H2@Scale Analysis

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National Renewable Energy Laboratory
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DOE Hydrogen and Fuel Cells Program
2018 Annual Merit Review and Peer Evaluation Meeting

Project ID # TV045

Overview

Timeline and Budget

- Project Type: Lab Call
- Project start date: 1/1/17
- FY17 DOE funding: $2,000K
  - NREL: $1,300K
  - ANL: $500K
  - LBNL: $50K
  - PNNL: $100K
  - LLNL: $50K
  - INL: Funded by DOE's Office of Nuclear Energy
- No FY18 funding
- Total DOE funds received to date: $2,000K

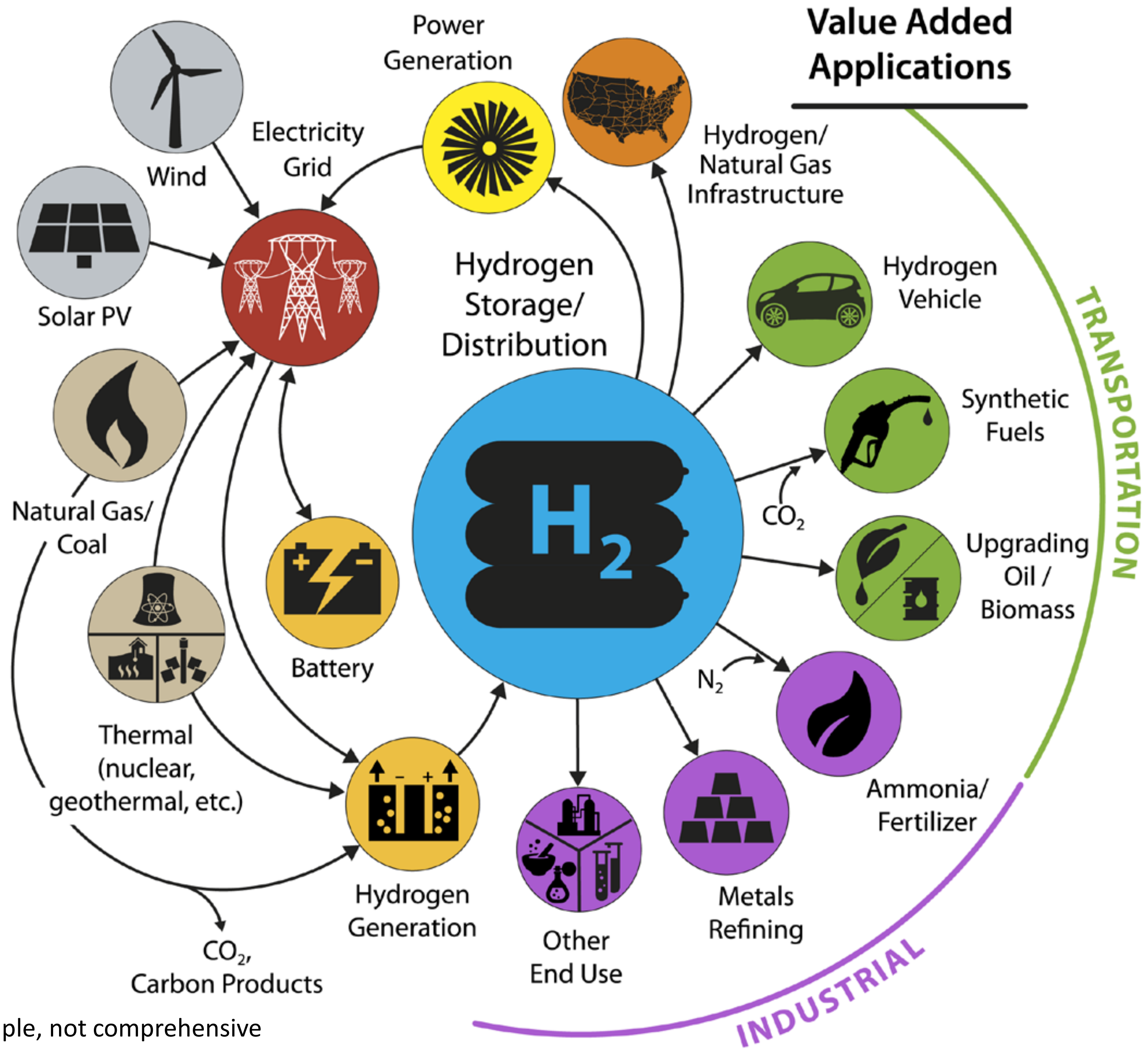
Partners

- 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 R&D

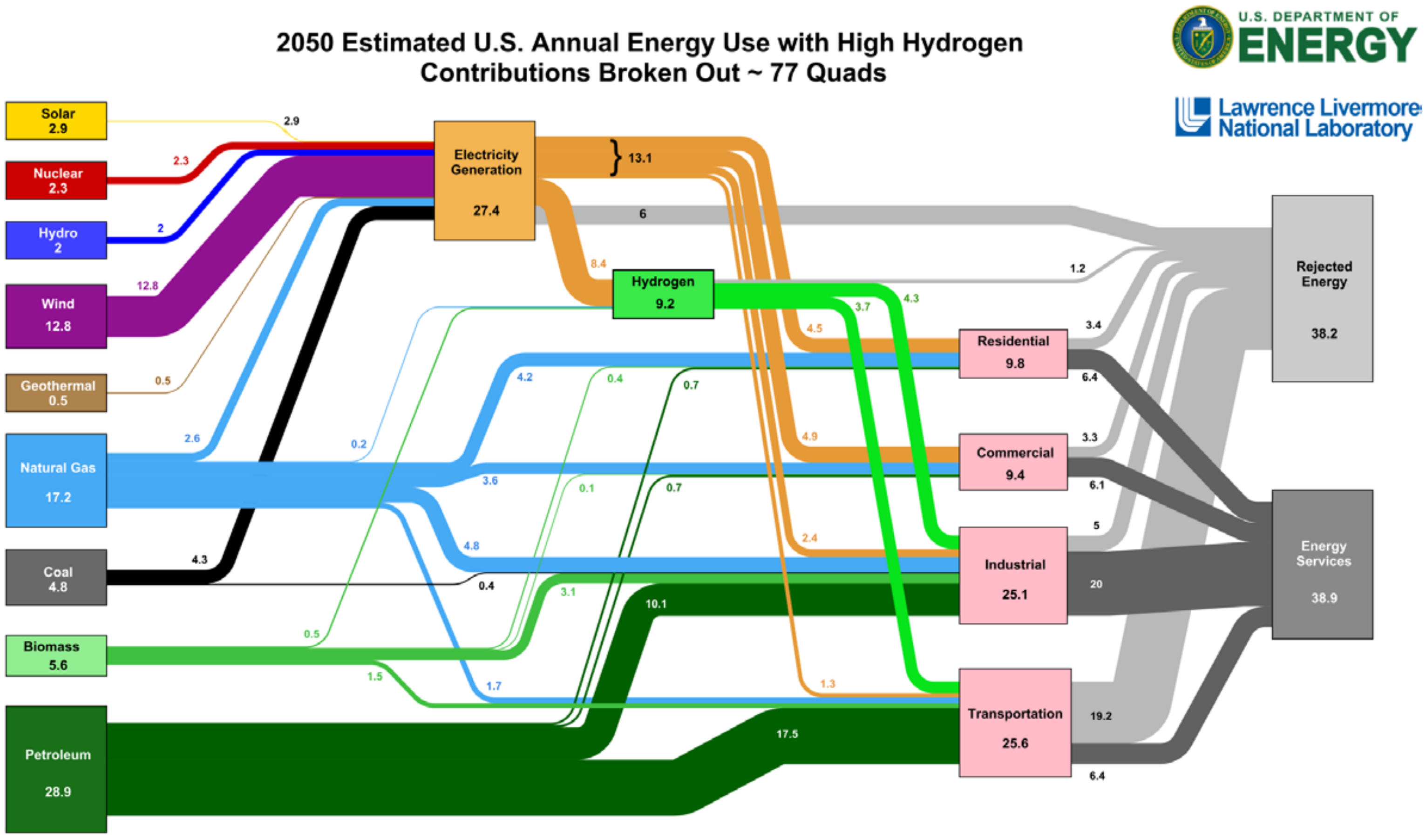
Relevance: Conceptual H2@Scale Energy System*



*Illustrative example, not comprehensive

Relevance: Improve Fidelity of H2@Scale Value Proposition

Preliminary analysis in 2016 showed opportunity for H2@Scale



Source: LLNL September 2015. Data is based on High Hydrogen Estimations and DOE/EIA-0383(2014). 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. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming 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, 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-676987

Please note, all results presented on this slide are PRELIMINARY and may be subject to corrections and/or changes. A cursory analysis was performed using available information and estimates of impacts due to changes to the modeled energy systems.

Source: Pivovar, Bryan. "H2@Scale: Deeply Decarbonizing Our Energy System HTAC Presentation" April 6, 2016. https://www.hydrogen.energy.gov/pdfs/htac_apr16_10_pivovar.pdf

Relevance: Improve Fidelity of H2@Scale Value Proposition

Preliminary analysis in 2016 showed opportunity for H2@Scale

2050 Estimated U.S. Annual Energy Use with High Hydrogen Contributions Broken Out ~ 77 Quads

U.S. DEPARTMENT OF ENERGY

This project is funded under an August 2016 DOE lab call requesting the team

- **Provide results that are supported by in-depth analysis of market potential and economics**
- **Quantify potential impacts**
  - **Economics**
  - **Resources**
  - **Emissions**
- **Identify regional opportunities and challenges**

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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 Standard Scenarios

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
HDSAM
SERA
Sankey Diagram Tool

Studies & Analysis

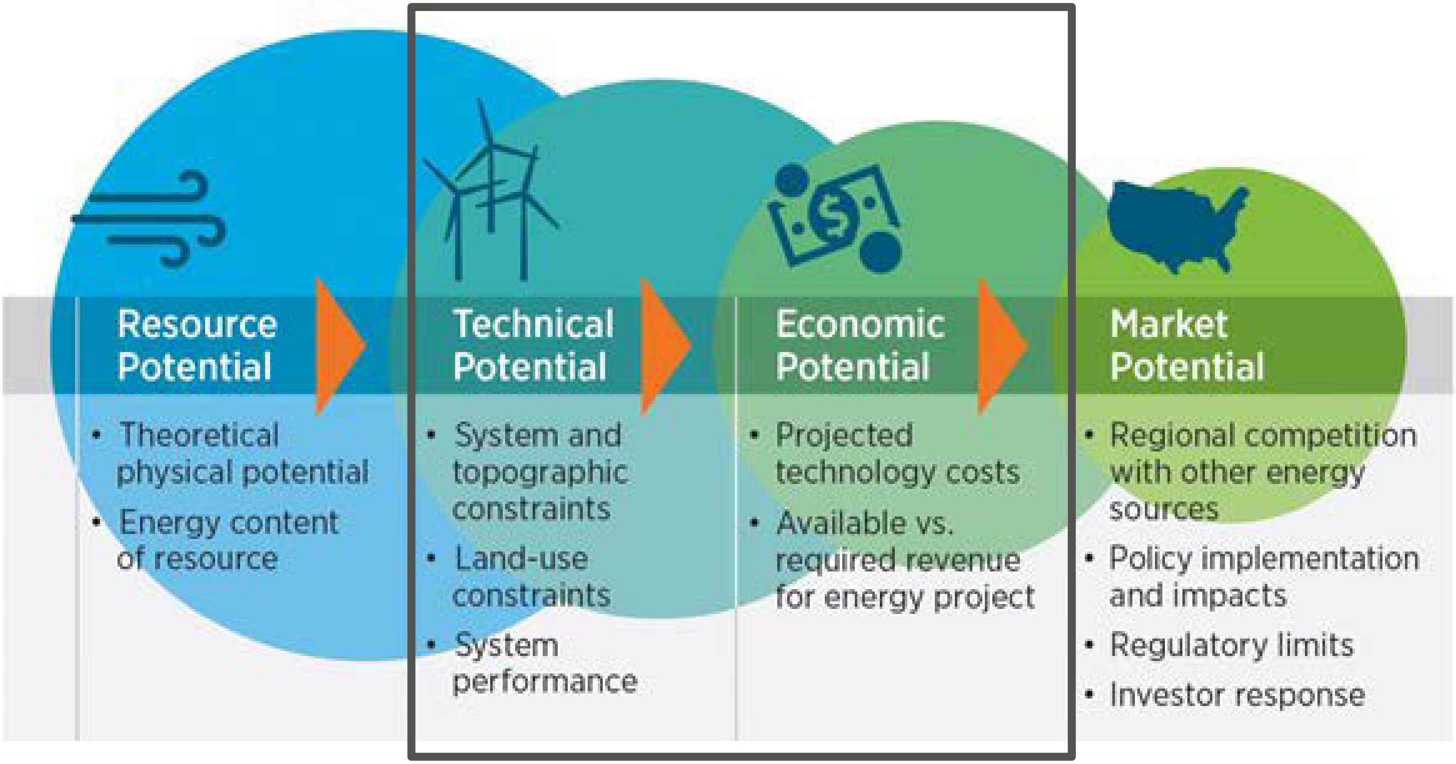
Demand assessment
Resource assessment
Grid analyses
Curtailed electricity
Economic equilibria
Impact assessment

Outputs & Deliverables

Analysis of H2@Scale concept and potential opportunity and impacts

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

Approach: Analyze the Technical and Economic Potential of the H2@Scale Concept

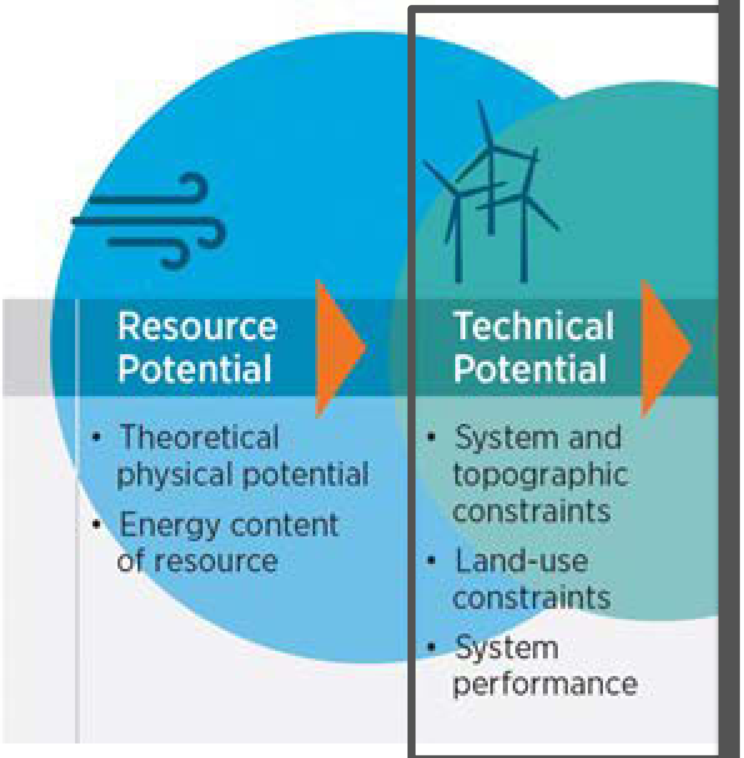


Technical potential – market and resource potential that is constrained by existing end-uses, real-world geography, and system performance. *Not constrained by economics.*

Economic potential – subset of the technical potential where hydrogen is less expensive than other options that can supply the end use.

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

Approach: Technical Potential



- **Identify possible hydrogen markets and estimate their technical potential**
- **Estimate resource requirements to meet all of those markets and compare them to the technical potential resource**
- **Compare county-level technical potential for demands to supplies**

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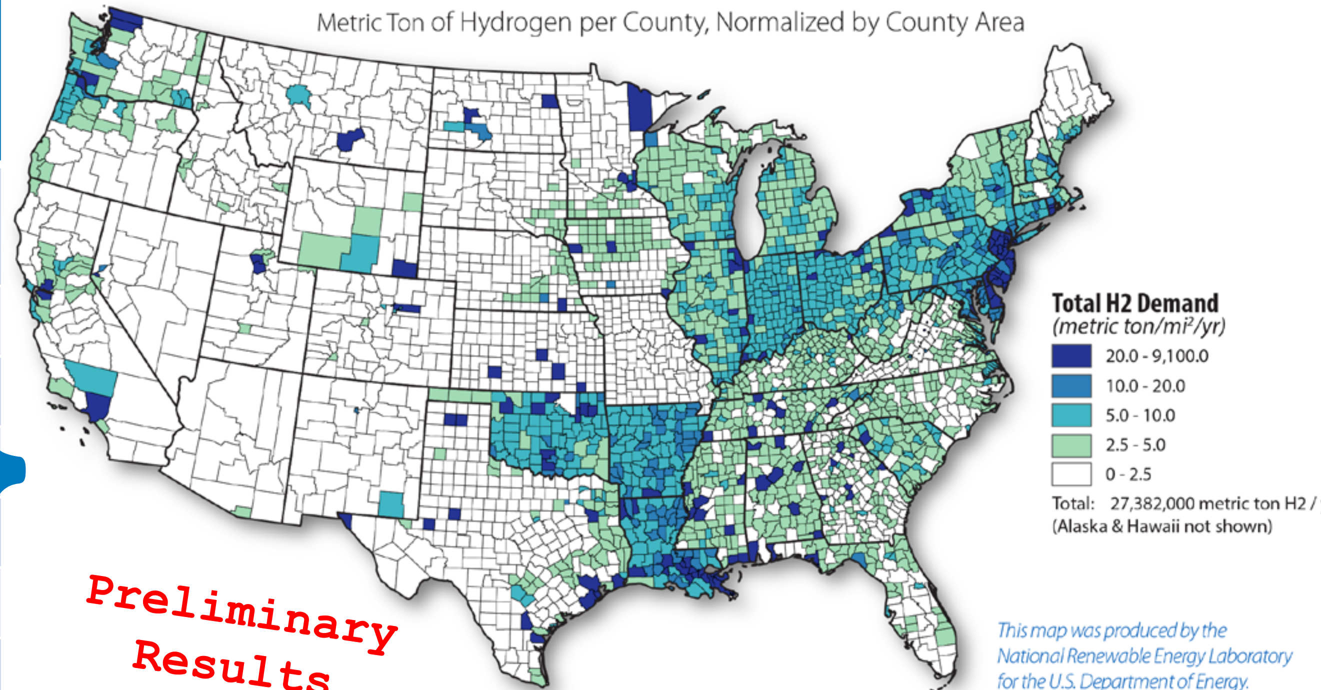
Accomplishment: Estimated Technical Potential Hydrogen Demand

Demand	Technical potential (MMT* / year)
Refineries & CPI§	8
Metals	6
Ammonia	5
Methanol	1
Biofuels	1
Natural Gas	7
Light Duty Vehicles	28
Other Transport	3
Electricity Storage	28
Total	**87**



This analysis represents the total hydrogen demand estimated to be achievable in the U.S. in the following sectors: refineries, biofuels, ammonia, metals, methanol, natural gas systems, and seasonal energy storage. Each industrial sector was summarized by county to identify the total hydrogen demand for the industrial sector and then normalized by area.

Data Source: NREL analysis

This map was produced by the National Renewable Energy Laboratory for the U.S. Department of Energy. Nicholas Gilroy, April, 2018

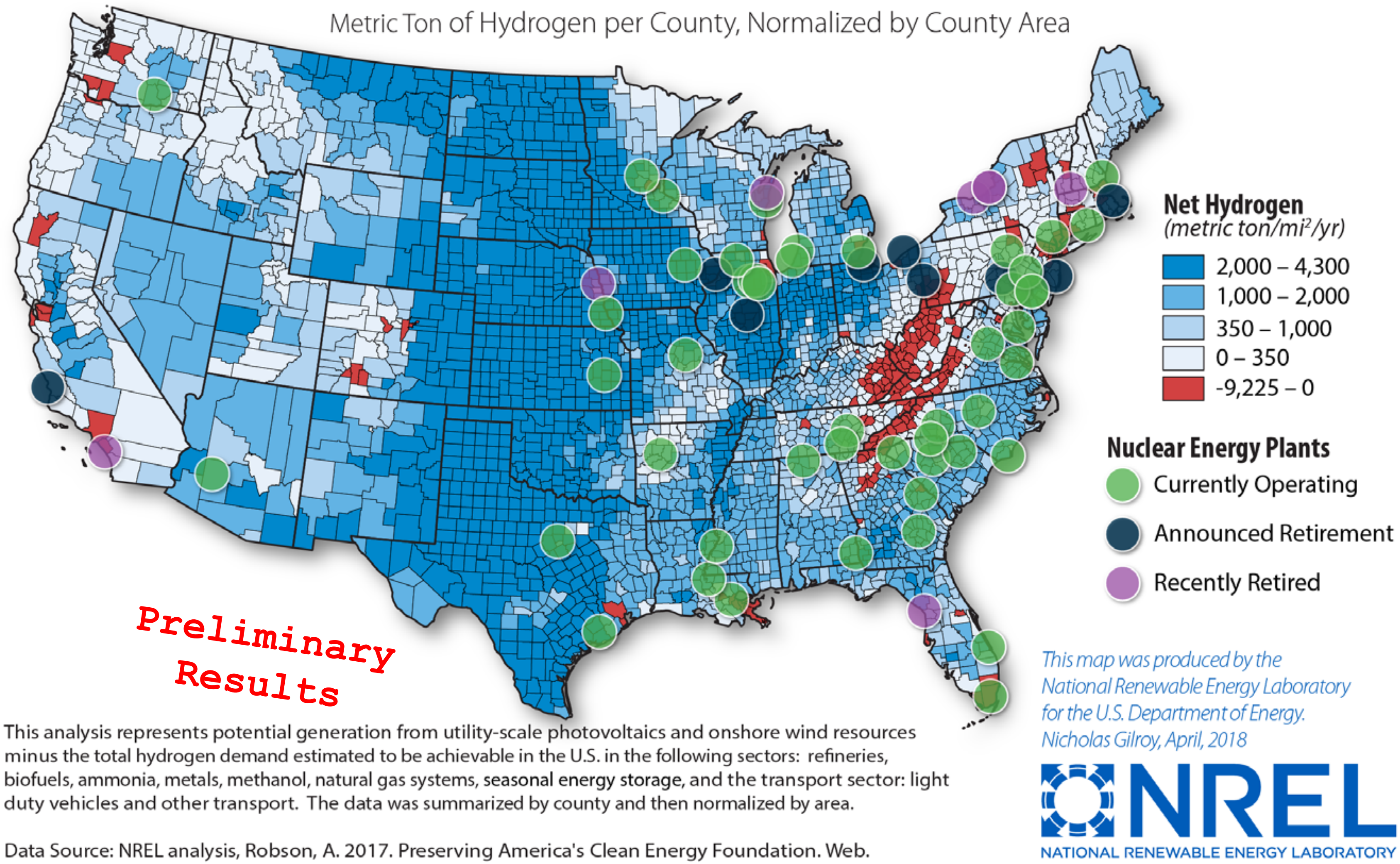
NREL NATIONAL RENEWABLE ENERGY LABORATORY

Technical Potential Demand: 87 MMT/yr

Current U.S. market: ≈ 13 MMT/yr
Including captive generation for ammonia and refining

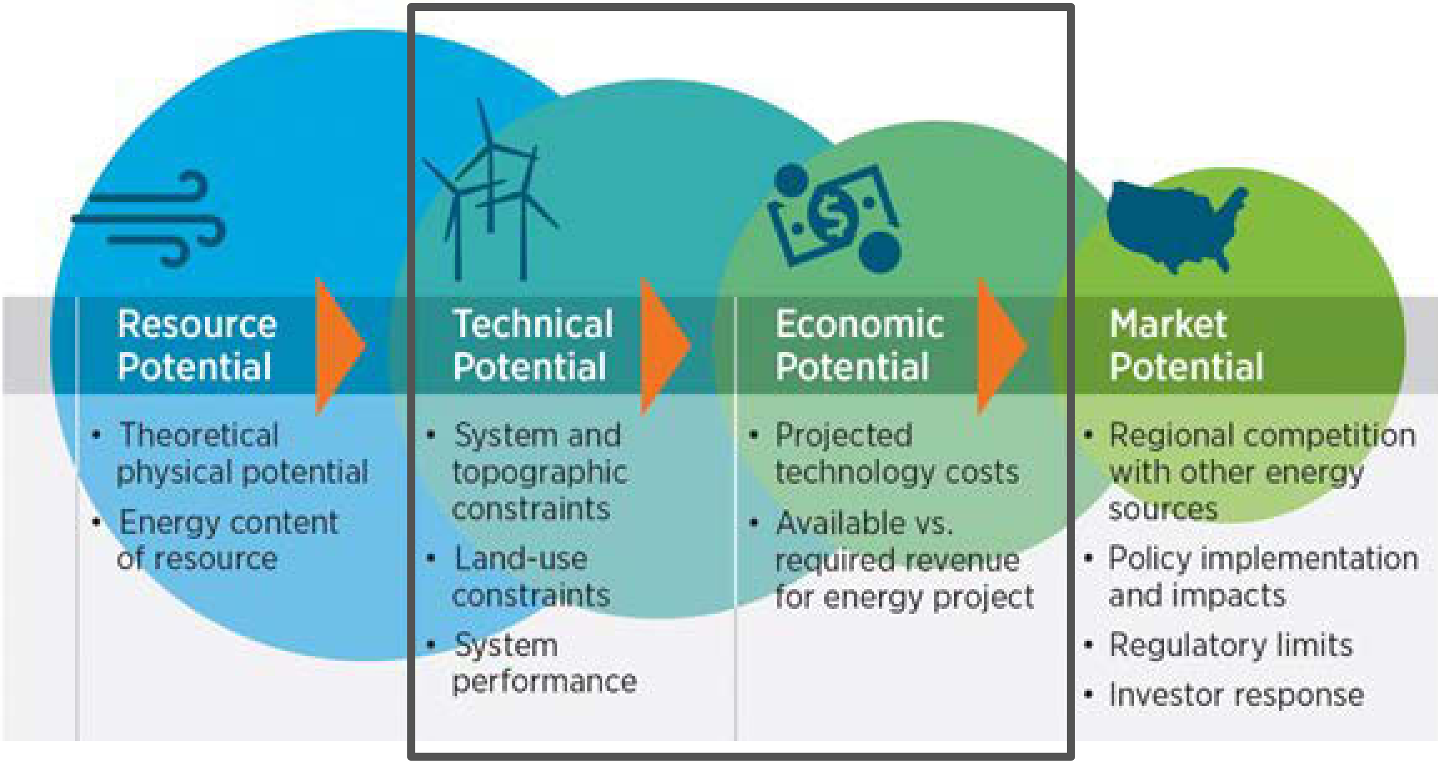
* MMT: Million metric tonnes
§ CPI: Chemical Processing Industry not including metals, ammonia, methanol, or biofuels
Light duty vehicle calculation basis: 190,000,000 light-duty FCEVs from http://www.nap.edu/catalog/18264/transitions-to-alternative-vehicles-and-fuels

Accomplishment: Resource Sufficiency to Meet Technical Potential Demand



Most counties have sufficient renewable resources. Those without have sufficient renewable or nuclear resources nearby.

Approach: Analyze the Technical and Economic Potential of the H2@Scale Concept



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Approach: Economic Potential

- **Develop national demand curves that quantify willingness to pay for hydrogen**
- **Develop national supply curves that link price and willingness to produce hydrogen**
- **Quantify hydrogen market sizes and prices for several scenarios and quantify impacts**

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raphy, and system performance. *Not*

Economic potential – subset of the technical potential where hydrogen is less expensive than other options that can supply the end use.

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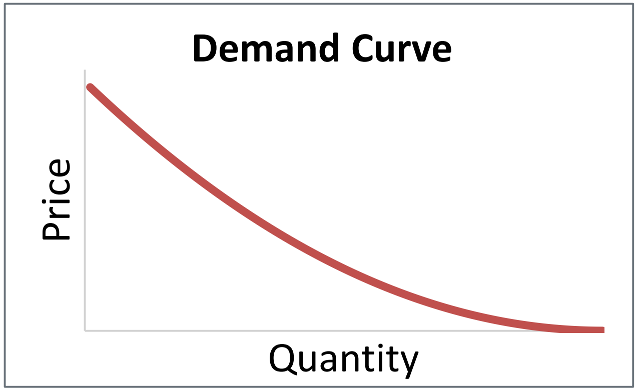
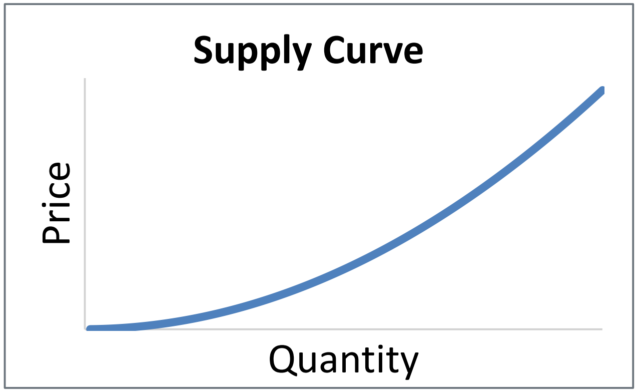
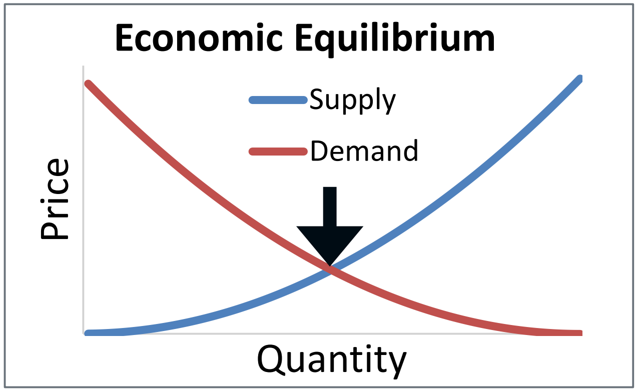
Approach: Estimate Economic Potential as Hydrogen Prices and Quantities at Market Equilibria



Demand Curve: how much are consumers willing and able to pay for a good?



Supply Curve: how much are producers willing and able to produce at various prices?



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

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

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

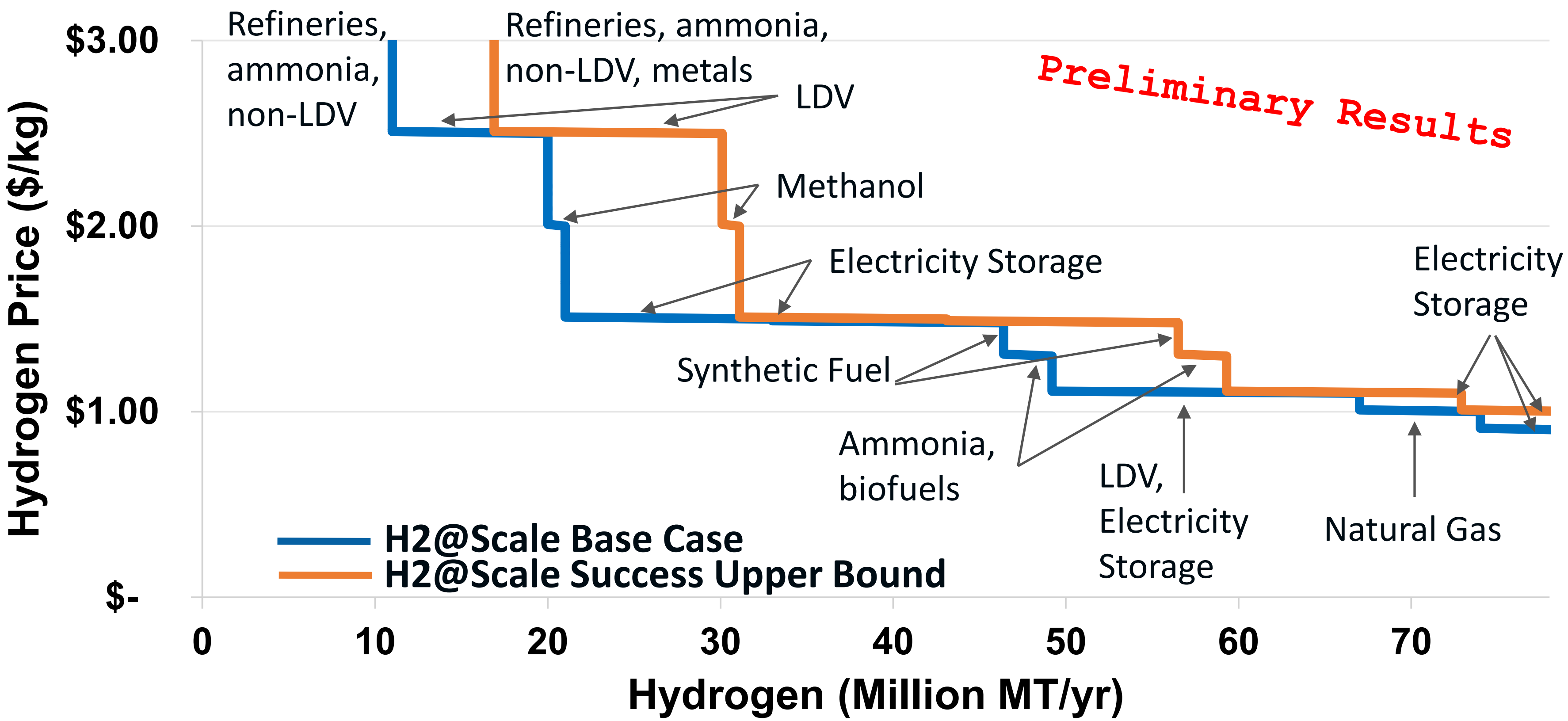
Approach: Developed Four Scenarios to Explore a Range of Economic Possibilities

Scenario Name	Traditional Energy Focus	H2@Scale Success Lower Bound	H2@Scale Base Case	H2@Scale Success Upper Bound
Scenario Definition	Limited H_2 demand growth; no electrolysis for grid support; low natural gas prices	Robust cross-sector H_2 demand growth; electrolysis providing grid support; low natural gas prices	Robust transportation H_2 demand growth; limited electrolysis for grid support; high natural gas prices	Robust cross-sector H_2 demand growth; electrolysis providing grid support; high natural gas prices
Natural Gas Price Assumptions	↓	↓	↑	↑
Otherwise- Curtailed Electricity Assumptions	↓	↑	↑	↑
Demand Assumptions	↓	↑	↓	↑

Arrows indicate direction of expected impact on the size of the hydrogen market. Details in the supporting slides

Accomplishment: Developed Demand Curves

Estimated market size and willingness to pay for 10 applications on a national basis – range is >$3/kg for refining and ammonia to ≤$1/kg for injection into the natural gas system and some seasonal electricity storage.



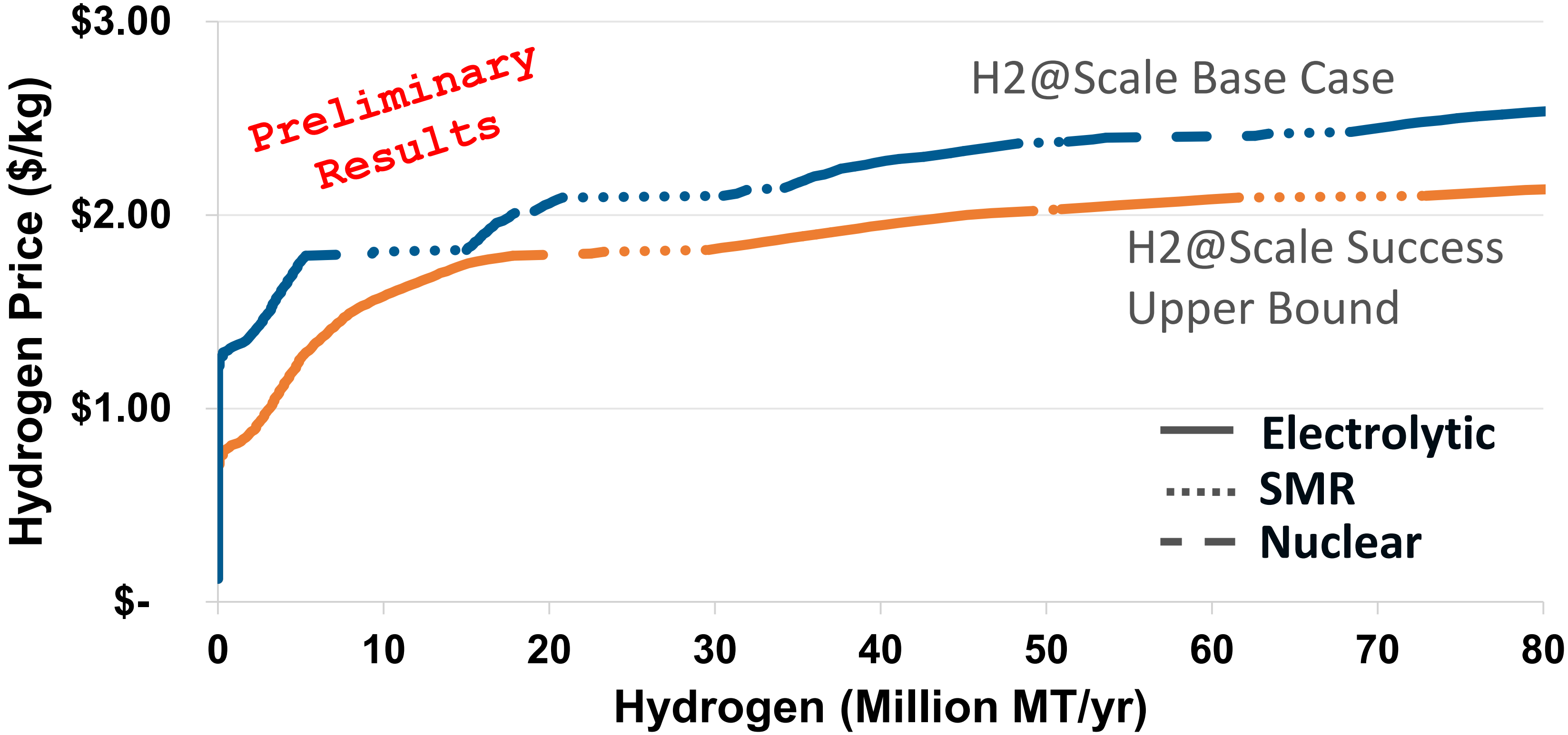
LDV: Light Duty Vehicles; "non-LDV" indicates energy for medium and heavy duty vehicle transportation
List of the 10 markets and demand curves for the other two scenarios are presented in the supporting slides

Accomplishment: Developed Supply Curves

Estimated price necessary to produce hydrogen from

- **Otherwise curtailed electricity via low-temp. electrolysis;**
- **Existing nuclear generation via high-temp. electrolysis; and**
- **Steam methane reforming of natural gas.**

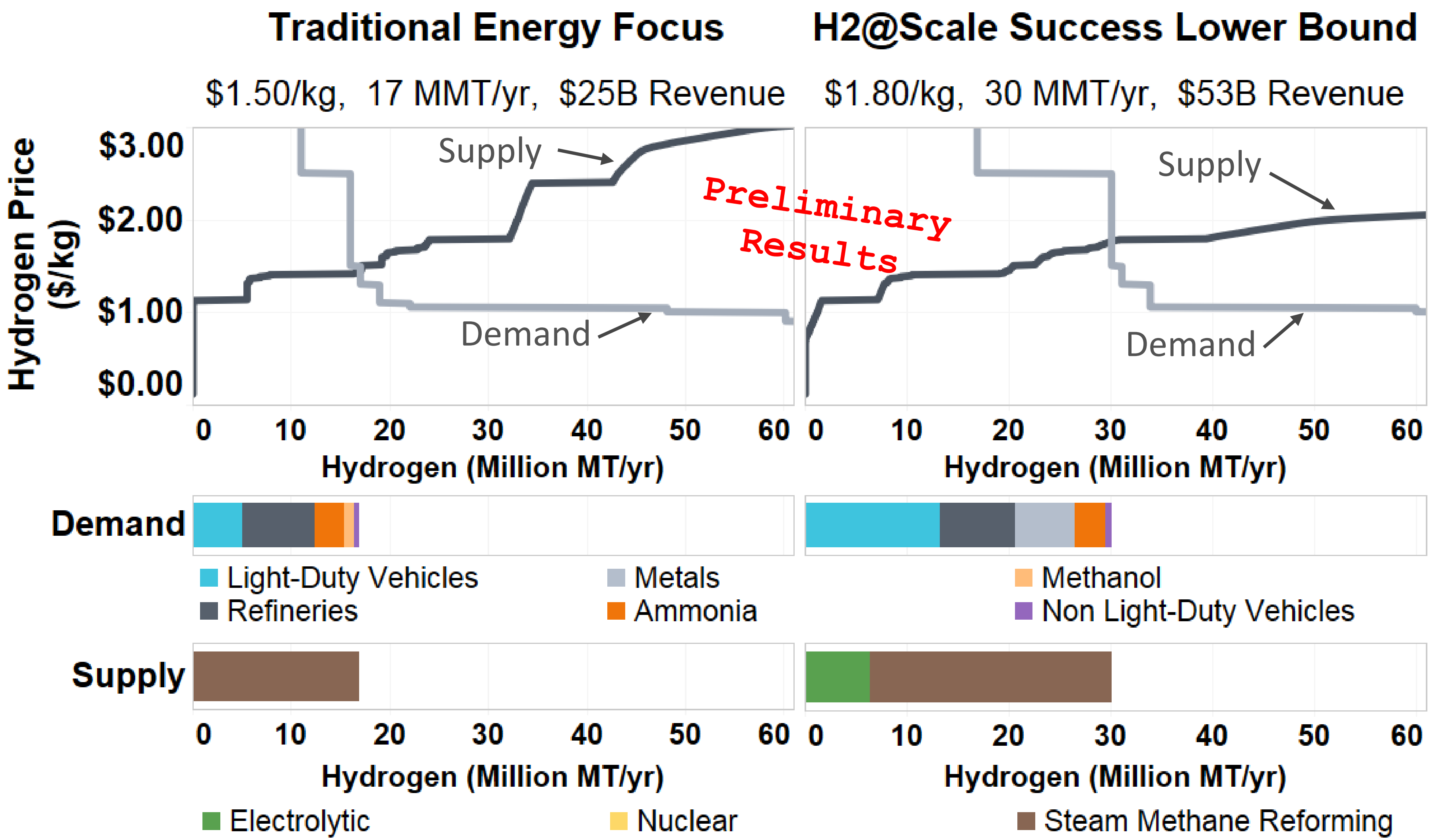
Aggregated supply curves and added delivery costs.



Supply curves for the other two scenarios are presented in the supporting slides

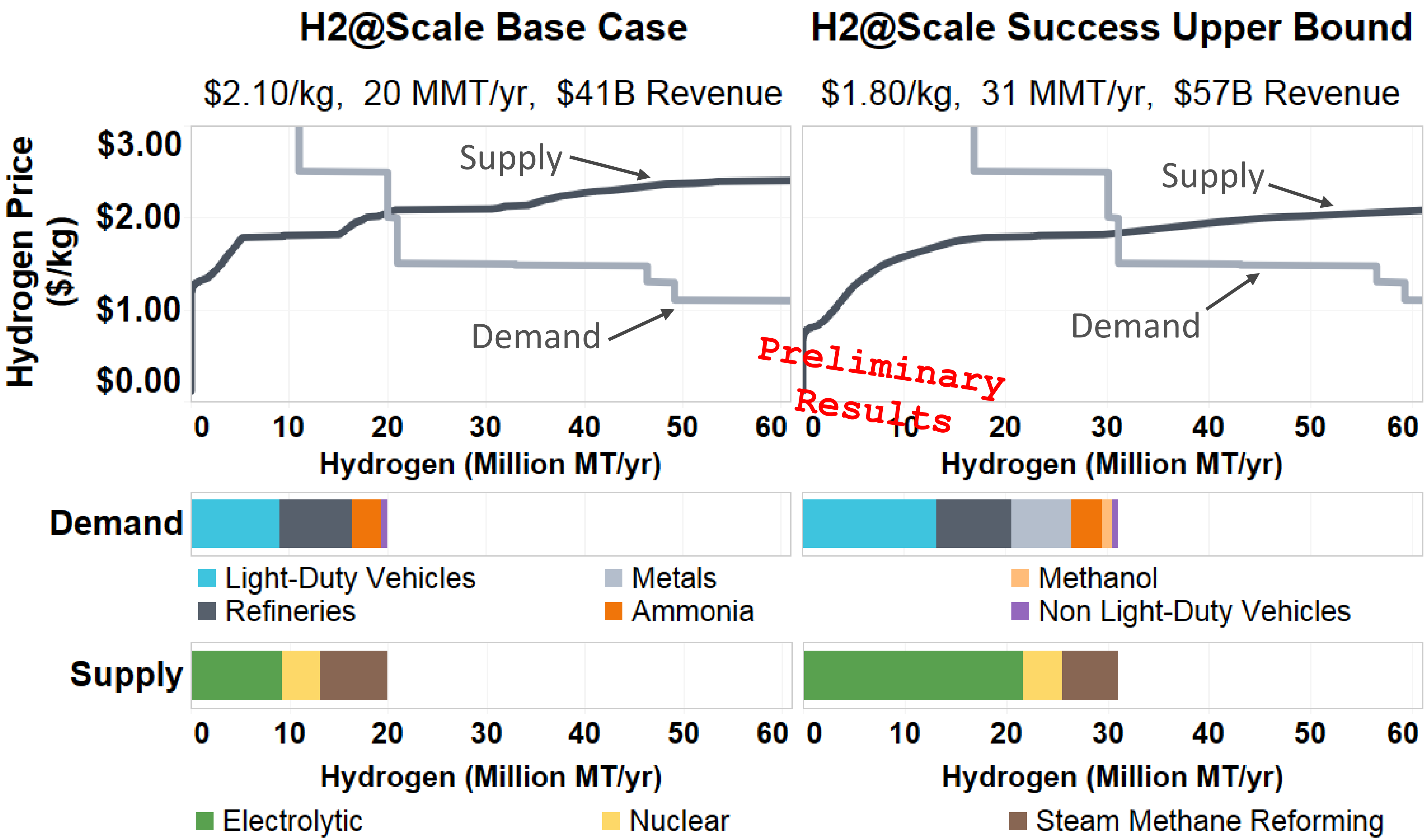
Accomplishment: Developed Four Economic Potential Scenarios

Estimated hydrogen market size: 17-30 MMT/yr with AEO Reference Natural Gas prices.



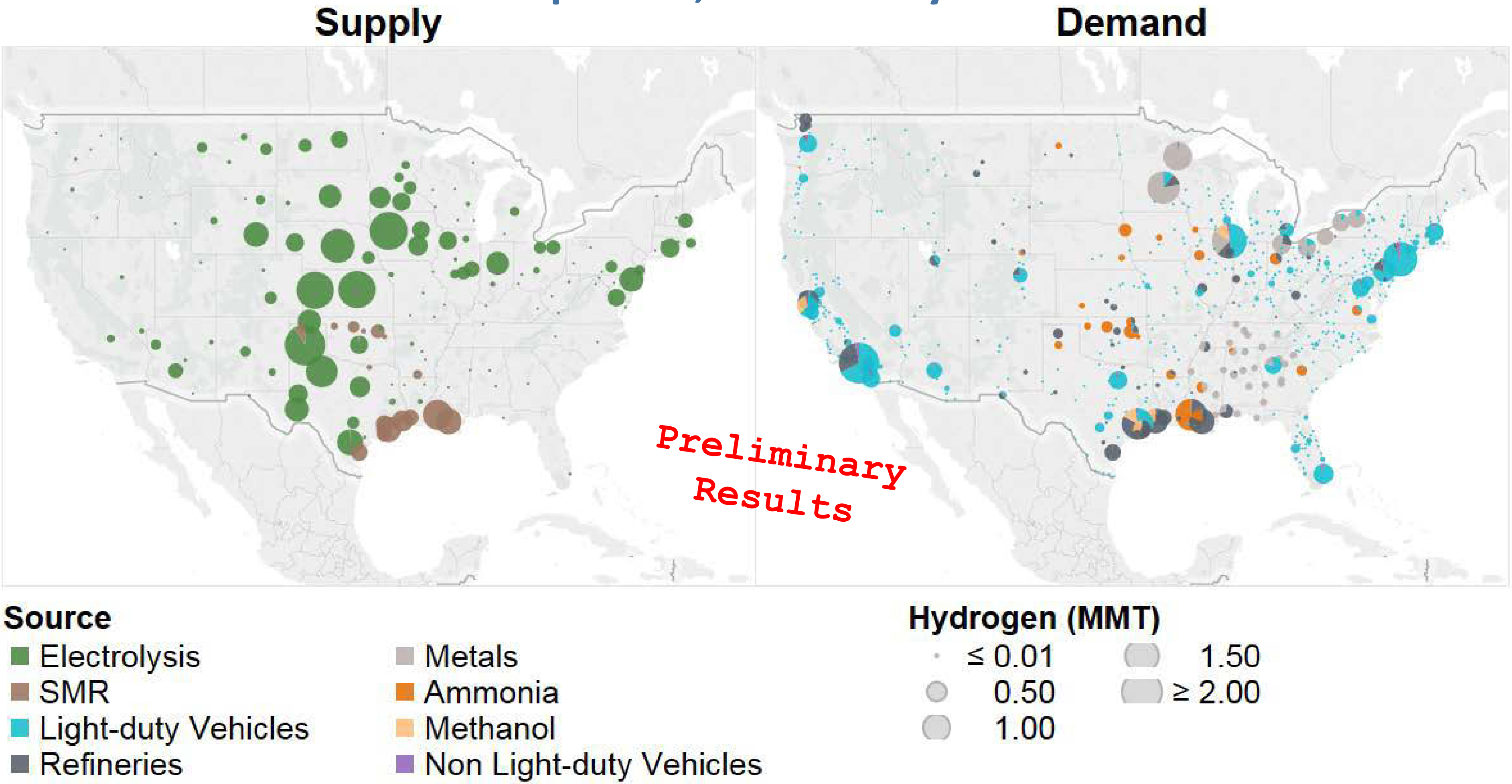
Accomplishment: Developed Four Economic Potential Scenarios

Estimated hydrogen market size: 20-31 MMT/yr with AEO Low Oil & Gas Resource Scenario natural gas prices.



Accomplishment: Initiated Analysis of Spatial and Temporal Issues

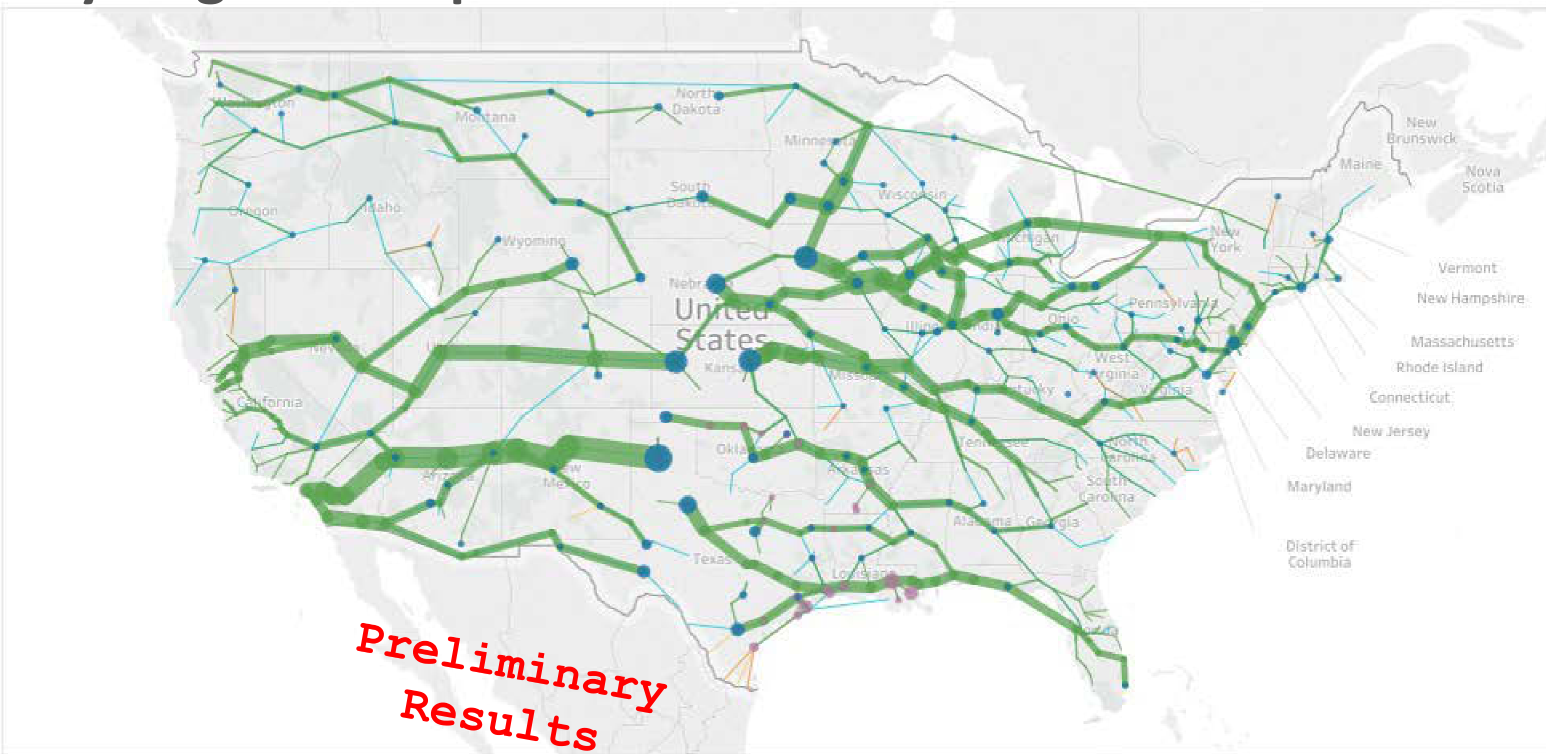
In the H2@Scale Success Upper Bound scenario, most of the hydrogen is produced from wind power in the middle of the country and demand is dispersed, but mainly on the coasts.



Electrolysis includes low-temperature and high-temperature electrolysis

Accomplishment: Initiated Analysis of Spatial and Temporal Issues

In the H2@Scale Success Upper Bound scenario, initial analyses indicate pipeline transport is the most economic method to get hydrogen from production to demand for most corridors.



Technology Type

- Electrolysis
- SMR
- GH2 Pipeline
- GH2 Truck
- LH2 Train
- LH2 Truck

Nameplate Capacity (MMT/yr)

0.00, 0.50, 1.00, 1.50, 2.00, ≥ 2.30

Electrolysis includes low-temperature and high-temperature electrolysis

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- ***Comment:* The project has inflated long-term demand numbers.**
  - *Response:* Only the technical potential was reported in 2017 – economic competitiveness was not considered at that time. The economic potential scenarios reported here consider competitiveness and their resulting demand is lower than the technical potential.
- ***Comment*: The team should include considerations such as subsidies and incentives.**
  - *Response*: The four scenarios used to estimate the economic potential include a range of considerations for both hydrogen production (natural gas prices, availability of different electricity prices) and demands (incentives for reshoring metal refining and light duty vehicle fuels).
- ***Comment*: Analysis does not include timelines or a roadmap to inform industry about how to participate in H2@Scale.**
  - *Response:* We recently began developing a case study describing a potential transition strategy for the state of Texas. That study and a roadmap that the program is developing should help inform industry about participation opportunities.

Collaboration and Coordination

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

Collaborator	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; identify opportunities for H2@Scale technologies and synergies including supply chain issues
PNNL	Support scenario development with a focus on grid interactions
INL	Funded by DOE's Office of Nuclear Energy. Analyze demand for metals industry; identify and quantify nuclear opportunities & technologies
LLNL	Develop visualizations including Sankey diagrams
DOE's Office of Nuclear Energy	Identify synergies between H2@Scale and nuclear energy
Industry	Providing input on scenarios, production opportunities, and alternative H_2 uses through workshops and advisory committees.

Many Challenges and Barriers Remain

	Challenge		Result
Economic potential quantification	Transport and storage needs are unknown	→	National economic potential analyses do not include regional fidelity or competition
Transition issues	Economic potential analysis does not consider transition strategy, needs, and opportunities	→	Transitions are likely to be driven regionally but regional strategies are unknown
Business cases & R&D targets	Business case examples do not exist	→	Analysis supporting research and development (R&D) targets

Proposed Future Work: Spatial / Temporal Analysis and Improve Regional Fidelity

Economic potential quantification

Transport and storage needs are unknown → National economic potential analyses do not include regional fidelity or competition

We are using the Scenario Evaluation and Regionalization Analysis (SERA) Model to perform spatial and temporal analyses.

- Milestone: Draft paper quantifying spatial and temporal issues due September 30, 2018

If funded, we plan to revise key supply and demand curves with regional data and then use SERA to analyze effects on hydrogen markets.

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

Proposed Future Work: Transition Analysis

Transition issues

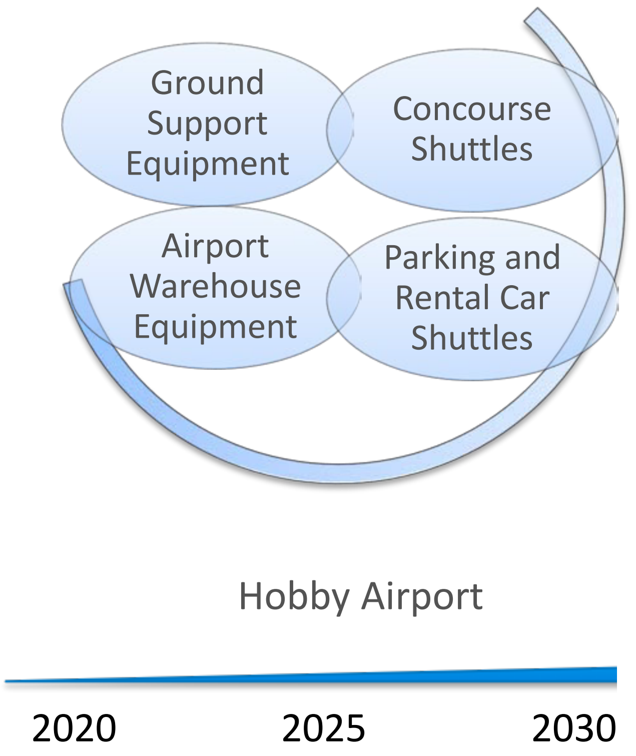
Economic potential analysis does not consider transition strategy, needs, and opportunities

→

Transitions are likely to be driven regionally but regional strategies are unknown

We are developing a qualitative case study for a possible transition across Texas.

If funded, we plan to work with stakeholders to improve that case study, investigate others, and develop roadmaps.



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 generation options and market opportunities to businesses looking to invest

Lab Team **Industry**

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

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 providing value for otherwise-curtailed electricity and transportation energy, feedstock for industry, and seasonal electricity storage.

- **Technical potential:** ***87 MMT H_2/ yr***

- **Economic potential:** ***17-31 MMT H_2 / yr*** can be produced, given R&D advancements and access to low-cost intermittent power

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

H_2
@Scale:
Energy system-wide benefits of increased H_2 implementation

Thank You

www.nrel.gov

NREL/PR-6A20-71497

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Technical Back-Up Slides

Approach: Developed Four Scenarios to Explore a Range of Economic Possibilities

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Natural Gas Price Assumptions	AEO 2017 Reference case		AEO 2017 low oil and gas resource and technology case	
Otherwise- Curtailed Electricity Assumptions	Available at retail price (↓)	Available at wholesale price (↑)	Available at price between retail and wholesale (↑)	Available at wholesale price (↑)
Demand Assumptions	Moderate growth in transportation, stability in petrochemical (↓)	Growth of hydrogen use in traditional and novel applications (metals, methanol) (↑)	Moderate growth in transportation, stability in petrochemical (↓)	Growth of hydrogen use in traditional and novel applications (metals, methanol) (↑)

Arrows indicate direction of expected impact on the size of the hydrogen market. Details presented in the supporting slides

AEO: Annual Energy Outlook

Key Scenario Assumptions

All scenarios analyses are based on national markets at equilibrium without spatial or temporal variability. They do not yet involve transition analyses

Key Demand Assumptions

Demand	Traditional Energy Focus	H2@Scale Success Lower Bound	H2@Scale Base Case	H2@Scale Success Upper Bound
Metals Reshoring	Economically competitive	Willingness to pay for H_2 for metals	Economically competitive	Willingness to pay for H_2 for metals
Light-Duty Vehicles	Economically competitive	Full potential at $2.50/kg	Economically competitive	Full potential at $2.50/kg
Other Demands	Economically competitive	Economically competitive	Economically competitive	Economically competitive

Key Supply Assumptions

Generator	Traditional Energy Focus	H2@Scale Success Lower Bound	H2@Scale Base Case	H2@Scale Success Upper Bound
Electrolytic	High cost/low availability	Low cost/high availability (Wholesale)	Retail w/ services elec. price	Low cost/high availability (Wholesale)
Nuclear	20% available at low cost	20% available at low cost	20% available at low cost	20% available at low cost
SMR	2017 AEO Reference NG prices	2017 AEO Reference NG prices	2017 AEO Low Oil & Gas Resource NG prices	2017 AEO Low Oil & Gas Resource NG prices

Key Delivery Assumptions

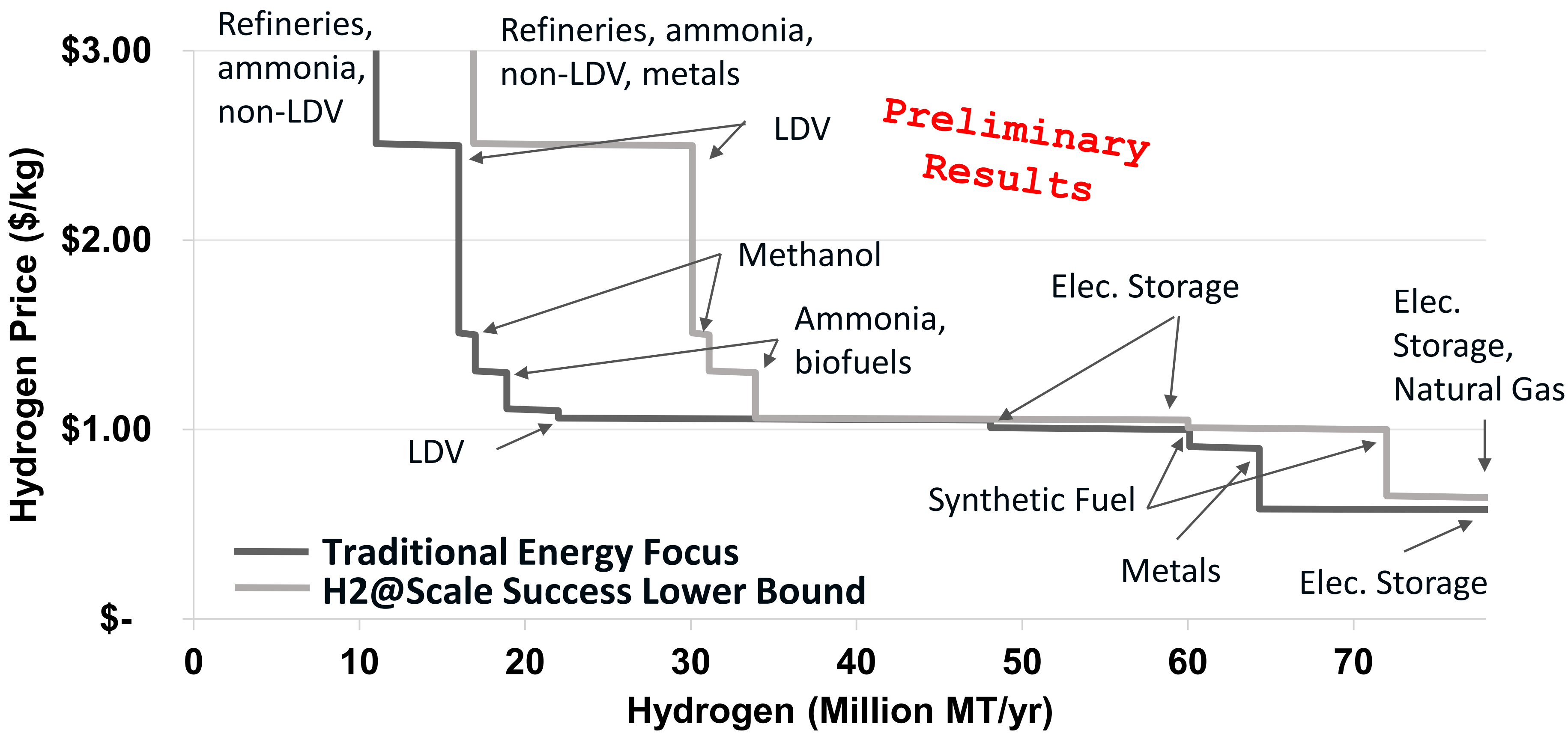
Generator	Distance	Volume	Delivery Technology	Pipeline Diameter (in)	Delivery Cost Adder ($/kg H_2)
Electrolytic & Nuclear	Long (250 km)	200,000 metric ton / yr	Transmission pipe with geologic storage & compression	15.75	$0.39
SMR	Short (16 km)	200,000 metric ton / yr	Transmission pipe with geologic storage & compression	9.25	$0.12

Markets Identified and Included in Demand Curve Estimates

- Refineries
- Ammonia
- Medium- and heavy-duty vehicles
- Light-duty vehicles (LDV)
- Methanol
- Synthetic fuel
- Biofuels
- Seasonal storage for electricity
- Natural gas injection
- Metals

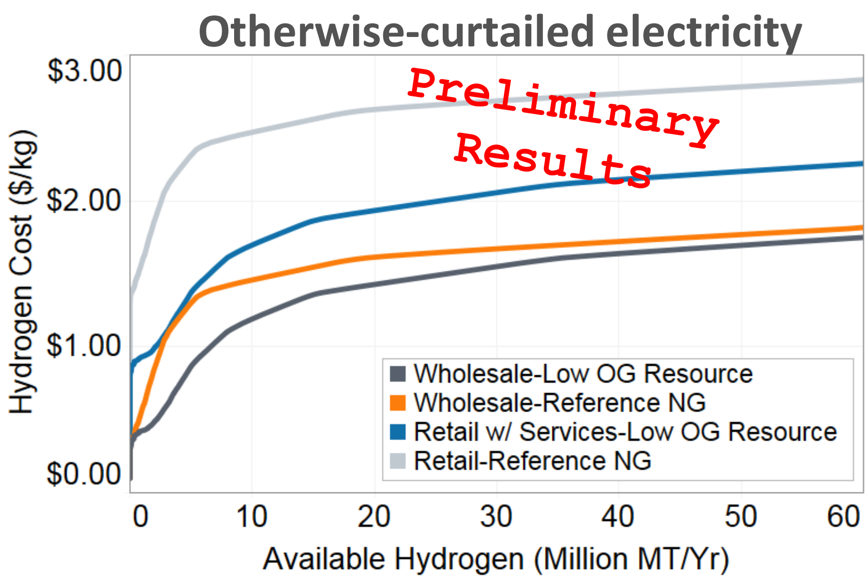
Accomplishment: Additional Demand Curves

Estimated willingness to pay for 10 applications on a national basis – range is >$3/kg for refining and ammonia to ≤$1/kg for injection into the natural gas system and some seasonal electricity storage.



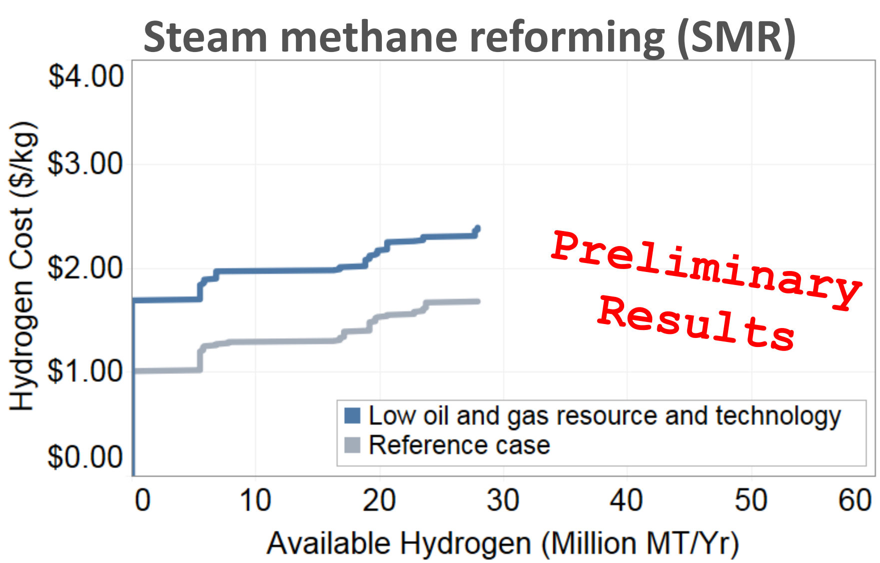
LDV: Light Duty Vehicles; "non-LDV" indicates energy for medium and heavy duty vehicle transportation

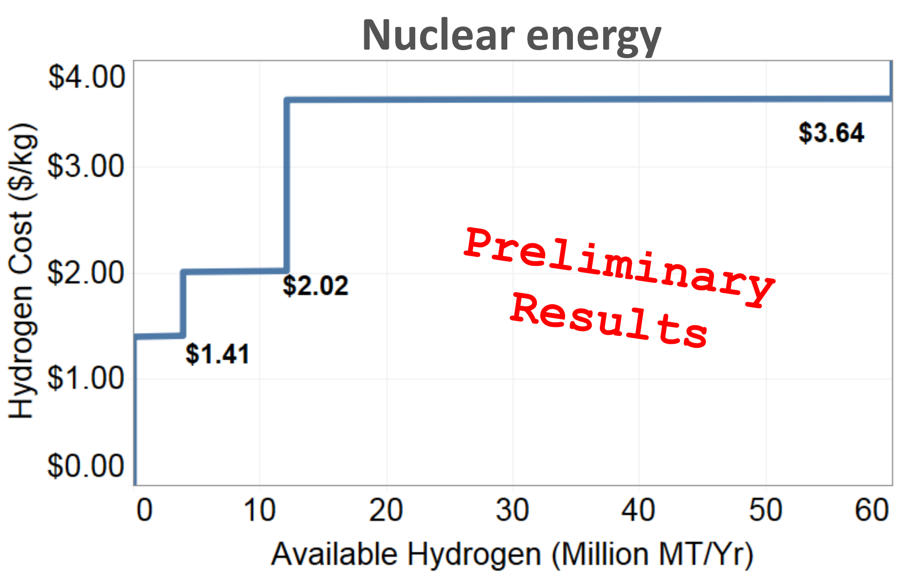
Accomplishment: Developed Hydrogen Supply Curves from Three Energy Sources



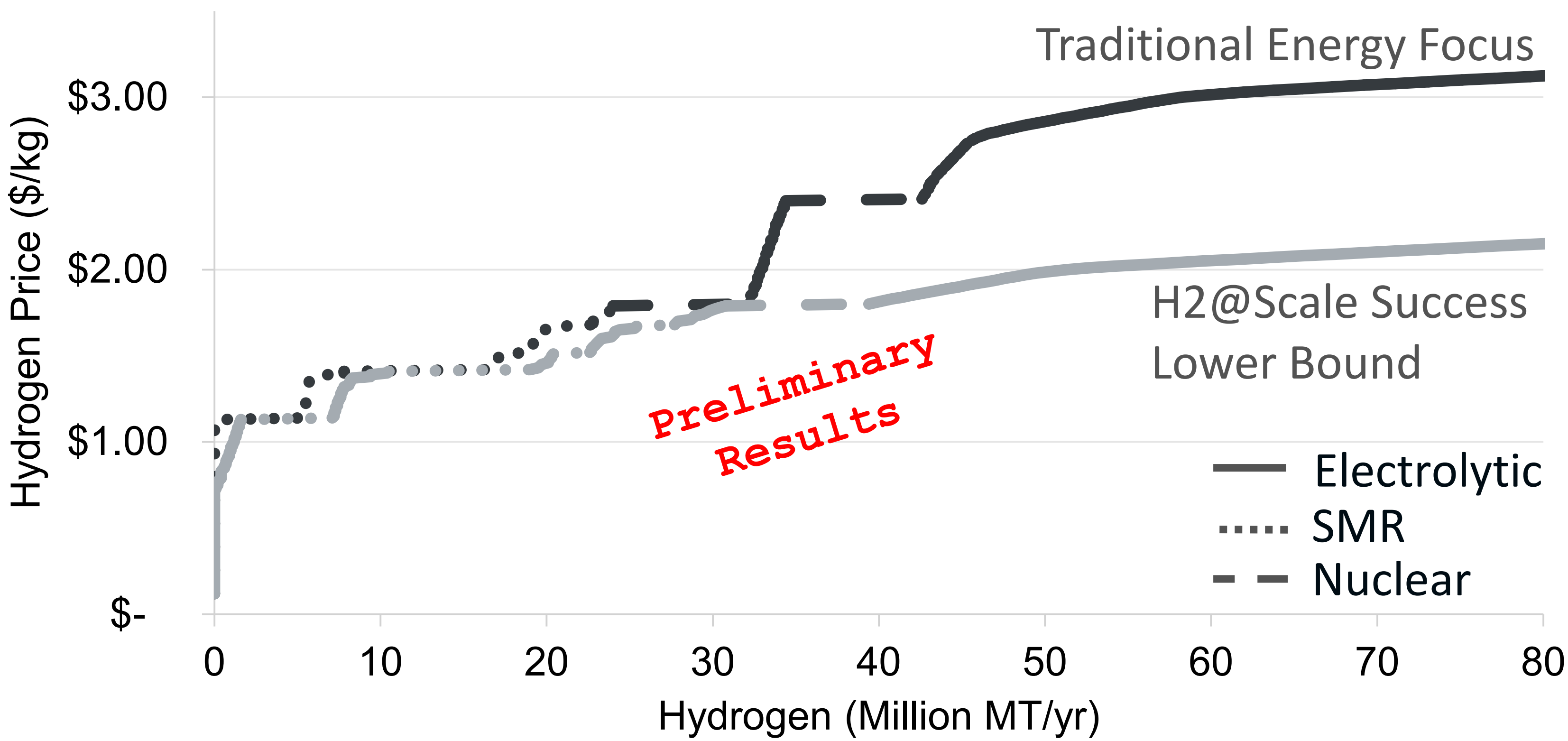
Developed supply curves that estimate hydrogen price and quantities from three energy sources:

- Otherwise-curtailed electricity
- Steam methane reforming (SMR) of 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





Accomplishment: Additional Aggregated Supply Curves



Each scenario uses a supply curve created by aggregating supply curves from multiple sources and adding an estimated delivery and storage cost.

Economic Potential Scenario Results Summary

Preliminary Results

	Traditional Energy Focus	H2@Scale Success Lower Bound	H2@Scale Base Case	H2@Scale Success Upper Bound
H_2 Use	17 MMT/yr	30 MMT/yr	20 MMT/yr	31 MMT/yr
H_2 Price	$1.50/kg	$1.80/kg	$2.10/kg	$1.80/kg
Revenue	$25 Billion	$53 Billion	$41 Billion	$57 Billion
Demand (MMT/yr)	• Refining (7), • Ammonia (3), • LDVs (5), • Non LDVS (1), • Methanol (1)	• Refining (7), • Ammonia (3), • Metals (6), • LDVs (13), • Non LDVS (1)	• Refining (7), • Ammonia (3), • LDVs (9), • Non LDVS (1)	• Refining (7), • Ammonia (3), • Metals (6), • LDVs (13), • Non LDVS (1), • Methanol (1)
Supply (MMT/yr)	• NG reforming (17)	• Low-temp. electrolysis (6), • NG Reforming (24)	• Low-temp. electrolysis (9), • Existing nuclear plants (4), • NG reforming (7)	• Low-temp. electrolysis (21), • Existing nuclear plants (4), • NG reforming (6)
Electrolysis	No grid electrolysis	320 TWh, 8% curtailment, $10-21/MWh wholesale price	470 TWh, 11% curtailment, $6-17/MWh wholesale price	1100 TWh, 27% curtailment, $12-23/MWh wholesale price

Accomplishment: Estimated Impacts on Energy Use & Emissions

H2@Scale can reduce emissions and fossil energy use by up to 10% on top of baseline electricity sector emissions

Preliminary Results

Reduction Metric	Reductions Due Exclusively to H2@Scale Technologies Compared to Baselines with Low-Emission Electricity Sectors			
	Traditional Energy Focus	H2@Scale Success Lower Bound	H2@Scale Base Case	H2@Scale Success Upper Bound
NO_X (Thousand MT)	52 (0%)	170 (1%)	150 (1%)	250 (2%)
SO_X (Thousand MT)	31 (1%)	200 (5%)	33 (1%)	200 (5%)
PM_{10} (Thousand MT)	8.6 (0%)	45 (2%)	10 (0%)	56 (2%)
Crude Oil (Million Barrels)	250 (4%)	620 (10%)	470 (7%)	620 (10%)
CO_2 (Million MT)	68 (1%)	290 (6%)	280 (9%)	470 (12%)

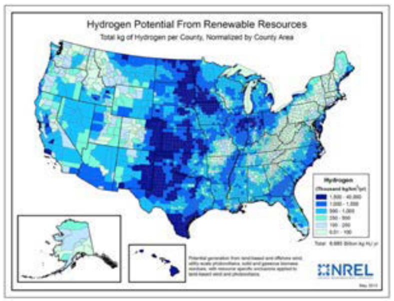
Details on the SERA Model

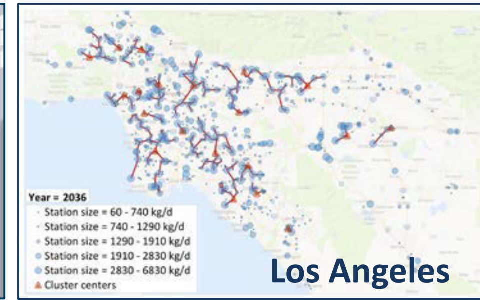
Scenario Evaluation and Regionalization Analysis (SERA)

Historically used to simulate hydrogen infrastructure supply system evolution for urban FCEV markets

We are focusing on least cost ultimate national system design

Energy Resources → **Hydrogen Production** → **Storage & Delivery** → **Retail Station Networks**





Energy Resources
- Energy prices (natural gas, electricity, etc.)
- Renewables (biomass, solar, wind)
- Terrain, rights of way, etc.

Hydrogen Production
- Central and onsite production facilities
- Capacity sized to meet forecasted demand
- Economies of scale balanced with delivery costs

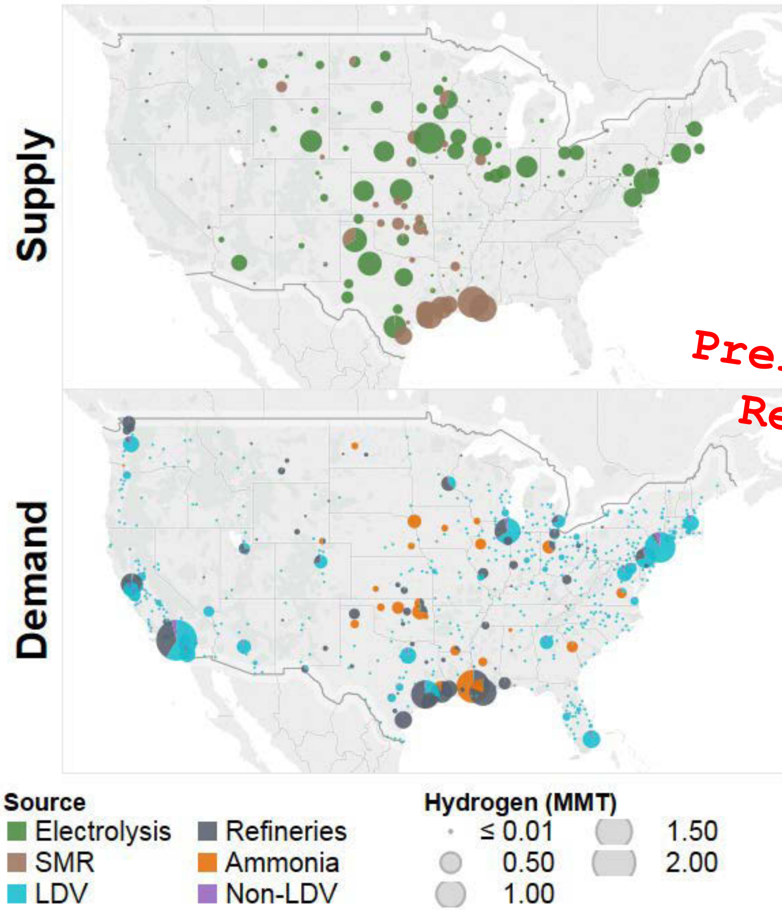
Storage & Delivery
- Truck delivery, rail, and pipeline.
- Cost is sensitive to volume, distance
- Seasonal and weekly storage
- Networked supply to multiple cities

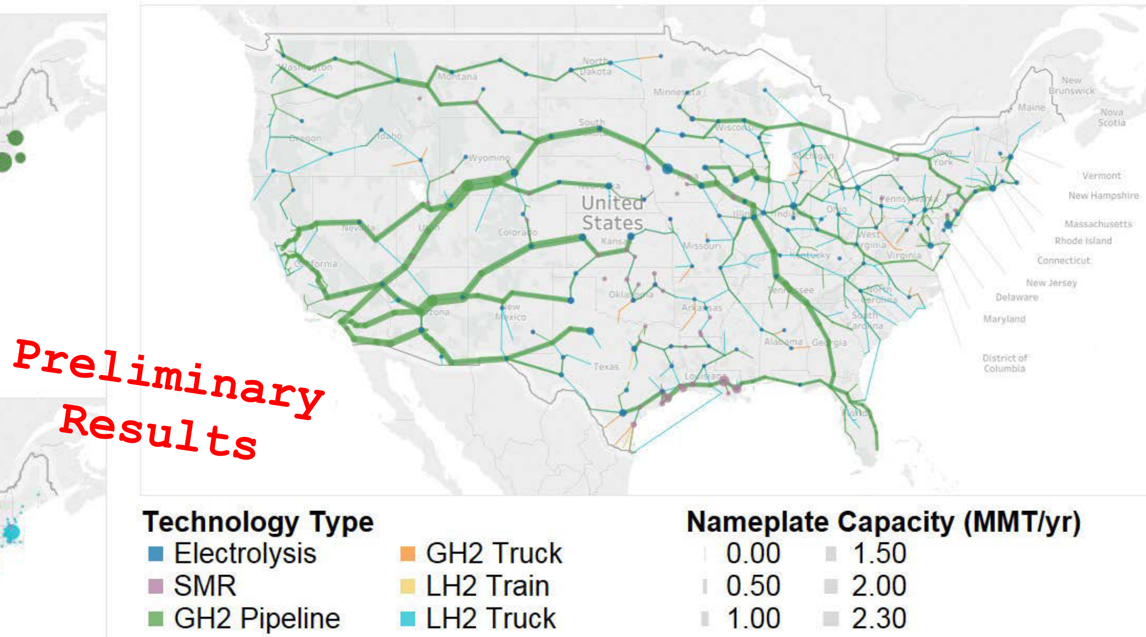
Retail Station Networks
- Coverage stations for FCEV introductions
- Station sizes increase with market growth
- Liquid and pipeline delivery networks compete for large stations

SERA model description adapted from presentations developed by the SERA team including https://www.nrel.gov/docs/fy18osti/70244.pdf

Initiated Analysis of Spatial and Temporal Issues: H2@Scale Base Case

H2@Scale Base Case





Electrolysis includes low-temperature and high-temperature electrolysis

In the H2@Scale Base Case scenario, much of the generation is from wind power in the middle of the country and SMR in the Gulf Coast, and demand is dispersed but mainly on the coasts. Thus pipeline transport is needed.