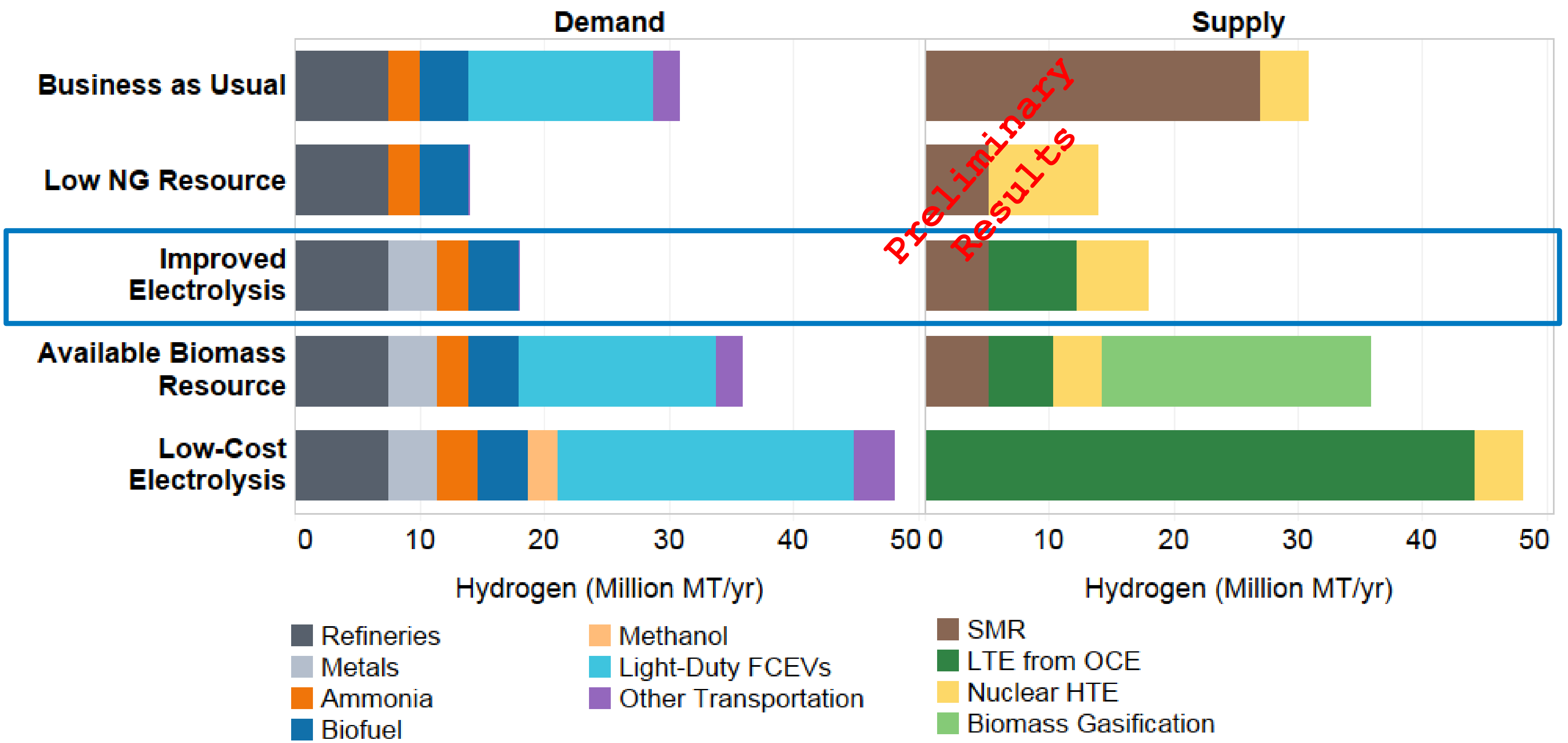
Accomplishment: Developed and Reviewed Economic Potential Results



Low NG Resources Scenario

Higher cost natural gas results in minimal growth in hydrogen applications

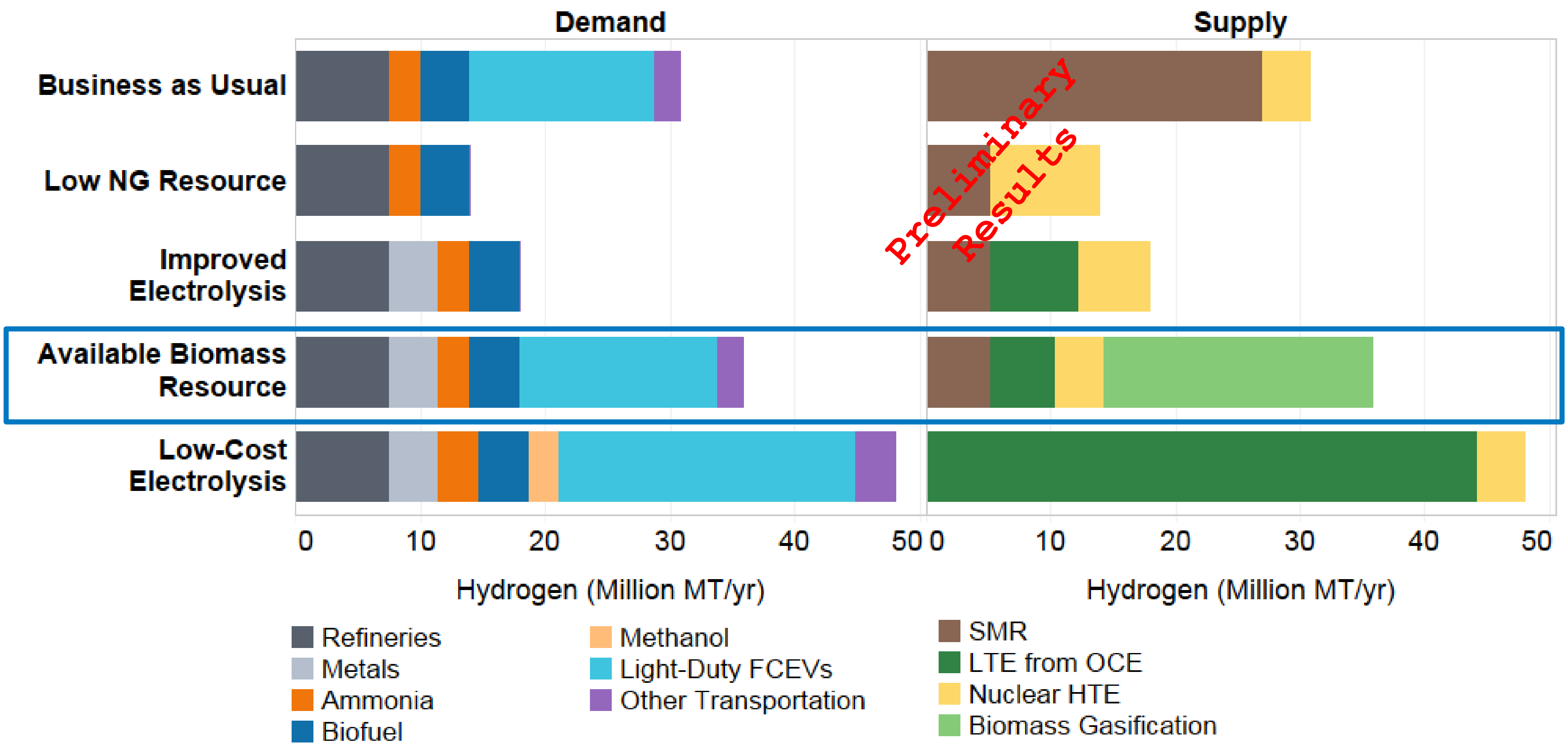
Accomplishment: Developed and Reviewed Economic Potential Results



Improved Electrolysis Scenario

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

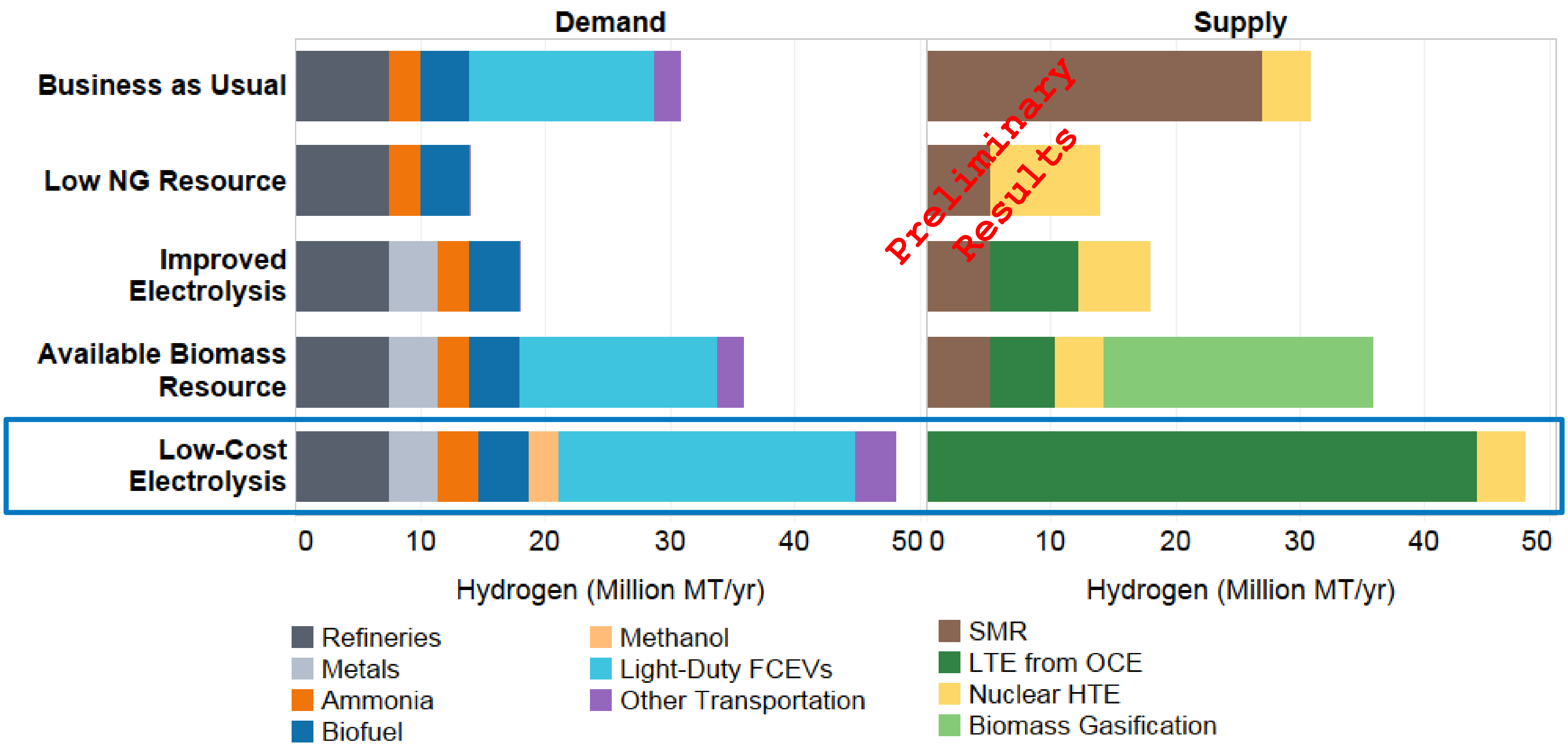
Accomplishment: Developed and Reviewed Economic Potential Results



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

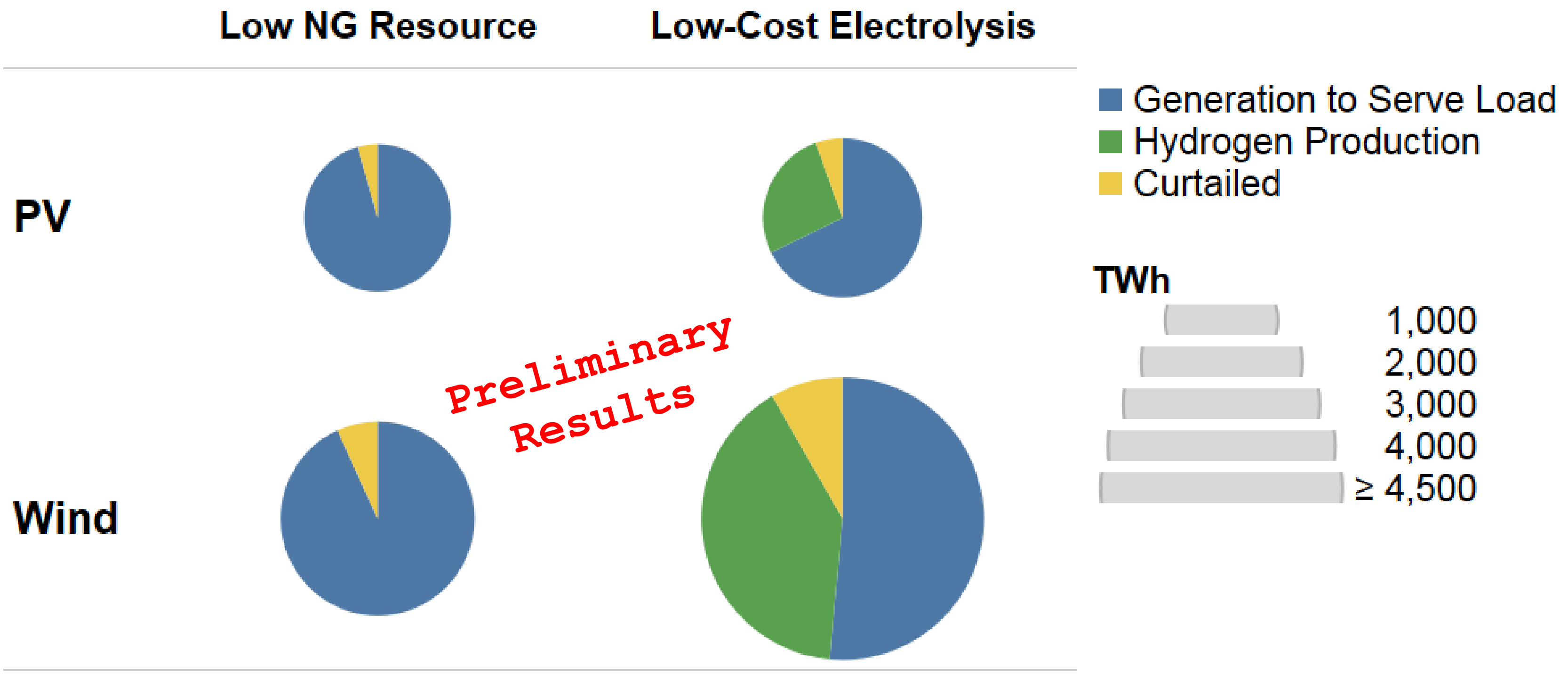


Low-Cost Electrolysis Scenario

Low-cost electrolyzers with high grid value can enable additional H2 applications

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
NREL	Lead; production cost estimates, supply-demand scenarios, impact assessments, spatial and temporal analysis, case studies
ANL	Deputy lead; hydrogen demand analysis, emission and water use impact analysis
LBNL	Support scenario development
PNNL	Support scenario development
INL	Nuclear and metals characterization
LLNL	Visualizations including Sankey diagrams
Office of Nuclear Energy	Identify synergies between H2@Scale and nuclear energy

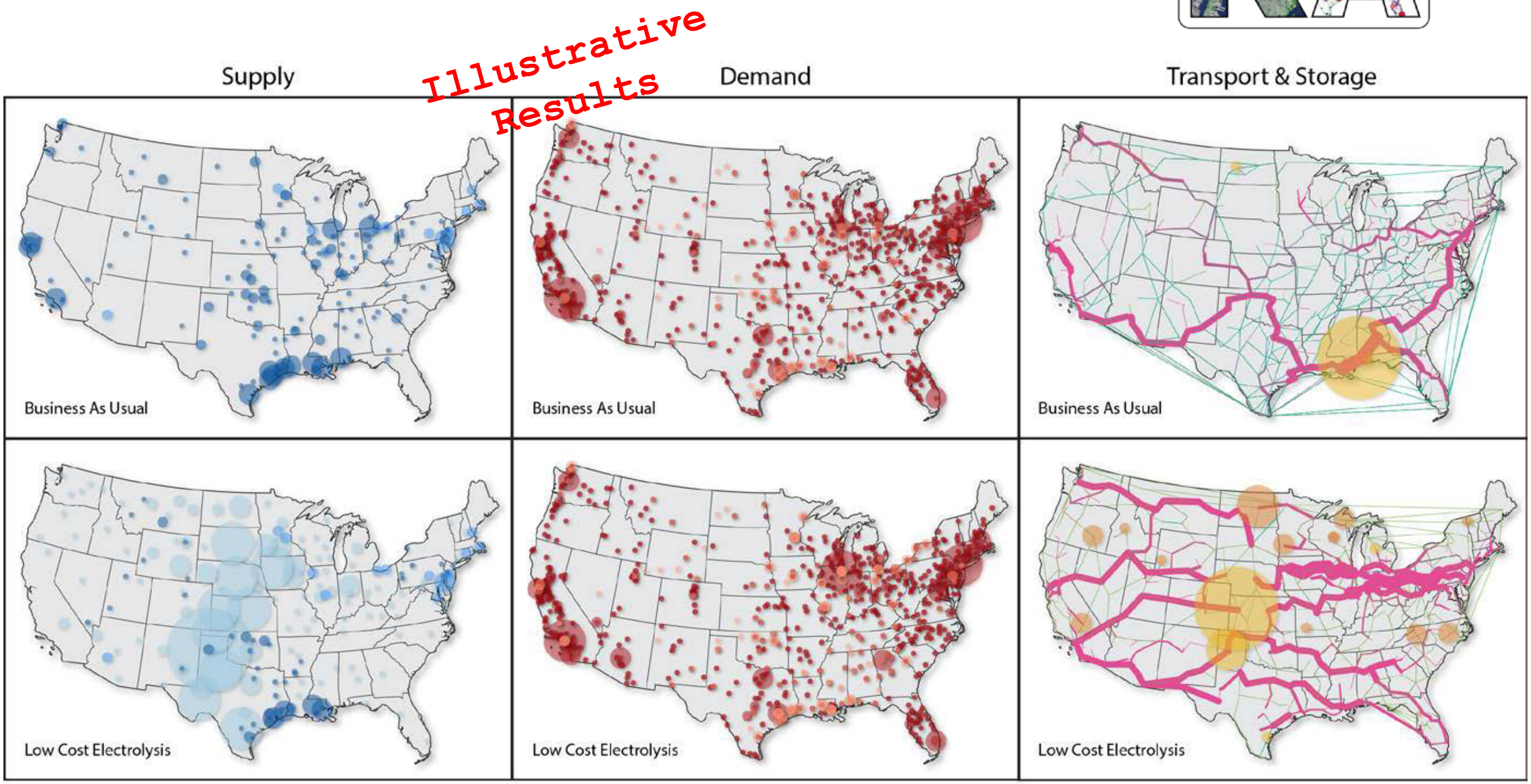
Organizations Providing Input and Review
EPRI
SoCal Gas
California Air Resources Board
Exelon
Shell
ExxonMobil
General Motors
NH3 Energy Association
Nexceris
DOE Office of Nuclear Energy
DOE EERE Offices (Fuel Cell Technologies Office, Solar Energy Technologies Office, Wind Energy Office, Bioenergy Technologies Office)
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

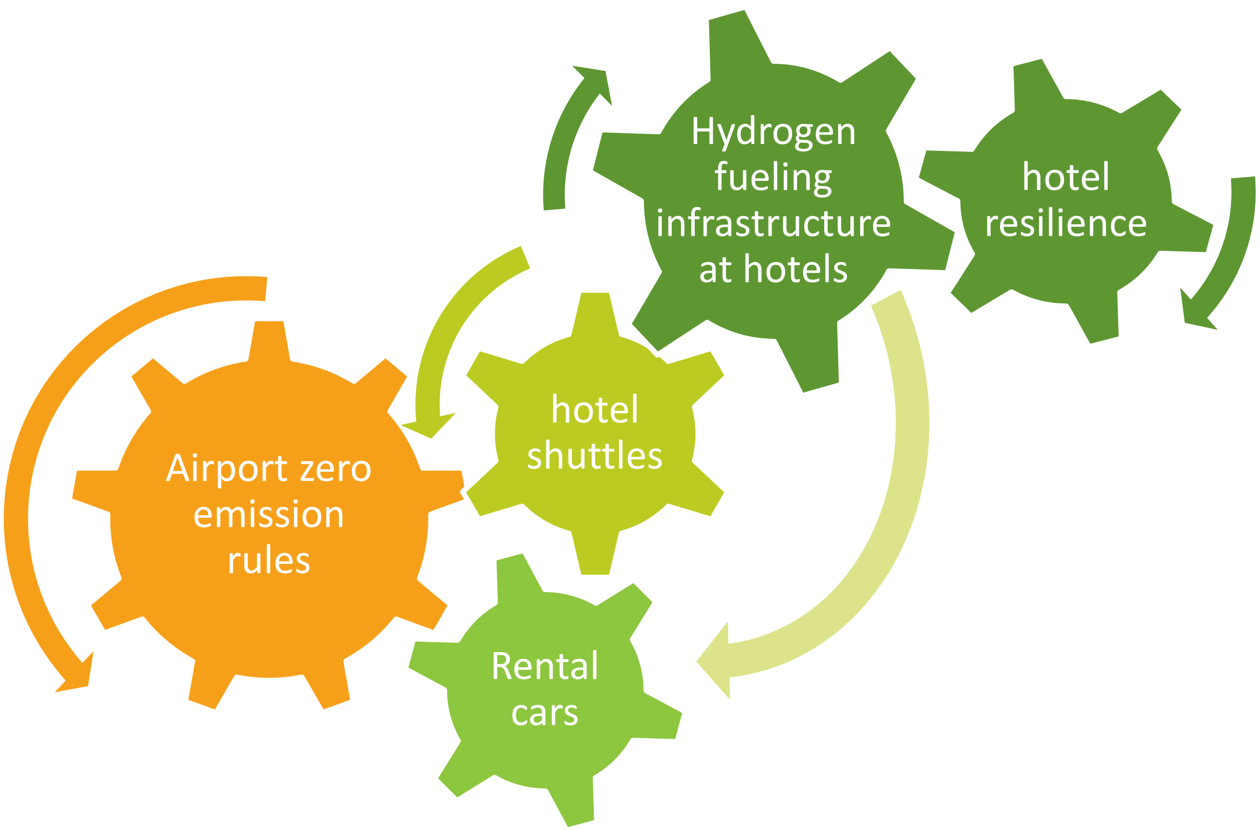
We are using the Scenario Evaluation and Regionalization Analysis (SERA) Model estimate optimal transport and storage infrastructure



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 H_2/ yr***
- **Economic potential:** ***14 - 48 MMT H_2 / yr***
- **Use of low-cost, low-availability electricity could increase wind & solar PV markets**

H_2 @Scale:

Energy system-wide benefits of increased H_2 implementation

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.

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

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NREL/PR-6A20-73559

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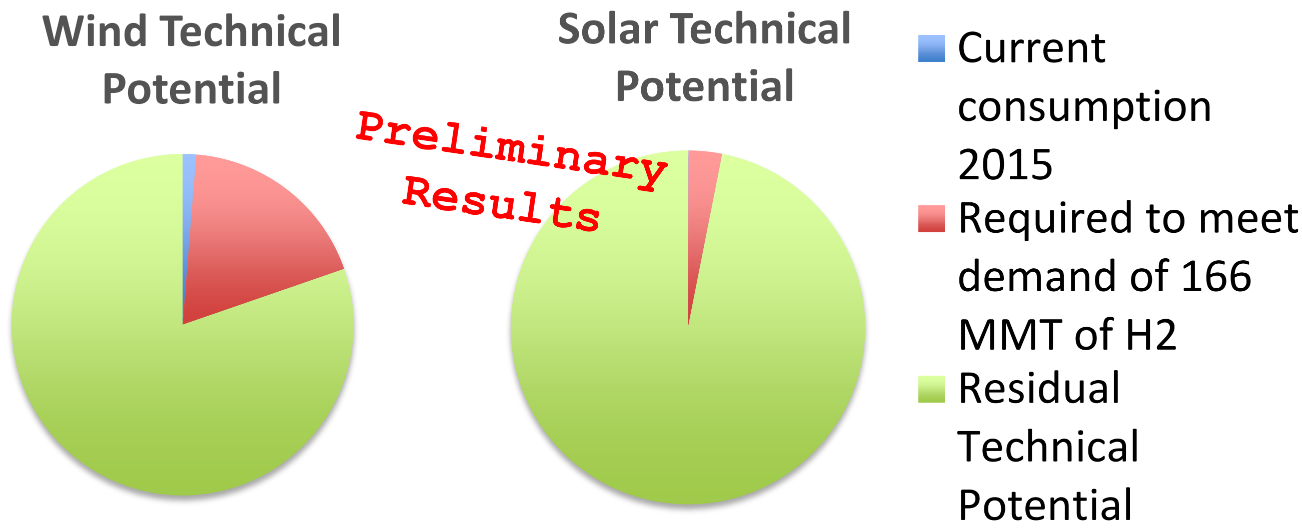
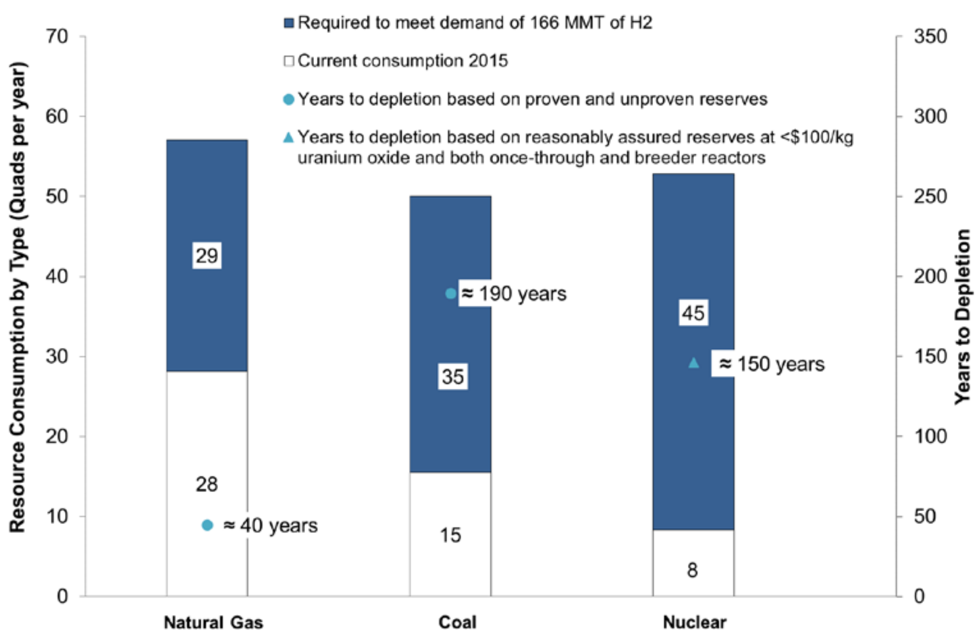
NREL Transforming ENERGY

Technical Backup Slides

Technical Potential Supply from Renewable, Fossil, and Nuclear Resources

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





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

ReEDS Results

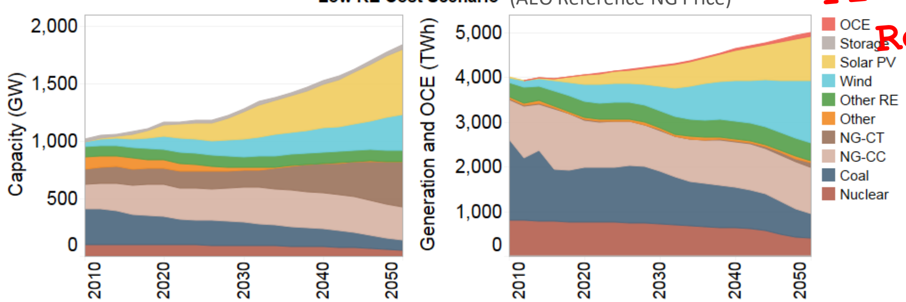
Used ReEDS to estimate generator fleet and generation mix at multiple OCE values

Buildout with $0/MWh OCE

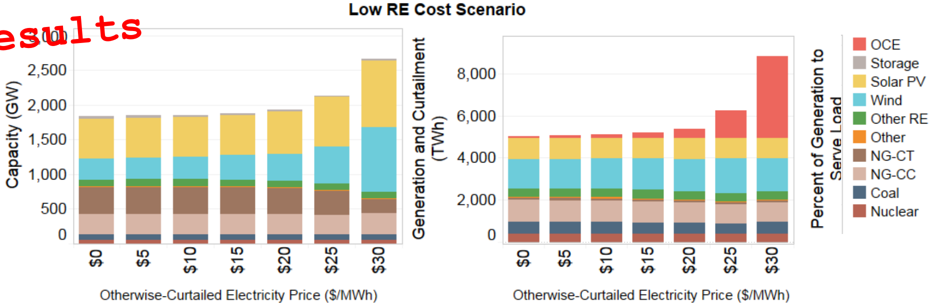
2050 Results at Various OCE Values

Preliminary Results

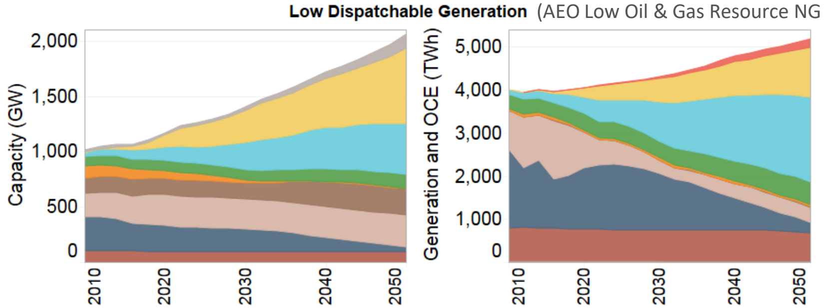
Low RE Cost Scenario (AEO Reference NG Price)



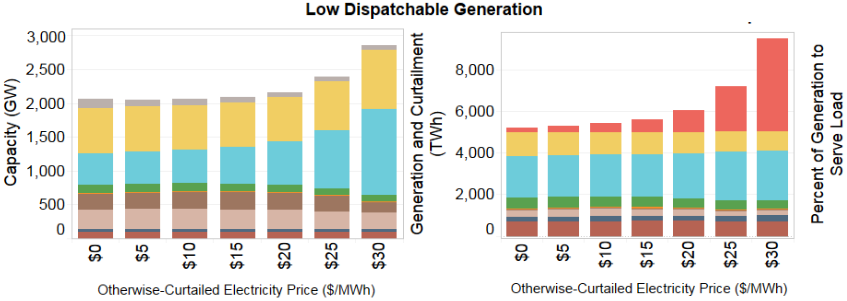
Low RE Cost Scenario



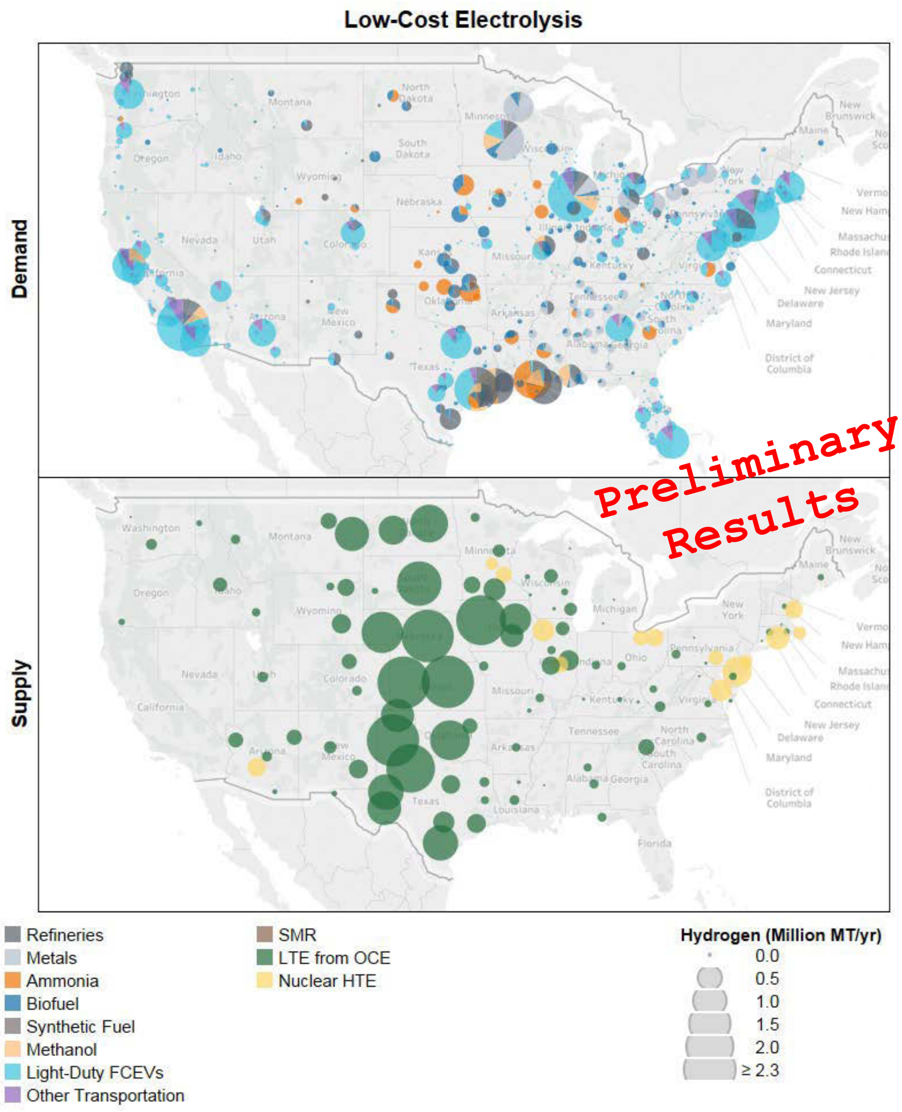
Low Dispatchable Generation (AEO Low Oil & Gas Resource NG Price)



Low Dispatchable Generation

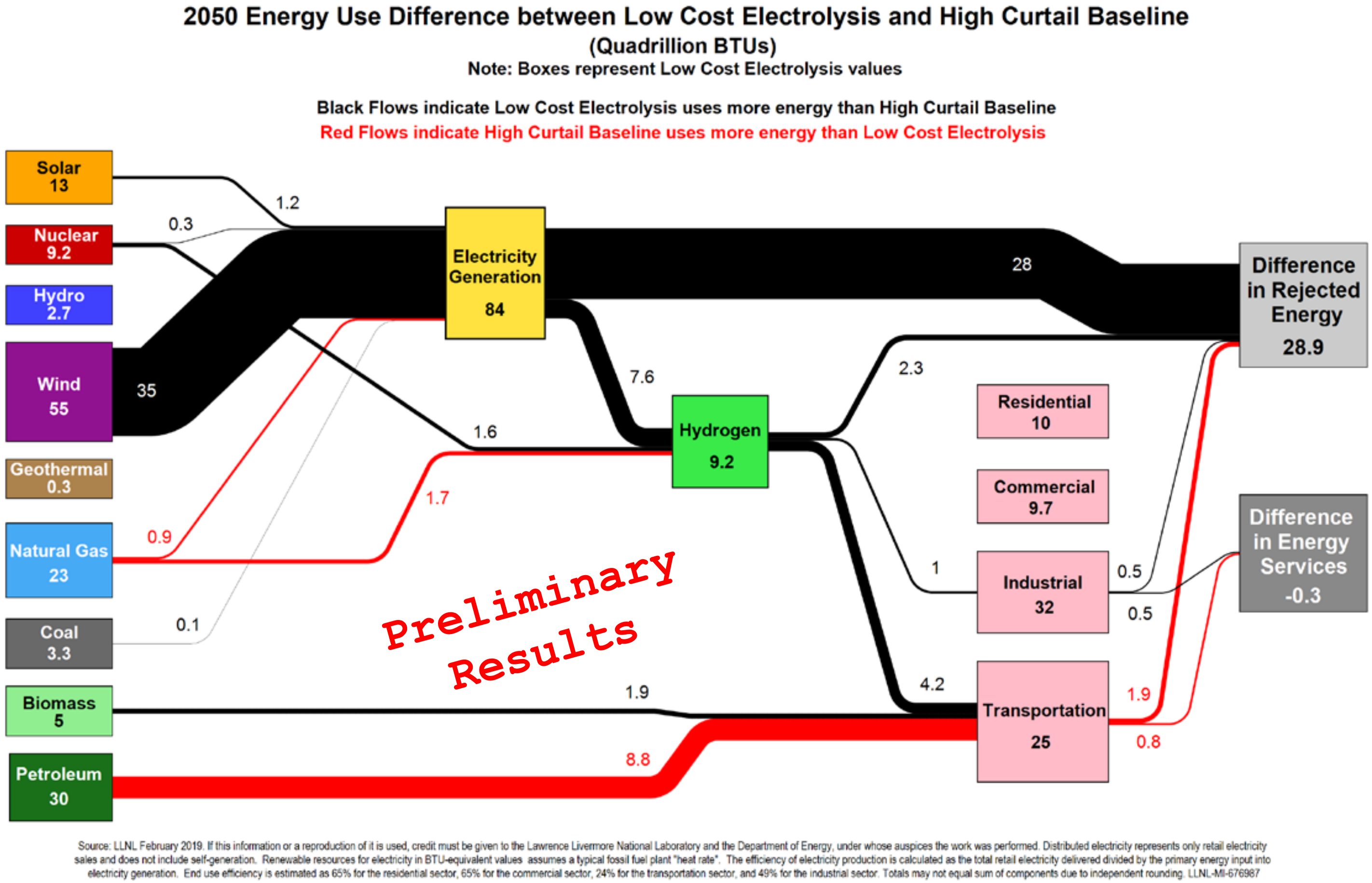


Accomplishment: Identified Spatial Aspects of Economic Potential Scenarios



- 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



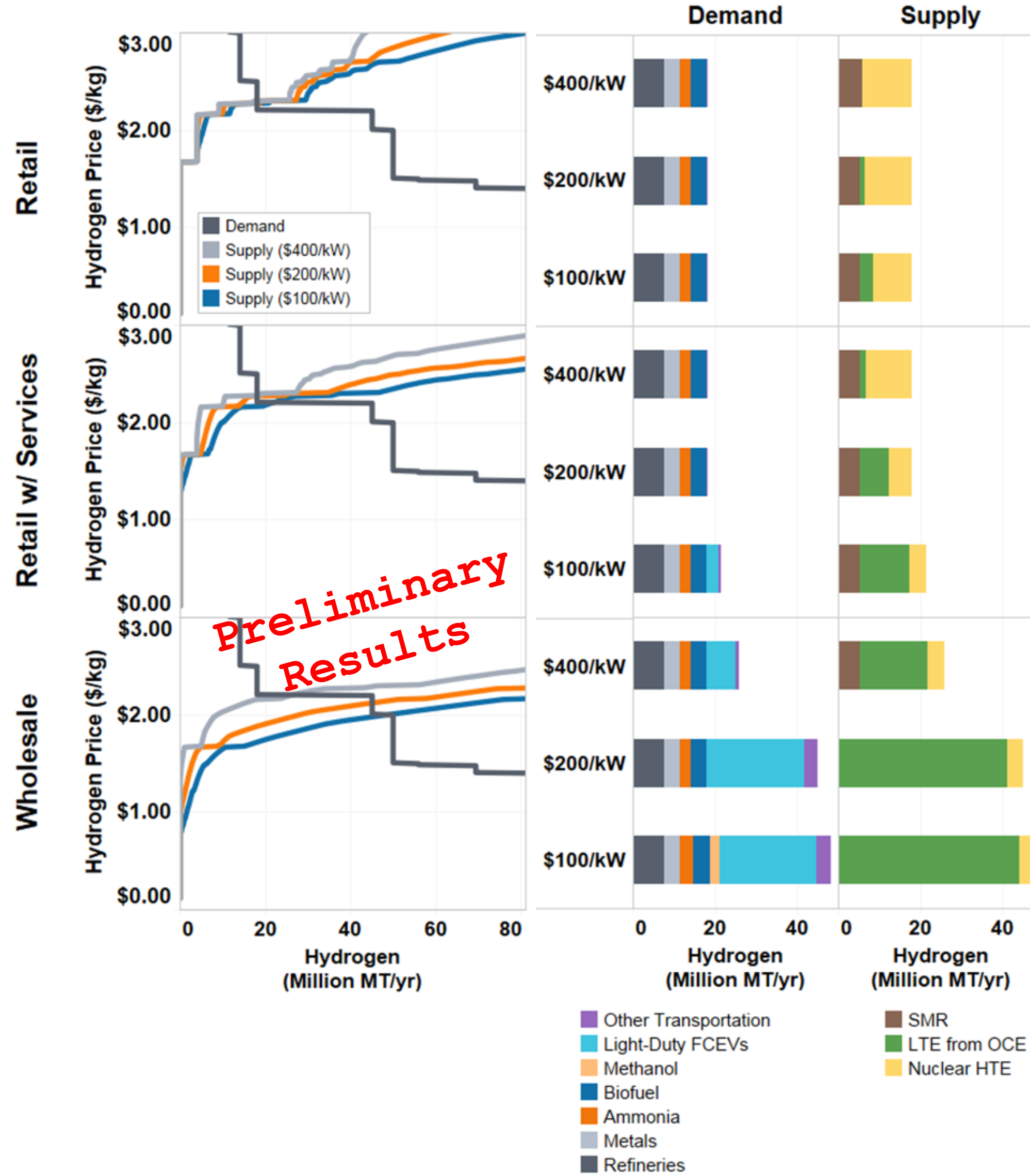
The Low-Cost Electrolysis Scenario primarily offsets oil for transportation with hydrogen from wind. It also reduces natural gas for electricity and hydrogen production.

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
NH3	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