H2@Scale Analysis

Mark F. Ruth, Paige Jadun:
National Renewable Energy Laboratory
Amgad Elgowainy: Argonne National Laboratory

May 31, 2020

DOE Hydrogen and Fuel Cells Program
2020 Annual Merit Review and Peer Evaluation

Project ID # sa171

Overview

Timeline and Budget

- Project start date: 10/1/18
  - Follow-on project after completing H2@Scale lab call
- FY19 DOE funding: $350,000
- FY20 DOE funding: $150,000
- Total DOE funds received to date: $500,000

Partners

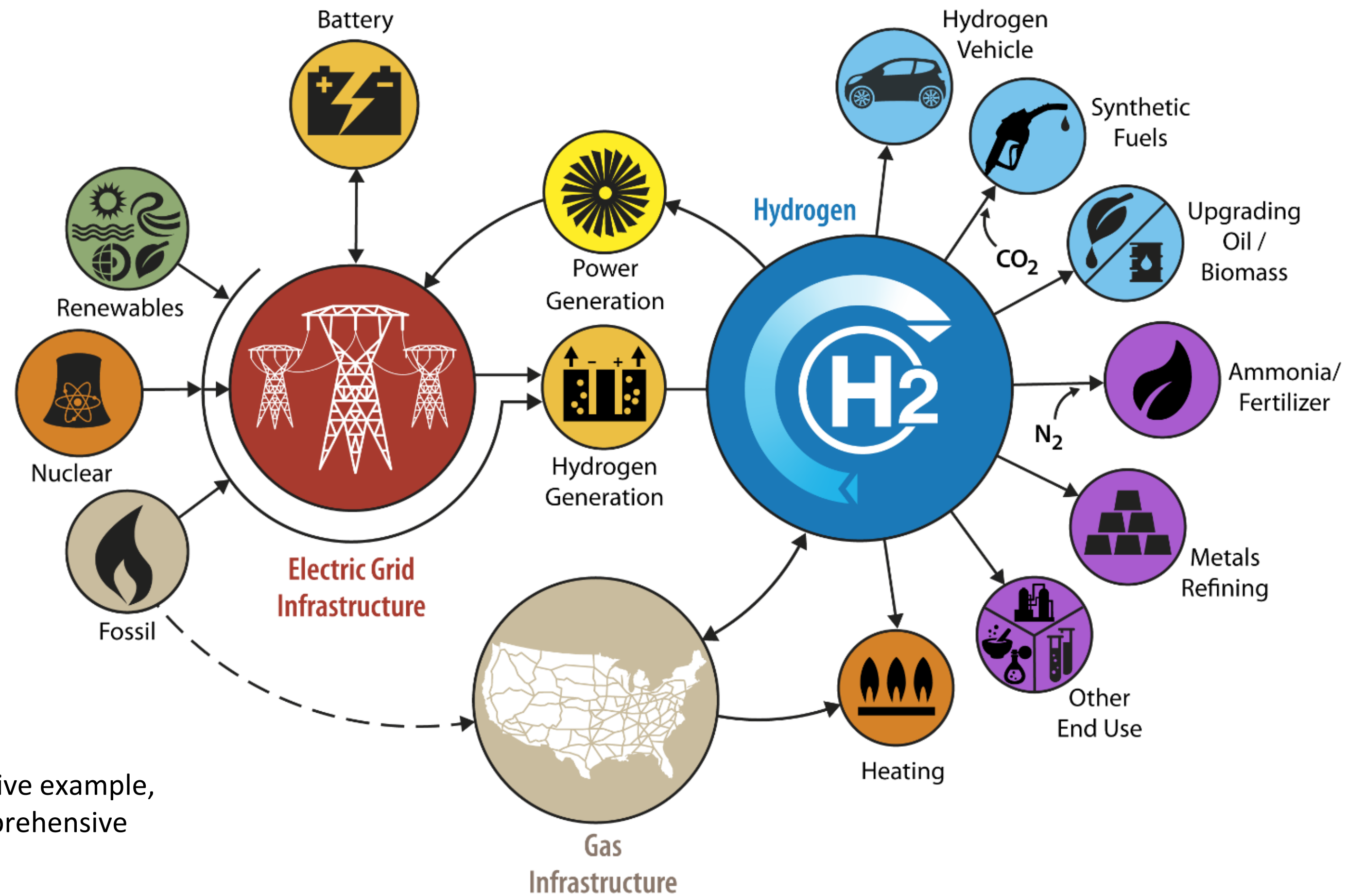
- Project lead: NREL
- Lab Partners: ANL, LBNL, PNNL, INL, LLNL
- DOE Partners: Nuclear Energy
- Industrial and Academic Reviewers

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. Since these tools are not available, a supply-demand method was developed.
- 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

Hydrogen can potentially be an energy intermediate that benefits both energy generation and energy utilization



*Illustrative example, not comprehensive

Source: 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.
- **Serviceable Consumption Potential and Resource Technical Potential**
  - The serviceable consumption potential is the the amount of hydrogen that would be consumed to serve the portion of the market that could be captured without considering economics
  - The resource technical potential is the 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

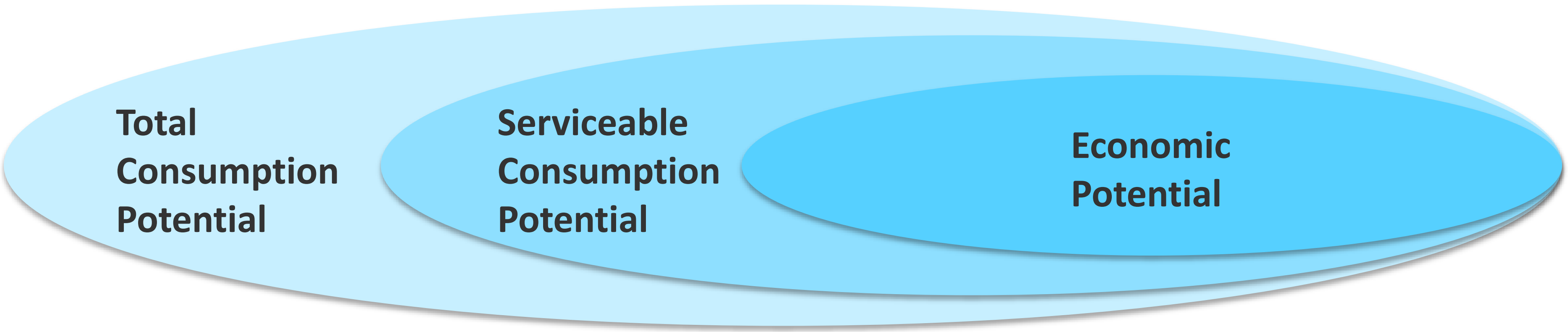
Demand assessment
Resource assessment
Grid analyses
Curtailed electricity
Economic equilibria
Impact assessment

Outputs & Deliverables

Analysis of H2@Scale concept and potential opportunity and impacts

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

Approach: Categories of Consumption Potential



- ***Total Consumption Potential:*** the amount of hydrogen that would be consumed if all consumers in a given industry utilized hydrogen without considering costs or economic competition. It is analogous to the maximum possible theoretical consumption.
- ***Serviceable Consumption Potential:*** the amount of hydrogen that would be consumed to serve the portion of the market that could be captured without considering economics (i.e., if the price of hydrogen were $0/kg over an extended period)
- ***Economic Potential*:** the amount of hydrogen that would be consumed by a sector when its price and the price for competing alternatives are considered.

Accomplishments: Improved Estimates of Serviceable Consumption Potential

Serviceable Consumption Potential of hydrogen market by 2050 is >10X.

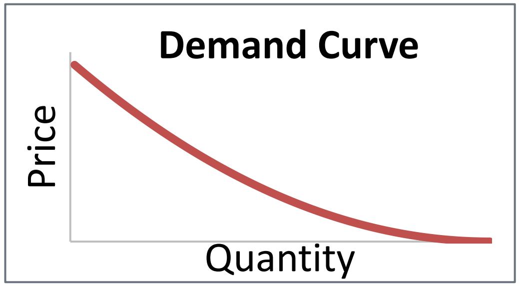
Other applications are possible based on technology and policy growth as well as smaller applications

Application	Serviceable Consumption Potential (MMT/yr)	2015 Market for On-Purpose H2 (MMT/yr)
Refineries and the chemical processing industry (CPI) [a]	8	6
Metals	12	0
Ammonia	4	3
Biofuels	9	0
Synthetic hydrocarbons	14	1
Natural gas supplementation	16	0
Seasonal energy storage for the electricity grid	15	0
Industry and Storage Subtotal	**78**	**10**
Light-duty fuel cell electric vehicles (FCEVs)	21	0
Medium- & Heavy-Duty FCEVs	8	0
Transportation Fuel Subtotal	**29**	**0**
Total	**107**	**10**

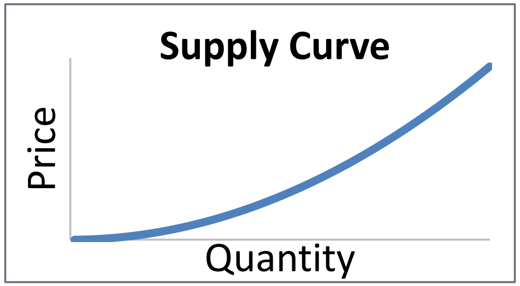
Preliminary Results
Do not cite

Approach: Economic Potential

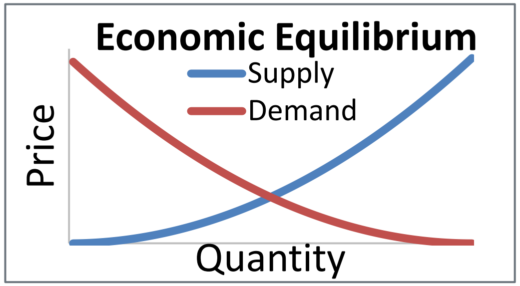
Develop national supply and demand curves for hydrogen and use them to estimate market size and composition



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: Limitations and Caveats of Economic Potential

- Market equilibrium methodology and market size estimates in 2050
  - Transition issues such as stock turnover are not considered
- New policy drivers, such as emission policies, are not included either for hydrogen or the grid
- Technology and market performance involve many assumptions about adjacent technologies
  - In all but the reference scenario, the assumption is that R&D targets are met
- Demand analysis is limited to sectors that could be forecast for the foreseeable future
  - Hydrogen use to convert biomass based on market size equal to 50% of aviation demand
  - Hydrogen for industrial heat is not included
  - Single price point only for all fuel cell vehicle estimates
- Estimates of delivery costs were standardized and without location specificity
- Potential long-term production technologies (e.g., photo-electrochemical) not included
- Economic feedback impacts are not considered
- Competing technologies (both for markets that use hydrogen and for resources to generate hydrogen) are addressed in a simplified manner only

Approach for Economic Potential: Five National Scenarios

Scenario Name	Reference	R&D Advances + Infrastructure	Low NG Resource / High NG Price	Aggressive Electrolysis R&D	Lowest-Cost Electrolysis
Description	Current status of hydrogen technologies; low natural gas (NG) prices	Expected cross-sector hydrogen technology improvement and demand growth; robust hydrogen demand for metals; no grid support; low natural gas (NG) prices	Expected cross-sector hydrogen demand growth; robust hydrogen demand for metals; no electrolysis for grid support; high NG prices	Robust metals hydrogen demand growth; limited electrolysis for grid support; high NG prices	Robust metals hydrogen demand growth; electrolysis providing grid support; high NG prices
Natural gas prices	AEO 2017 Reference scenario		AEO 2017 Low Oil and Gas Resource and Technology scenario		
Availability of SMR facilities	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				
Nuclear costs	20% of current nuclear fleet available at $\$25/MWh_e$ opportunity cost				
HTE costs	$820/kW	$423/kW			
LTE capital costs	$900/kW	$400/kW		$200/kW	$100/kW
LDE market assumption	Available at retail price			Between retail and wholesale	Wholesale price
Distribution for FCEVs	Current costs	FCTO cost targets met			
Metals demand	Must compete with existing technologies	Markets are willing to pay a premium for metals refined using hydrogen			

Key differences between scenarios: 1) natural gas price assumption, 2) distribution costs, 3) electrolyzer cost assumption, 4) electrolyzers' access to grid service markets, & 5) increased price point in metals industry

Modifications during the last year:

- **Added reference scenario. It's key assumptions are no R&D improvement and high costs of hydrogen distribution for vehicles.**
- **Removed scenario that investigates the opportunity to produce hydrogen from biomass but retained that information in sensitivity analyses**

Accomplishment: Updated Demand Estimate Biofuels

- Opportunity:
  - 50% of total jet fuel demand in 2050 (38.6 billion gal/yr AEO Reference)
  - 1.8 billion gal/yr is from fats, oils, & greases (FOGs)
  - 17.5 billion gal/yr based on catalytic fast pyrolysis of biomass
- Serviceable Consumption Potential:
  - FOGs require 76 g H_2/gal → 0.14 MMT/yr
  - Catalytic fast pyrolysis requires 490 g H_2/gal → 8.6 MMT/yr*
  - Total: 8.74 MMT H_2/yr
- Threshold Price: High because of non-hydrogen price drivers → $\$3.00/kg_{H2}$

Preliminary Results
Do not cite

Source: http://yelloblu.com/blog/biofuels-part-three-biomass-future-fuels

* Designs have hydrogen produced from non-condensibles in the process. We assume those can go to higher value products. Further analysis is needed

Accomplishment: Updated Demand Estimate Natural Gas Supplementation

- Serviceable Consumption Potential:
  - 20% (volume) assumed to not have significant impact on technologies that utilize natural gas
  - 16 MMT_{H2}/yr

Preliminary Results
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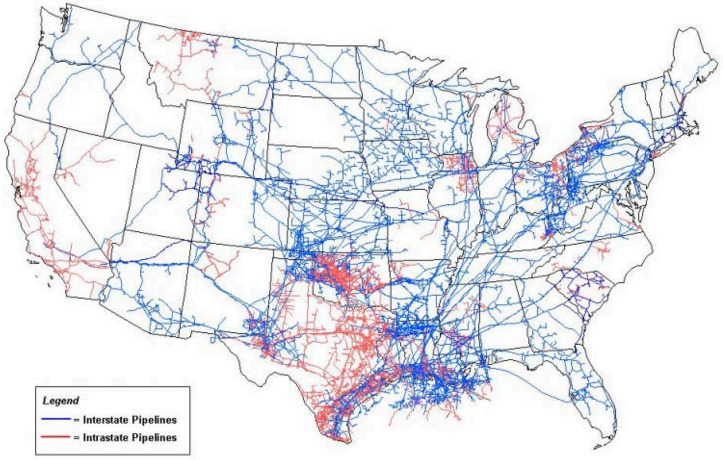
- Threshold Price:
  - Energy value on a higher heating value (HHV) basis
  - \$0.80/kg_{H2} for AEO reference case (\$5.88/MMBtu)
  - \$1.40/kg_{H2} for AEO Low Oil & Gas Resource case (\$10.23/MMBtu)

U.S. Natural Gas Pipeline Network



Source: M. W. Melaina, O. Antonia, M. Penev. 2013. Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues. NREL/TP-5600-51995. https://www.nrel.gov/docs/fy13osti/51995.pdf

Accomplishment: Updated Demand Estimate Light-Duty Fuel Cell Vehicles (FCEVs)

- Serviceable Consumption Potential:
  - 41% of LDV fleet in 2050 from the Ambitious Scenario in "Roadmap to a US Hydrogen Economy"
    - 66 million of 162 million cars:
      - 10 MMT_{H2}/yr at 99.8 mpgge
    - 63 million of 153 million light-duty trucks:
      - 11.4 MMT_{H2}/yr at 64.3 mpgge
- Threshold Price:
  - Calculation
    - Reference Scenario: Current delivery and dispensing costs are \$11-\$14/kg, thus production cost would be <\$0/kg to be competitive without incentives
    - "Ultimate" H_2 price at pump: \$5.0/kg pump (\$2.20/kg at terminal) - \$5.0/kg is based on the FCTO target of \$4/kg in 2007\$, inflated to 2015\$, with \$0.5/kg in taxes added.
      - Equivalent to \$2.20/kg at terminal
    - Equilibrium market demand from MA3T vehicle choice model
  - Hydrogen consumption at market equilibrium (18% of cars and 26% of light-duty trucks), 11.7 MMT H_2/yr

Preliminary Results Do not cite

Source: NREL Photo Library #49729

Accomplishment: Updated Demand Estimate Medium- & Heavy-Duty FCEVs

- Serviceable Consumption Potential:
  - 35% of both HDV and MDV fleet by 2050 from the Ambitious Scenario in "Roadmap to a US Hydrogen Economy"
  - 4.2 million of 12 million Medium Duty:
    - 2.2 MMT_{H2}/yr at 33 mi/kg
  - 2.0 million of 5.7 million Heavy Duty:
    - 6.0 MMT_{H2}/yr at 14.7 mi/kg

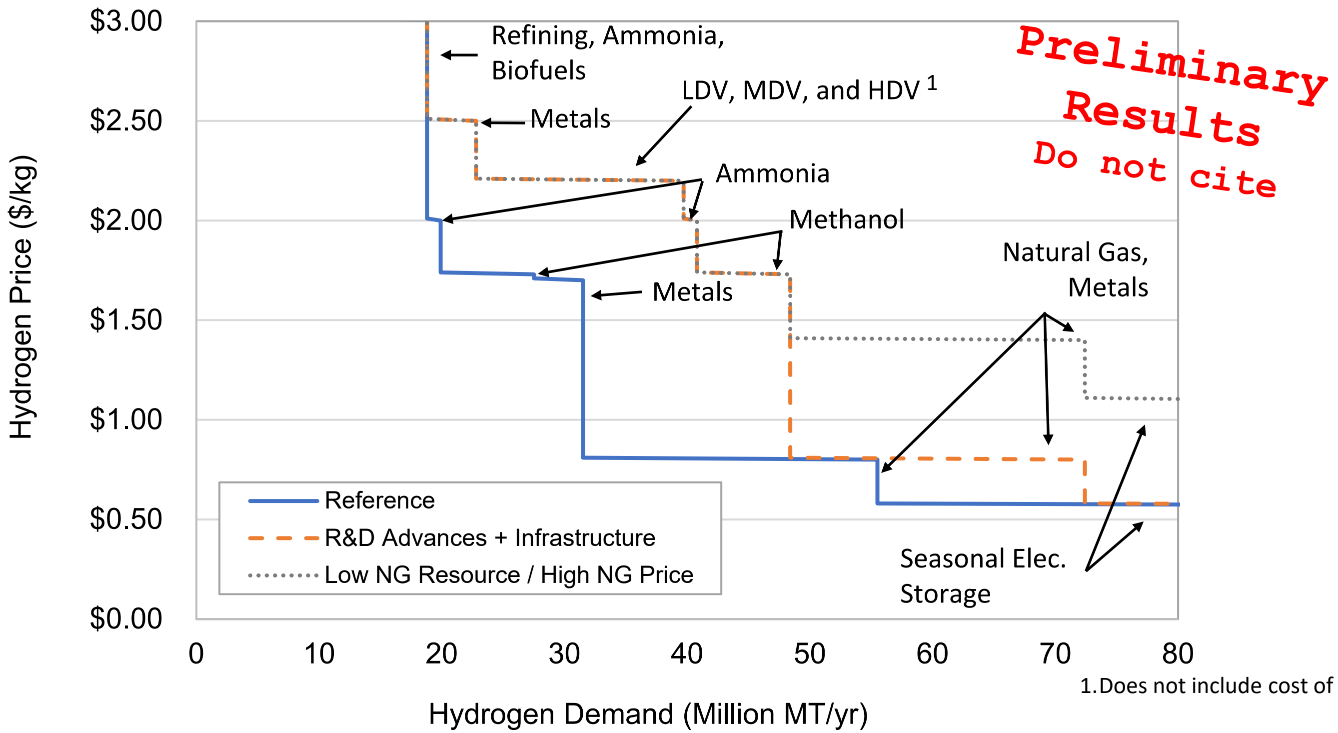
Source: Nikola Motor Company

Preliminary Results
Do not cite

- Threshold Price:
  - Calculation
    - Reference Scenario: Current delivery and dispensing costs are $11-$14/kg, thus production cost would be <$0/kg to be competitive without incentives
    - "Ultimate" H_2 price at pump: $5.0/kg pump ($2.20/kg at terminal) - $5.0/kg is based on the FCTO target of $4/kg in 2007$, inflated to 2015$, with $0.5/kg in taxes added.
      - Equivalent to $2.20/kg at terminal
  - Hydrogen consumption at 22% market penetration (the weighted average of the LDV penetration at equilibrium), 5.2 MMT_{H2}/yr

Accomplishment: Aggregated Demand Curves Across End Uses

Demand curves represent aggregated threshold prices (at the terminal) for the potential hydrogen applications



1.Does not include cost of fueling station.

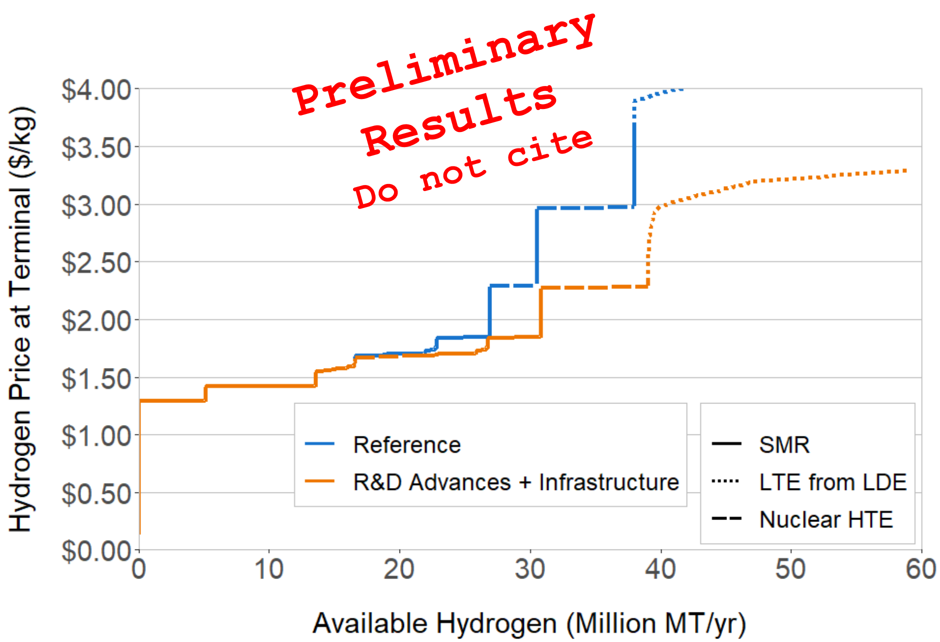
The Aggressive Electrolysis R&D and Lowest Cost Electrolysis scenarios use the same demand curve as the Low NG Resource / High NG Price scenario

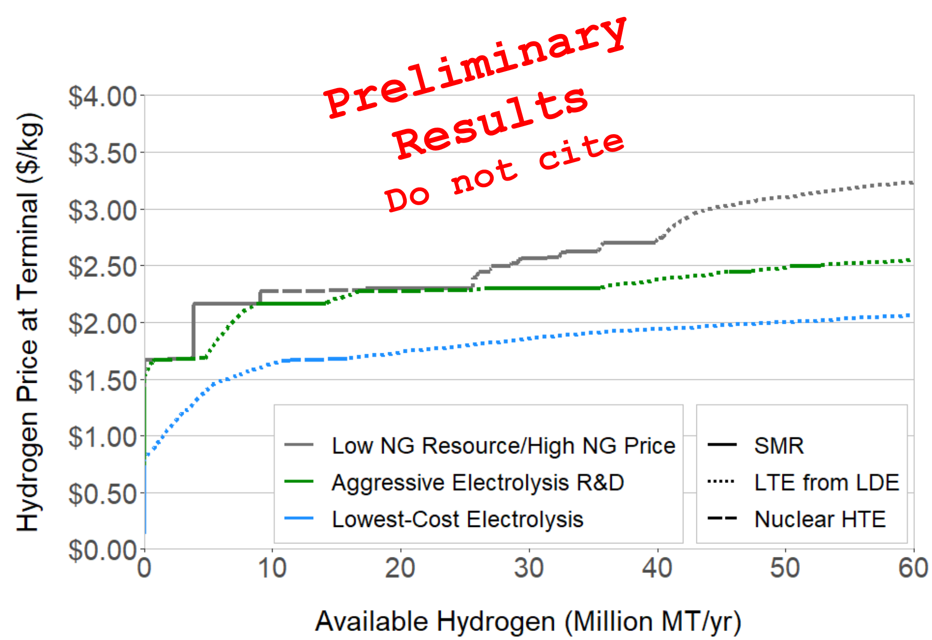
Modifications during the last year:

- **Increased demand for biofuel due to increased market opportunity in aviation**
- **Decreased demand for vehicle transport due to changes in market estimates**
- **Increased potential demand for methanol to address technology development**

Accomplishment: Aggregated Supply Curves Across Production Options

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

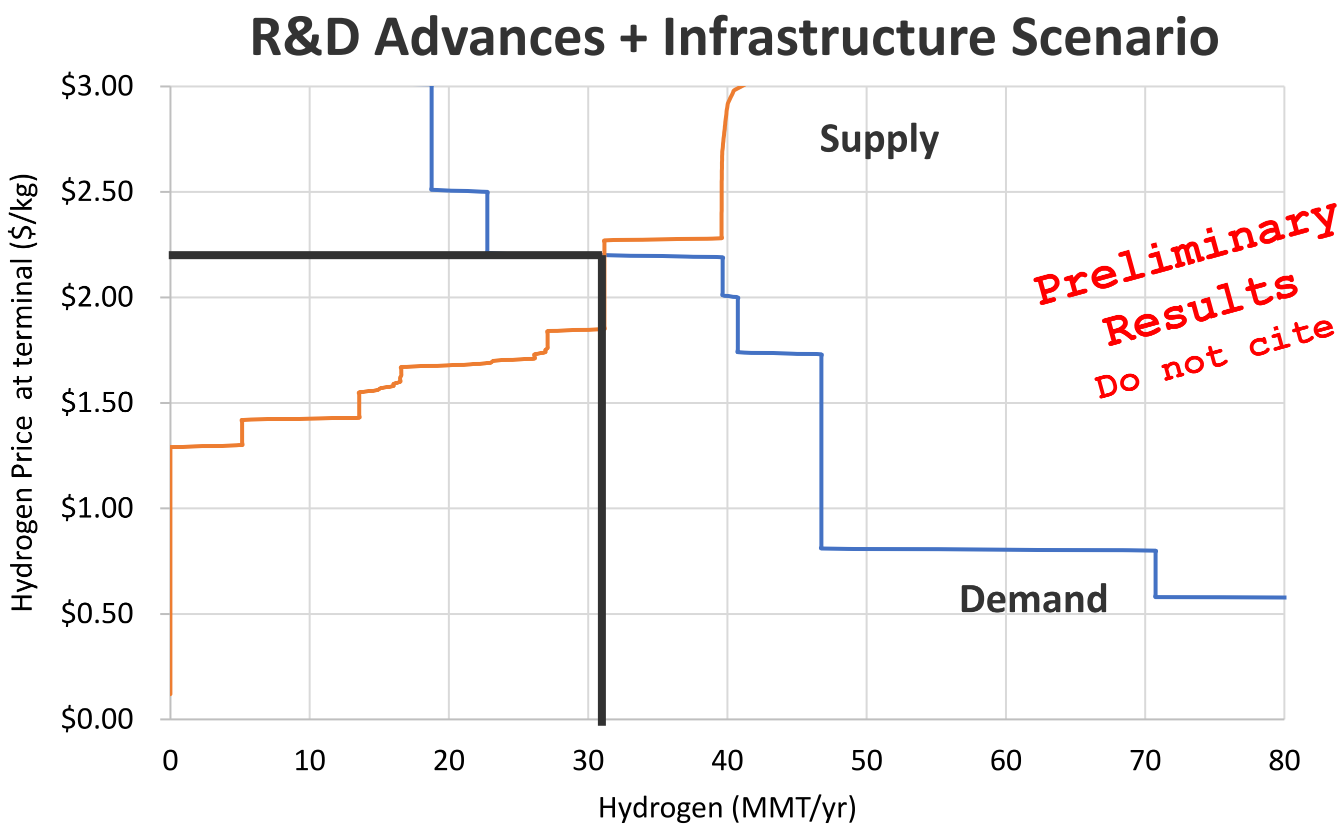




Modifications during the last year:

- **Created Reference Scenario based on AEO Reference Case and no R&D improvements**
- **Updated nuclear high-temperature electrolysis (HTE) assumptions based on updated data**

Accomplishment: Identified Market Prices and Equilibrium for Each Scenario



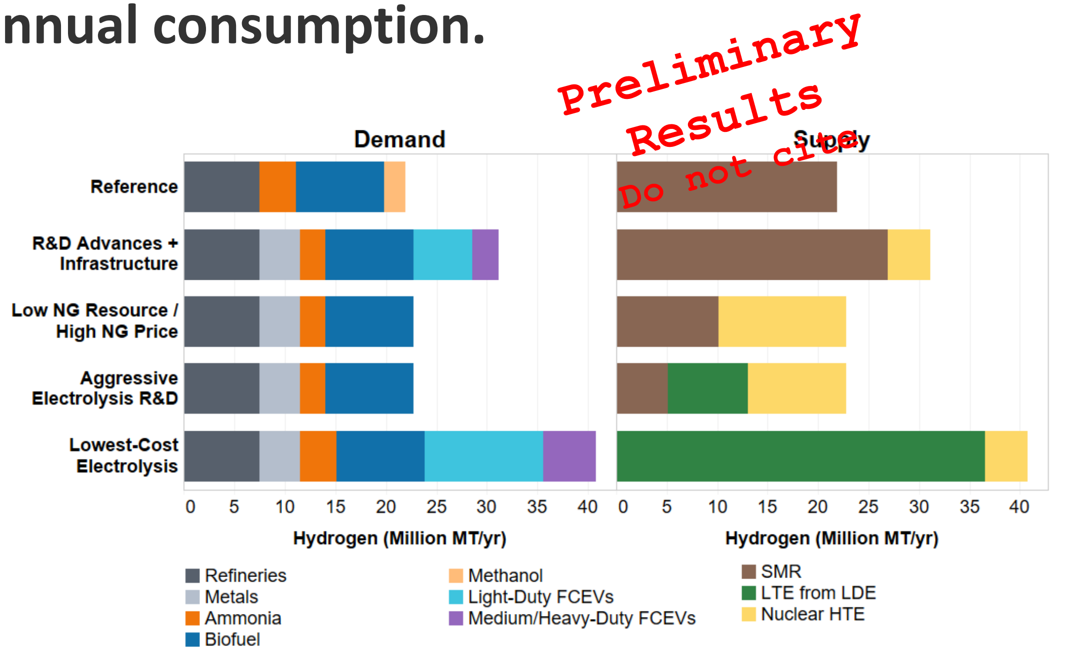
The intersection of the supply and demand curves indicate the market size and price at equilibrium.

All scenarios have been updated during the last year

Accomplishment: Economic Potential in Five Scenarios

The economic potential of hydrogen demand in the U.S. is 2.2-4.1X current annual consumption.

Scenario	Insights
Reference	Growing markets for refining, ammonia, and biofuels met with low-cost NG
R&D Advances + Infrastructure	Higher penetrations of FCEV + drivers for metals, SMR dominates production due to low cost NG but have some nuclear HTE
Low NG Resource / High NG Price	High NG price increases cost of hydrogen for same quantity and limits FCEV penetration but more nuclear HTE
Aggressive Electrolysis R&D	Some LTE penetration at \$200/kW capital cost with grid value.
Lowest-Cost Electrolysis	Low-cost electrolyzers with high grid value reduces hydrogen cost and can enable additional H_2 applications

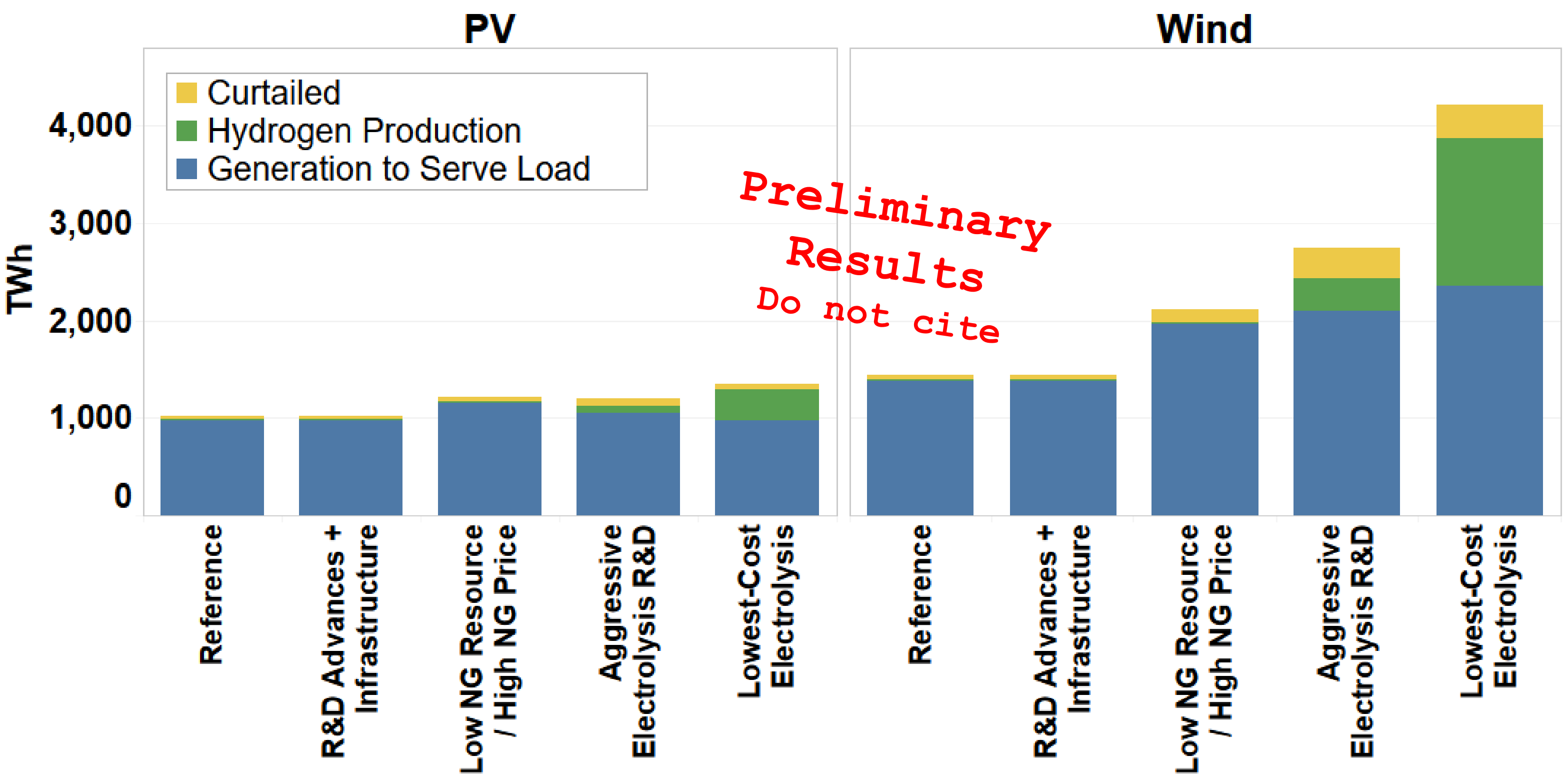


FCEV: Fuel-cell electric vehicles
SMR: Steam methane reforming
LTE: Low-temperature electrolysis
LDE: Low-cost, dispatch-constrained electricity
HTE: High-temperature electrolysis

Updated all scenarios and results during past year

Accomplishment: 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

Accomplishment: Emissions Estimates for all Scenarios

H2@Scale could reduce emissions because of its potential to reduce fossil energy use

Preliminary Results
Do not cite

	Reference	R&D Advances + Infrastructure	Low NG Resource / High NG Price	Aggressive Electrolysis R&D	Lowest-Cost Electrolysis
NO_x (Thousand MT)	110 (1%)	210 (2%)	150 (1%)	170 (2%)	490 (4%)
SO_x (Thousand MT)	-22 (-1%)	4 (0%)	-12 (0%)	-1 (0%)	72 (2%)
PM_{10} (Thousand MT)	-10 (0%)	5 (0%)	-12 (0%)	-11 (0%)	38 (1%)
Crude Oil (Million Barrels)	320 (5%)	680 (10%)	320 (5%)	320 (5%)	1,000 (15%)
CO_2e (Million MT)	120 (3%)	250 (6%)	240 (6%)	290 (7%)	750 (19%)

Table reports emissions and petroleum-use reductions incremental to the reductions from power-sector changes

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

- ***Comment:*** **This project has limited validation of demand elasticities and the absence of timelines for demand growth.**
  – *Response:* Demand categories were revisited in detail this year; however, we agree that more validation and additional elasticity estimates would improve the project
- ***Comment*****: Results rest heavily on low-temperature electrolysis's reaching $100/kW.**
  – *Response*: This project is designed to help identify opportunities and R&D targets. Extensive sensitivities help the reader consider variations not provided in the 5 scenarios.
- ***Comment*****: A metric to gauge environmental and life-cycle GHG benefits is needed.**
  – *Response:* Life-cycle GHG benefits are reported this year.

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

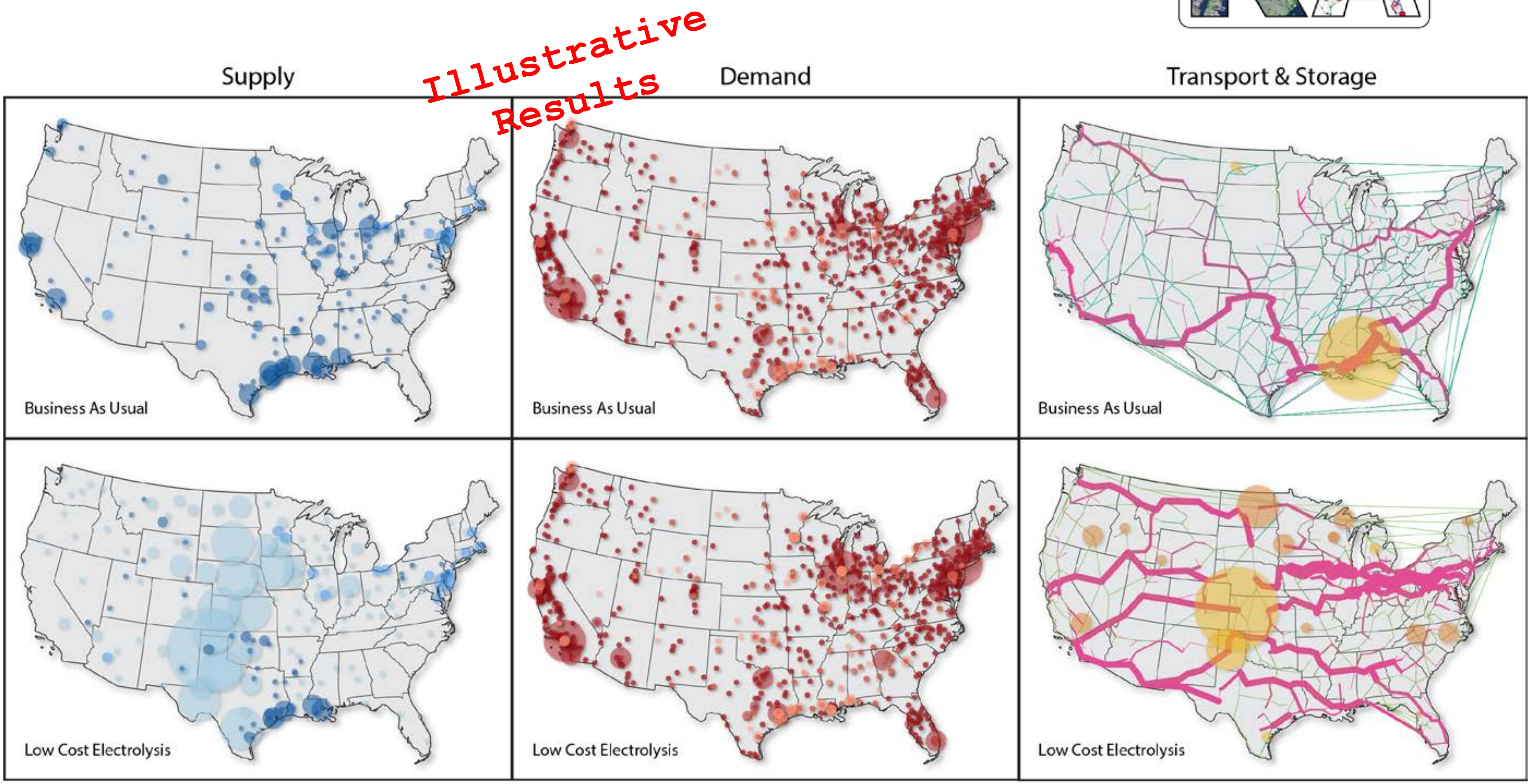
Organizations Providing Input and Review
EPRI
SoCal Gas
California Air Resources Board
Exelon
Shell
ExxonMobil
General Motors
NH3 Energy Association
Nexceris
DOE Office of Nuclear Energy
DOE EERE Offices (Fuel Cell Technologies Office, Solar Energy Technologies Office, Wind Energy Office, Bioenergy Technologies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

Remaining Challenges and Barriers

Economic Potential Estimates	• More in-depth analysis of hydrocarbons • National analysis does not represent regional opportunities and challenges • Alternative futures such as high renewable penetration / low-emissions scenario • Transportation and storage requirements and costs are overly simplified • Rebound effects are not captured
Transition	• Strategies for achieving economic potential should be developed on a regional basis
Business Cases	• Only a few opportunities for individual businesses have been identified; more are needed
R&D Targets	• Technology roadmaps to meet R&D targets have not been developed

Proposed Future Work: Estimate Hydrogen Transport and Storage Costs

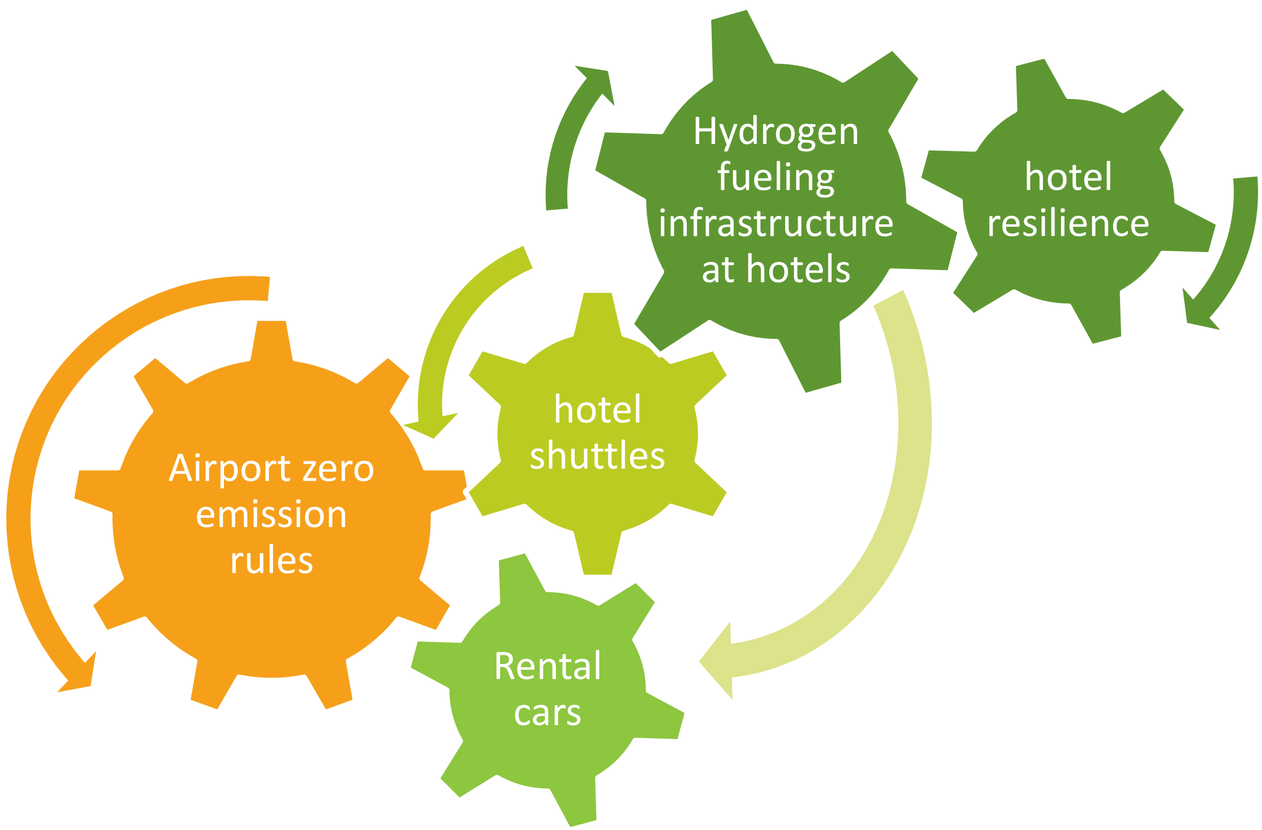
We are using the Scenario Evaluation and Regionalization Analysis (SERA) Model estimate optimal transport and storage infrastructure



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 "Lowest 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**

- **Serviceable consumption potential:**
  107 MMT H_2/ yr

- **Economic potential:**
  22 - 41 MMT H_2/ yr

Report is near completion

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

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: $2.04-2.15/kg. Adding storage and delivery cost would be $2.43-$2.54/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 (44 MMT/yr) and other sources
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 10

Thank You

www.nrel.gov

Publication Number: PR-6A20-73511

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Fuel Cell Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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