



Geospatial Analysis of Hydrogen Production Pathways

Project ID AN016

2010 U.S. DOE Hydrogen Program
Annual Merit Review
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Reference No.: D0511



Timeline

- ◆ Start date: May 2009
- ◆ End date: June 2010
- ◆ 95% Complete

Budget

- ◆ Total project funding
 - » Base Period = \$200K
 - » No cost share
- ◆ FY09 = \$100K
- ◆ FY10 = \$80K

Barriers

- ◆ Systems Analysis Barrier:
 - » A. Future Market Behavior
 - » B. Stove-piped/Siloed Analytical Capability
 - » D. Models and Tools

Partners

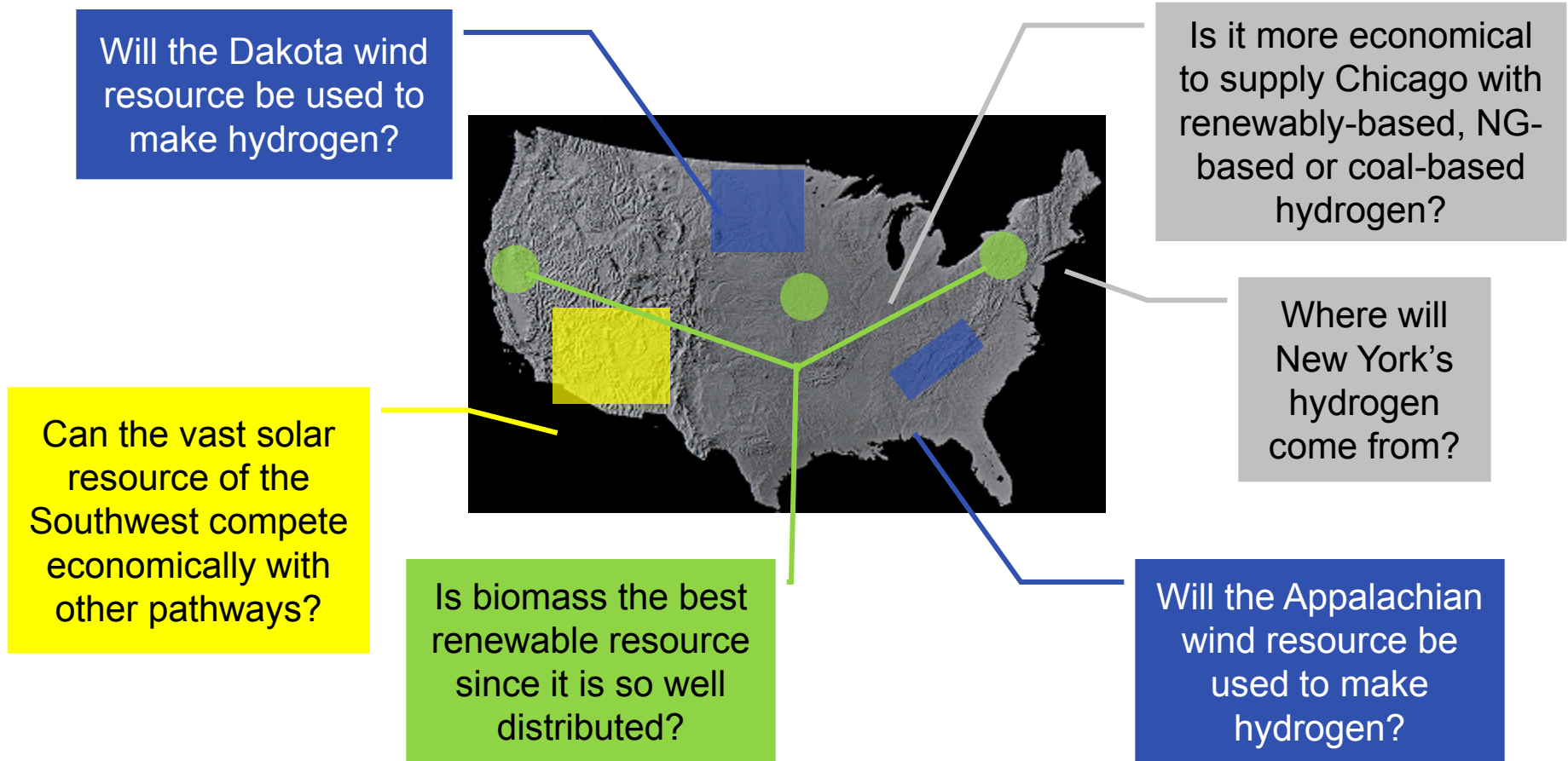
- ◆ Collaboration with NREL:
Project management and technical input

NREL – National Renewable Energy Lab

Project Objectives

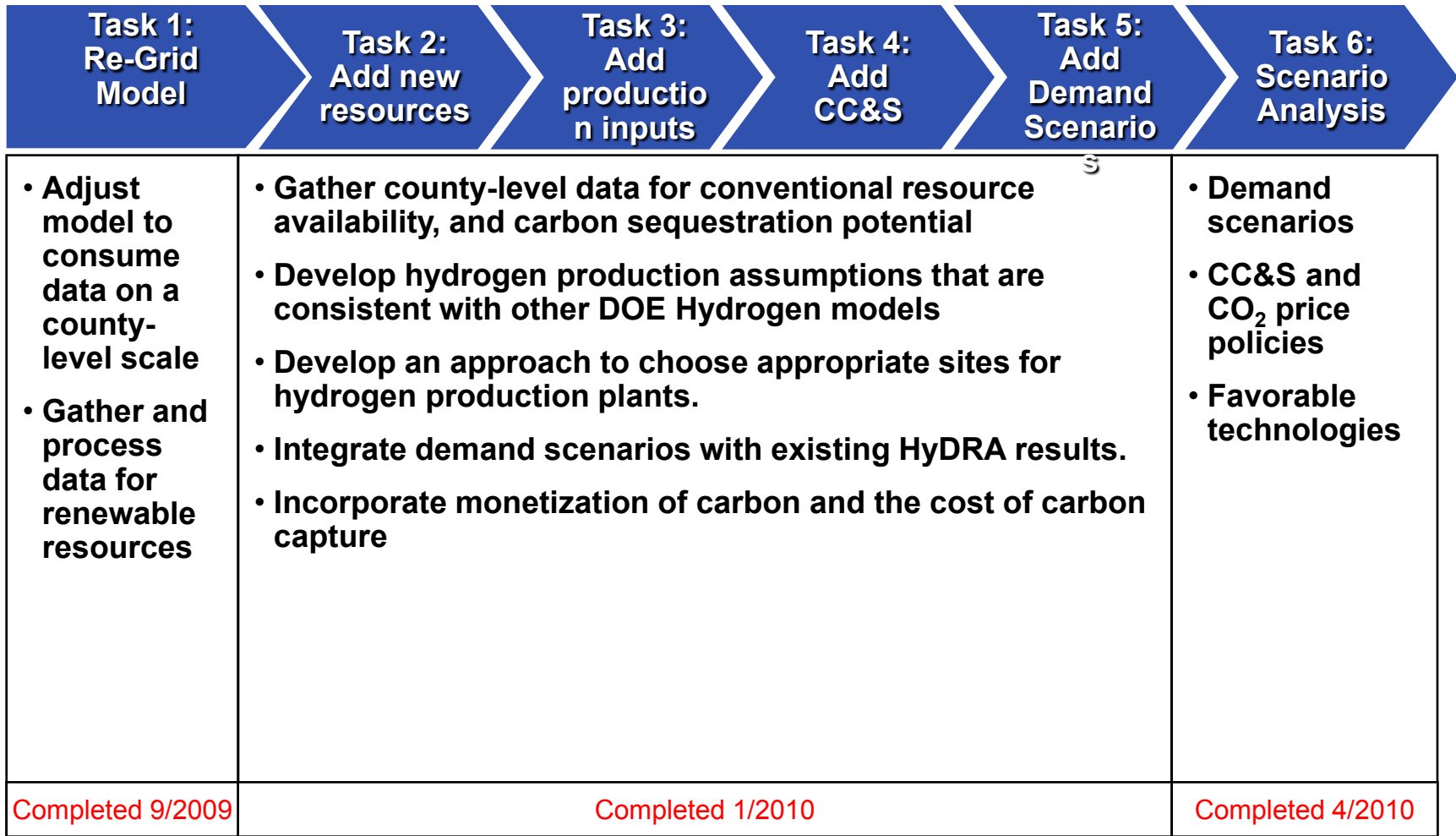
Objectives	Barriers
<ul style="list-style-type: none"> ▪ Develop a tool (the Hydrogen Logistics Model) to compare hydrogen production pathways and policy options 	<ul style="list-style-type: none"> ▪ Models & Tools
<ul style="list-style-type: none"> ▪ Compare production pathways using a single common framework: <ul style="list-style-type: none"> ➤ Input assumptions consistent with other Hydrogen Analysis tools ➤ Account for geographically sensitive characteristics, such as resource availability, cost, and the location of demand centers. ➤ Offer flexibility to test a variety of input assumptions. 	<ul style="list-style-type: none"> ▪ Stove-piped/Siloed Analytical Capability
<ul style="list-style-type: none"> ▪ Perform Scenario Analysis <ul style="list-style-type: none"> ➤ Identify low-cost hydrogen production pathways at demand centers across the United States ➤ Characterize the effect of monetizing carbon emissions, varying hydrogen demand scenarios, and economic inputs on hydrogen price, resource utilization, and CO₂ emissions. 	<ul style="list-style-type: none"> ▪ Future Market Behavior

The price of hydrogen from central production, especially from renewables, will vary widely depending on location.



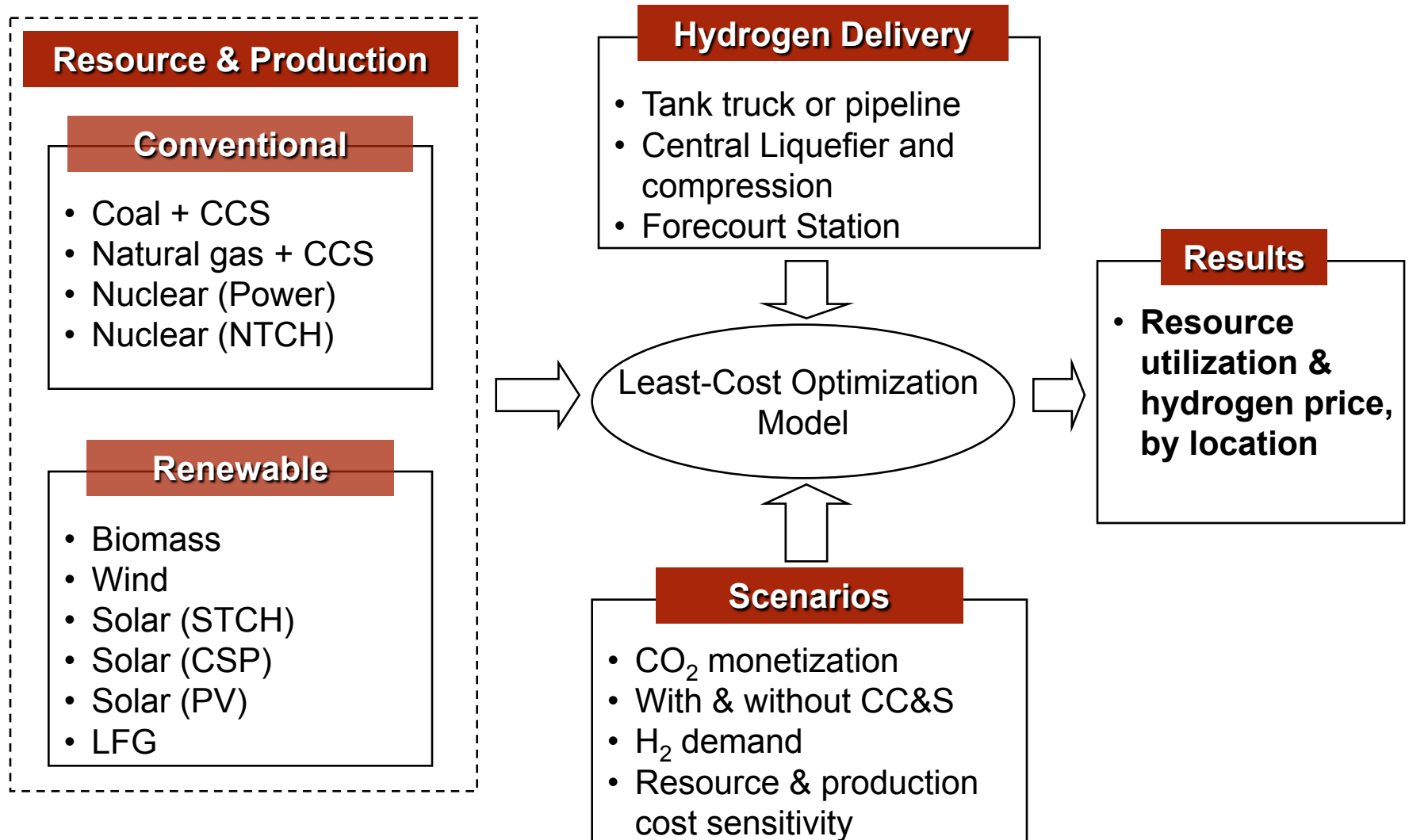
Factors such as demand for hydrogen, resource availability, and resource quality interact to determine the final selling price.

This project was designed to evaluate future renewable H₂ pathways in competition with fossil-based pathways in the U.S.



TIAX has completed analysis and is currently preparing the final report for review by NREL and DOE.

We developed the Hydrogen Logistics Model to select the combination of production pathways that minimizes the average price for hydrogen at individual demand centers across the U.S.



GIS data from NREL, EIA, and EPA are inputs to the model

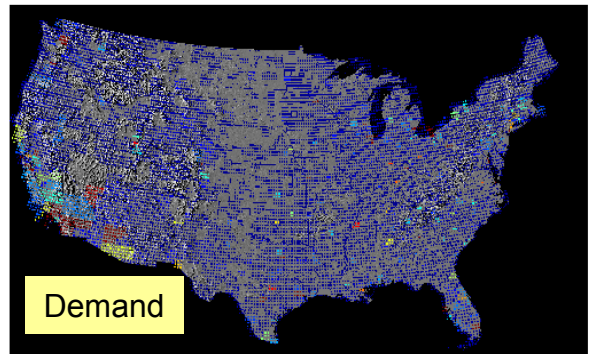
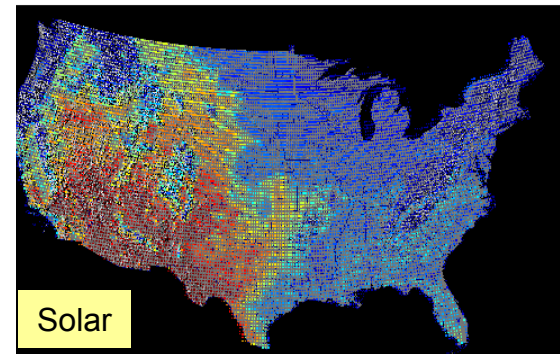
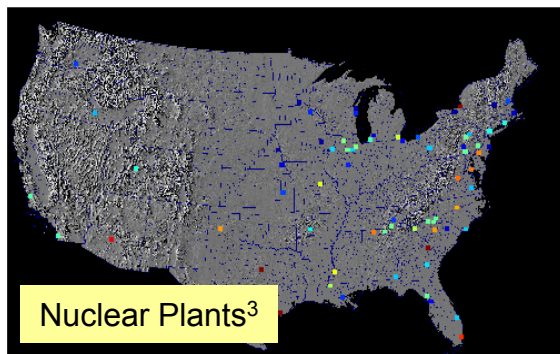
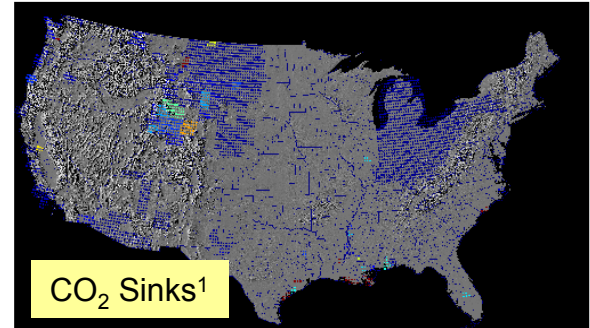
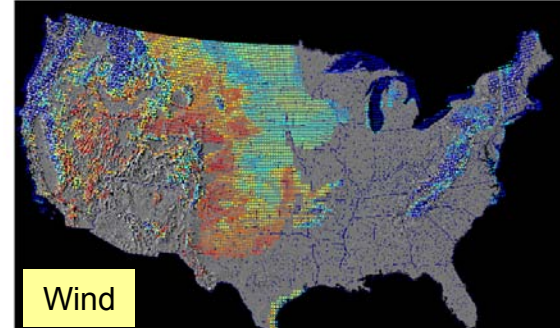
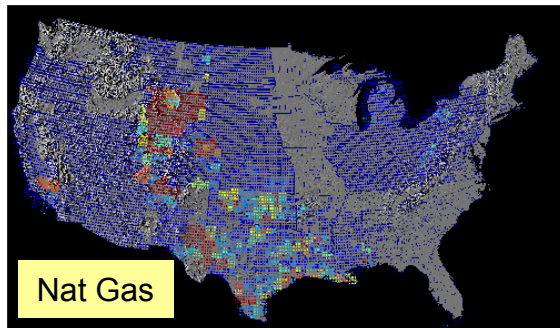
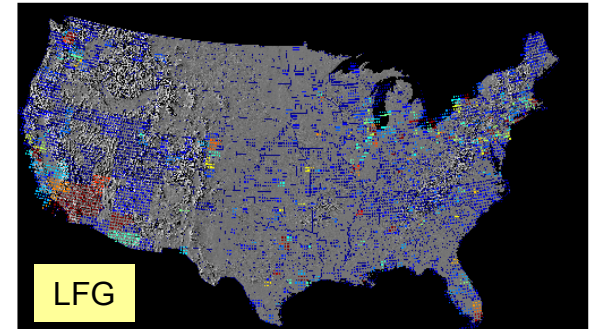
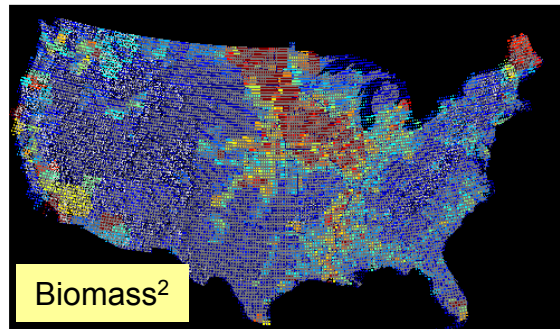
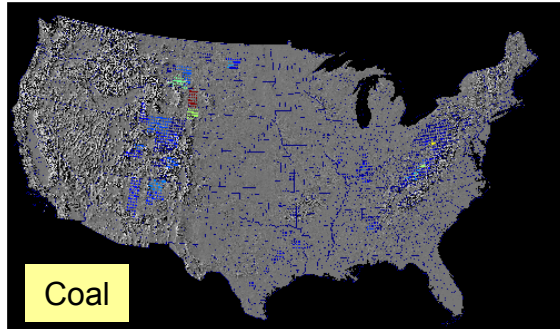
Resource	Resource Transport to Production Site	Production Process	CC&S	Resource Base Estimates
Coal	Rail	Coal Gasification	Yes	30% of 2008 coal production by county ^[1] [EIA 2008]
Natural Gas (NG)	Pipeline	Steam Reforming	Yes	30% of 2008 natural gas production by county ^[1] [HyDRA]
Nuclear Electricity	N/A – Onsite	High-temp electrolysis	No	30% of current and proposed nuclear plant capacity ^[1] [EIA 2009 & EGrid]
Nuclear Thermal (NTCH)	N/A – Onsite	Thermochemical Water Splitting	No	30% of current and proposed nuclear plant capacity ^[1] [EIA 2009 & EGrid]
Biomass ^[2]	Truck	Biomass Gasification	No	County estimates of agricultural residue, energy crop, forest residue, and urban woodwaste supply [NREL 2005]
Wind Electricity	N/A – Onsite	Electrolysis	No	Wind class and quantity by grid ^[3] [NREL]
Solar Thermal (STCH)	N/A – Onsite	Thermochemical Water Splitting	No	Solar insolation and quantity by grid ^[3] [NREL]
Solar CSP & PV	N/A - Onsite	Electrolysis	No	Solar insolation and quantity by grid ^[3] [NREL]
Landfill Gas (LFG)	N/A - Onsite	Gas Upgrade + Distributed Steam Reforming of N Gas	No	County estimates of LFG supply [NREL 2005]

^[1] Conventional resources are restricted to 30% of total supply to reflect alternate end-uses (e.g., electricity)

^[2] Includes energy crops, and agricultural, forest, and urban wood residues

^[3] Wind & Solar data are consumed in grid cells measuring 0.25 x 0.25 deg

The location and quantity of resource feedstocks, carbon sinks, and demand centers are estimated from GIS data at discrete nodes across the U.S.



¹Includes saline aquifers, depleted oil fields, and unmineable coal seams

²Includes agricultural residues, forest residues, urban woodwaste, and energy crops

³Current & proposed nuclear plants

While this is a new project, TIAX developed a previous version of the Hydrogen Logistics Model to investigate renewable hydrogen production pathways.

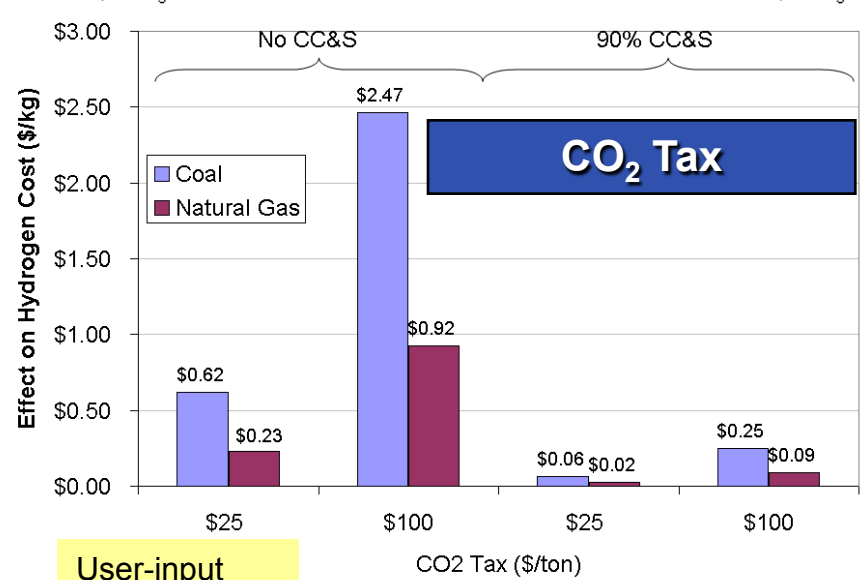
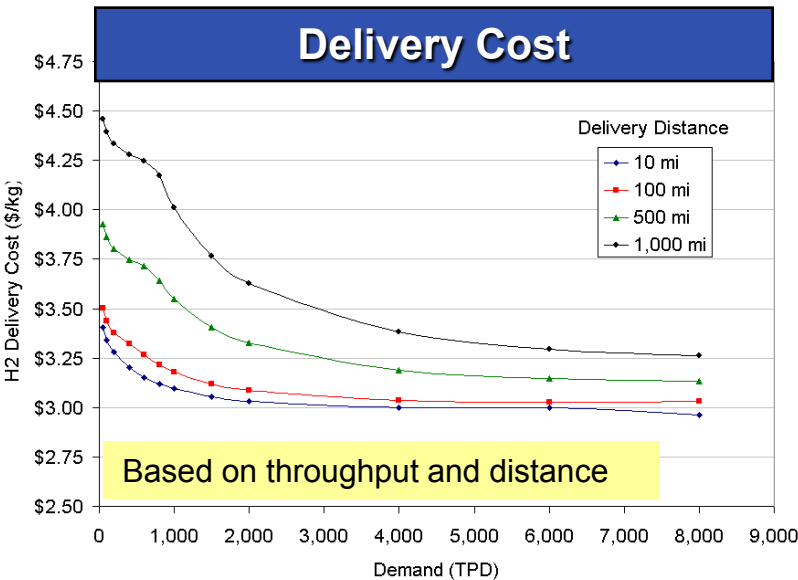
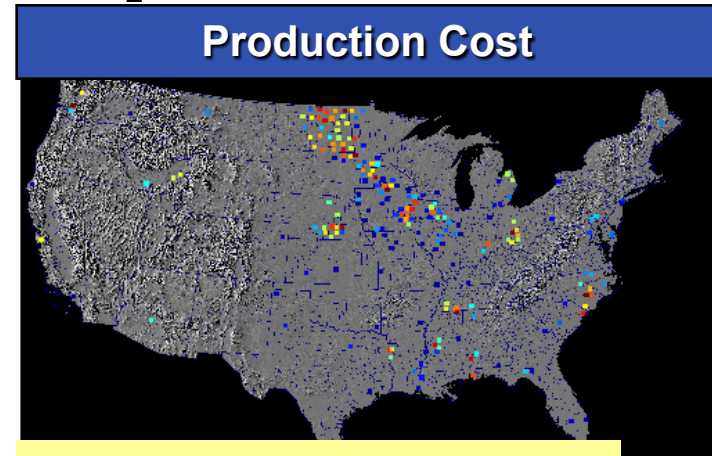
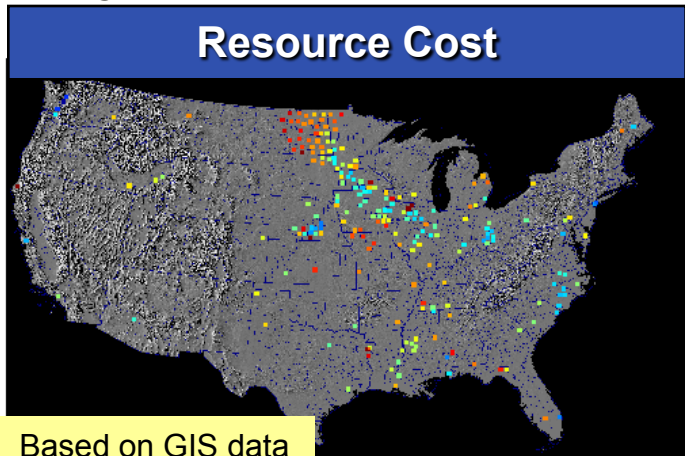
- The previous evaluation focused on the net economic and greenhouse gas emissions impacts of a future renewable-based hydrogen infrastructure, including only:
 - Biomass
 - Wind
 - Solar (PV & CSP)
- The analysis reached the following conclusions:
 - Production is dominated by biomass and wind production pathways. Biomass offered lower costs, but was more constrained geographically.
 - Solar resources were not utilized, even with favorable assumptions.
 - On an average basis, renewable hydrogen could be produced at an average premium of 25 to 30% compared to natural gas pathways.

Technical Accomplishments - Overview	Barriers
<ul style="list-style-type: none"> ▪ Updated the Hydrogen Logistics Model <ul style="list-style-type: none"> ➤ Gathered and parsed GIS data on the location and quantity of feedstocks, demand, and carbon sinks ➤ Developed input cost functions to calculate resource, production, delivery, CC&S, and CO₂ tax costs based on major cost drivers ➤ Optimized calculation engine to allow more rapid scenario analysis ➤ Utilized an interactive user-interface to allow scenario analysis 	<ul style="list-style-type: none"> ▪ Models & Tools
<ul style="list-style-type: none"> ▪ Compared production pathways using a common framework: <ul style="list-style-type: none"> ➤ Calculates location-specific delivered costs ➤ Coordinated input assumptions with staff from NREL to ensure harmonization with other hydrogen energy models (e.g., HyDRA, H2A) 	<ul style="list-style-type: none"> ▪ Stove-piped/Siloed Analytical Capability
<ul style="list-style-type: none"> ▪ Performed scenario analysis to identify key drivers, high sensitivity variables, and inform future program direction. 	<ul style="list-style-type: none"> ▪ Future Market Behavior

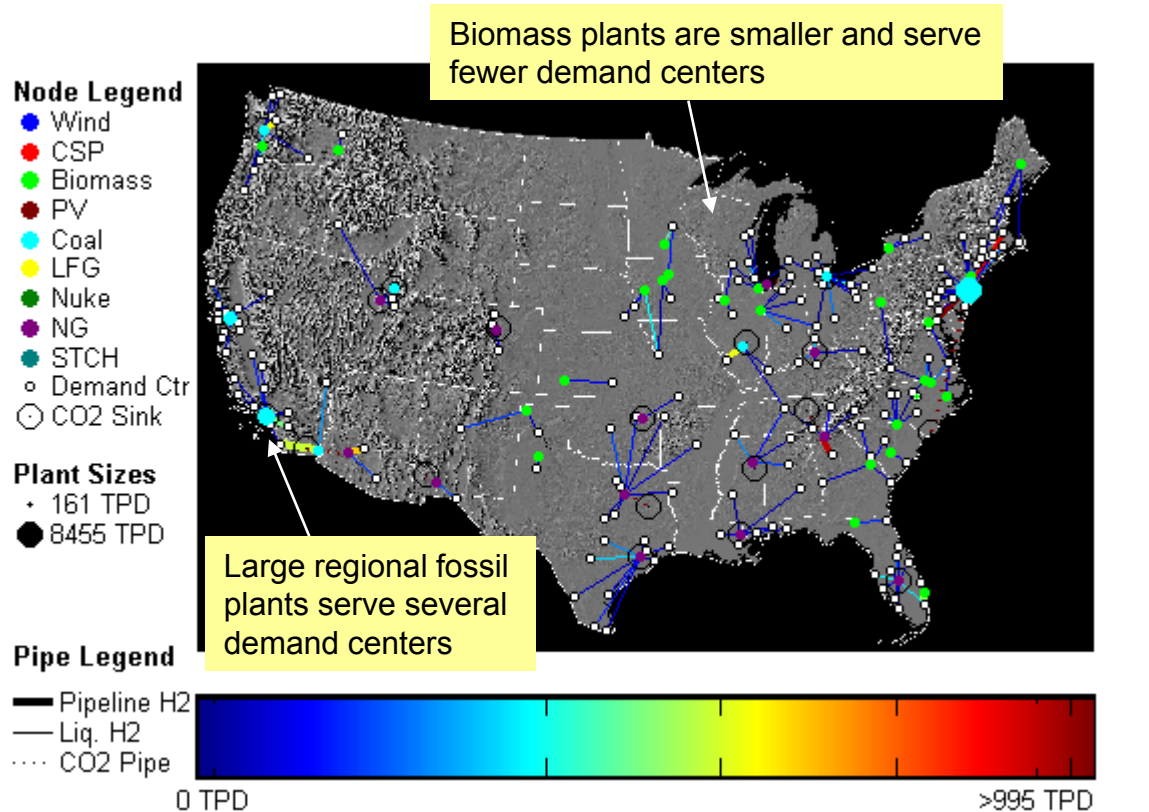
Conclusions – Base Case

- **Fossil resources dominate:** Hydrogen is produced primarily from fossil resources (~80% of supply), with biomass accounting for the remaining 20%.
- **Avg price of \$4.90:** Base case results (\$25/ton CO₂ tax) estimate that hydrogen could be supplied at an average selling price of \$4.90.
- **Population density (size of the demand center) is the primary determinant of variation in hydrogen selling price.** Prices vary across the US from ~\$4.50 to \$5.95 per kg. Large clusters of demand centers enable large, low-cost fossil plants.
- **Delivery costs (mostly fixed) are the dominant contributor to hydrogen selling price.** Delivery costs average \$3.25 per kg (nearly 70% of the selling price), and do not vary appreciably with production pathway.
- **Carbon mitigation costs (CO₂ tax and CC&S cost) are relatively minor contributors.** They account for <5% of the average delivered cost.

The cost of hydrogen is modeled as the sum of the resource, production, delivery, and CC&S costs, plus user-defined CO₂ taxes.



The base case scenario projects that hydrogen production is dominated by the natural gas pathway, with some contribution from biomass and coal.



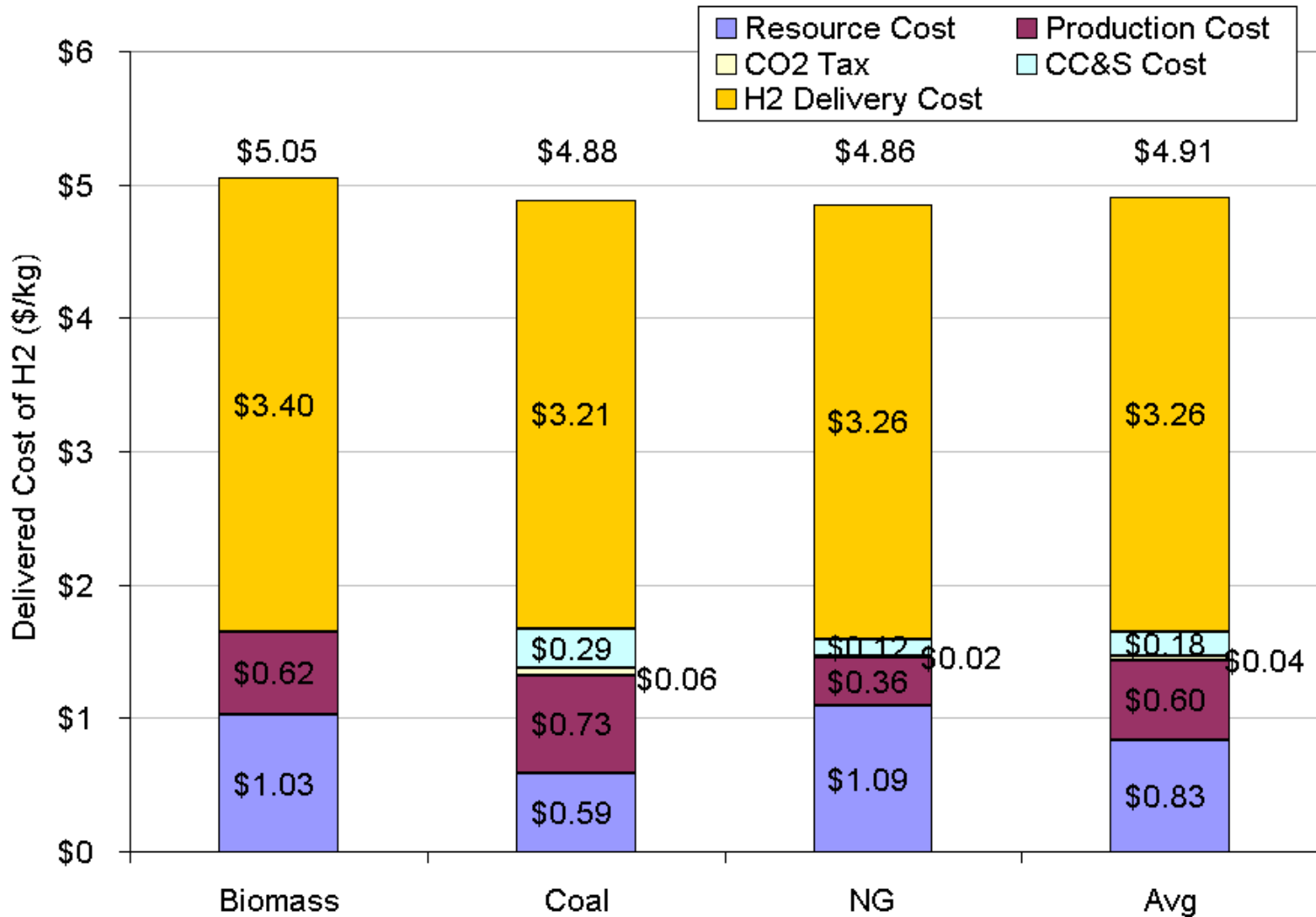
Biomass plants are smaller and serve fewer demand centers

Large regional fossil plants serve several demand centers

- Colored dots reflects hydrogen production plant locations
- Color of dots reflects TYPE of plant.
- Size of dot reflects the SIZE of the plant
- White squares represent demand centers
- Solid colored lines show hydrogen delivery pathways.
- Thick lines reflect pipeline delivery; thin lines correspond to liquid truck delivery.
- The color of the delivery lines corresponds to throughput
- Dotted lines show carbon pipelines; the thickness of the line reflects the throughput

Type	Prod. (TPD)	Pct	Avg Cost (\$/kg)	# Plants	Avg Plant Size (TPD)	Avg. Delivery Dist (mi)
Biomass	8,040	20%	\$5.05	28	320	100
Coal	20,000	50%	\$4.88	10	2,020	80
NG	11,800	30%	\$4.86	13	915	70
Total	39,800	100%	\$4.91	51	805	80

The average delivered price of hydrogen is ~\$4.90 per kg, the majority of which is fixed delivery cost.

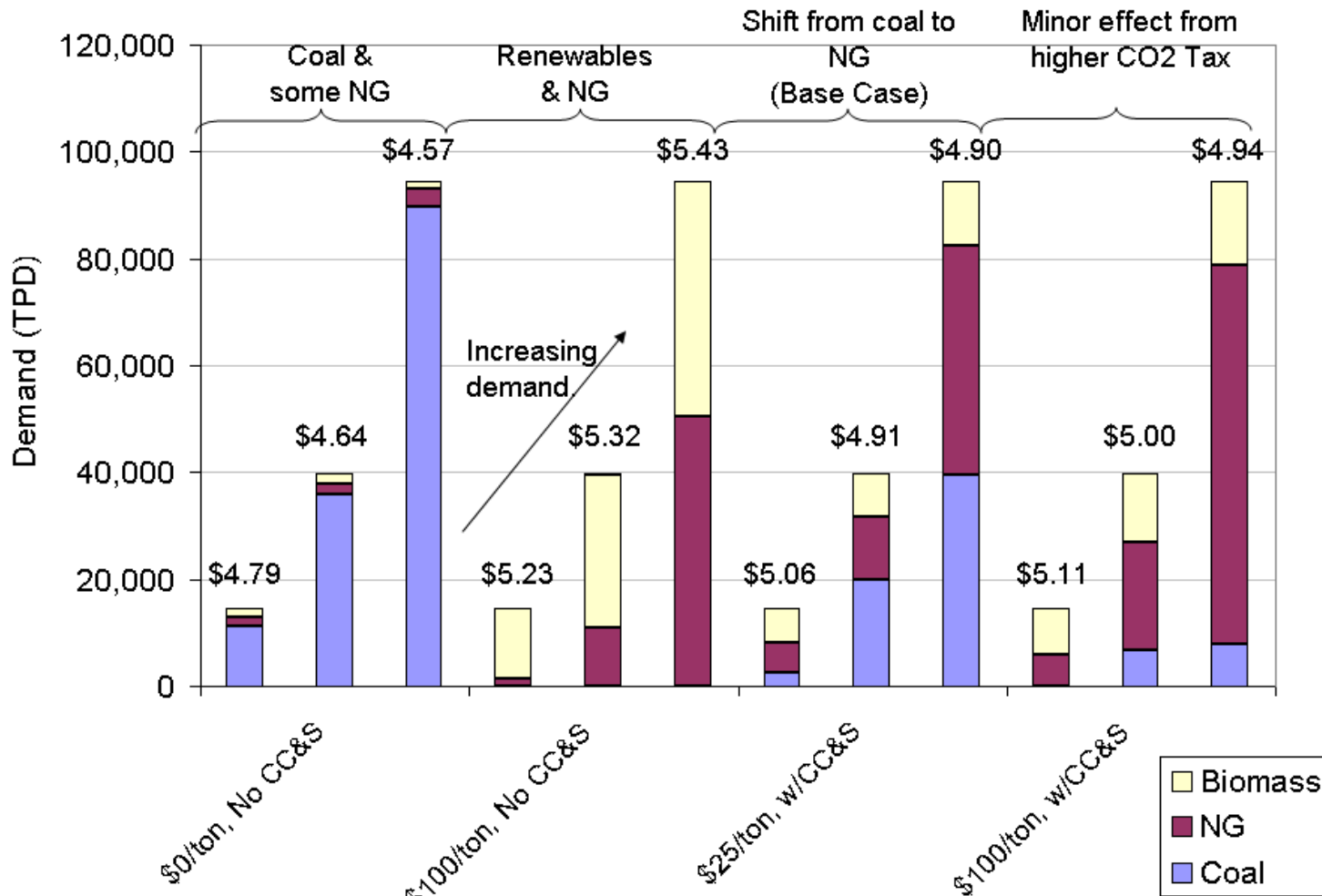


Conclusions – Sensitivity Cases

- **The adoption of non-fossil pathways is highly dependent on demand, the efficacy of carbon capture, and the price of carbon:**
 - Varies from 0% (no CO₂ tax, high demand) to >95% (\$100/ton CO₂ tax, no CC&S, low demand).
 - LFG and biomass are the most economic non-fossil production pathways
- **The delivered price of hydrogen varies widely depending on the efficacy of carbon capture and the level of demand:**
 - Average price ranges from \$4.60/kg (no CO₂ tax, high demand) to \$5.45/kg (\$100 per ton CO₂ tax, no CC&S)
- **At low demand, every scenario examined can reduce carbon emissions by upwards of 90% with a relatively minor price impact:**
 - Carbon mitigation costs range from ~\$15 (if CC&S is available) to \$25 per ton (no CC&S) at low demand.
- **At high demand, carbon mitigation costs and efficacy vary widely depending on the scenario:**
 - Carbon mitigation costs and efficacy range from \$15/ton with >90% reduction in CO₂ to ~\$50 per ton with a 80% reduction in CO₂.

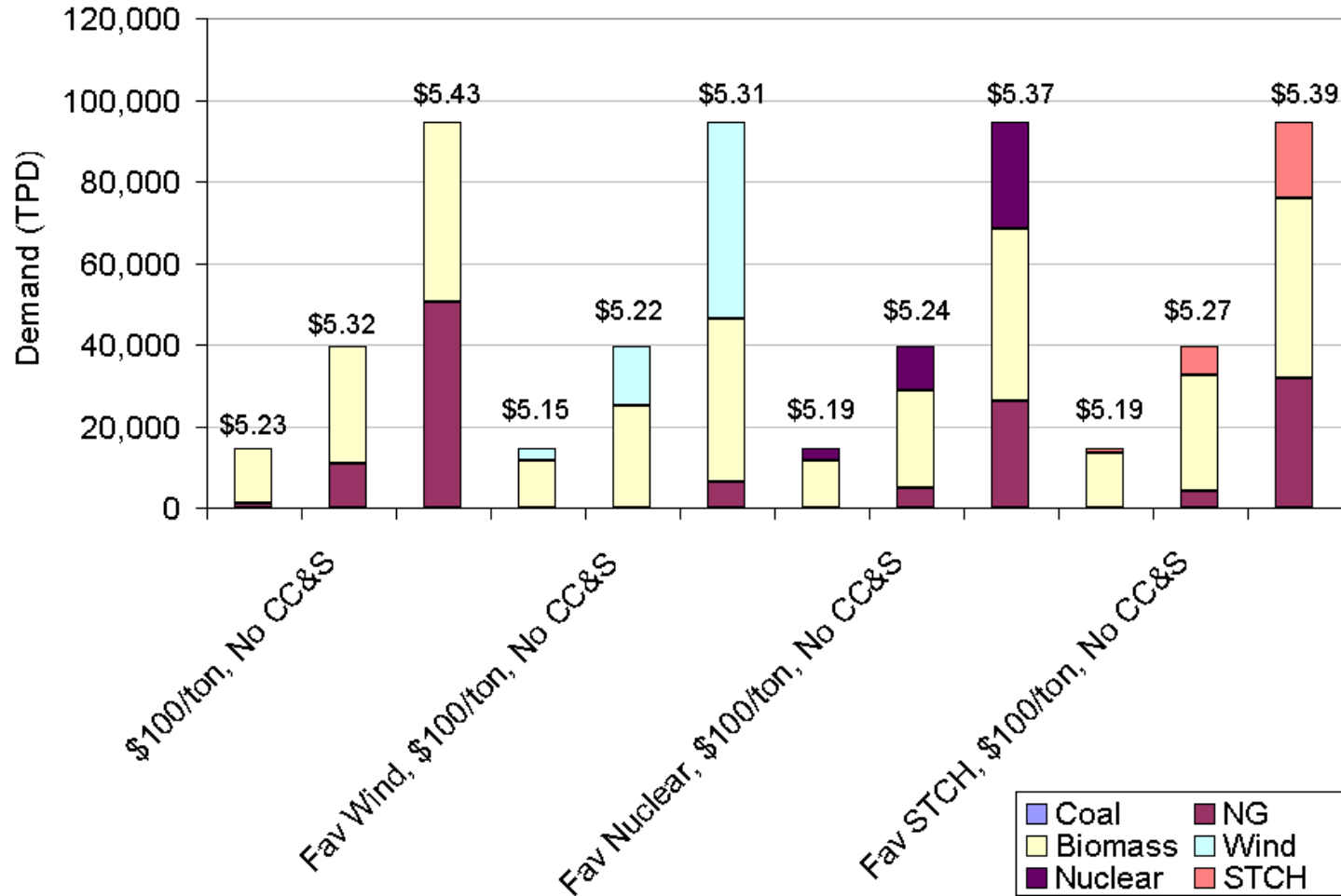
Sensitivity Analysis: Effect of carbon constraints and demand on resource utilization

Biomass, coal, and natural gas are the only resources utilized.



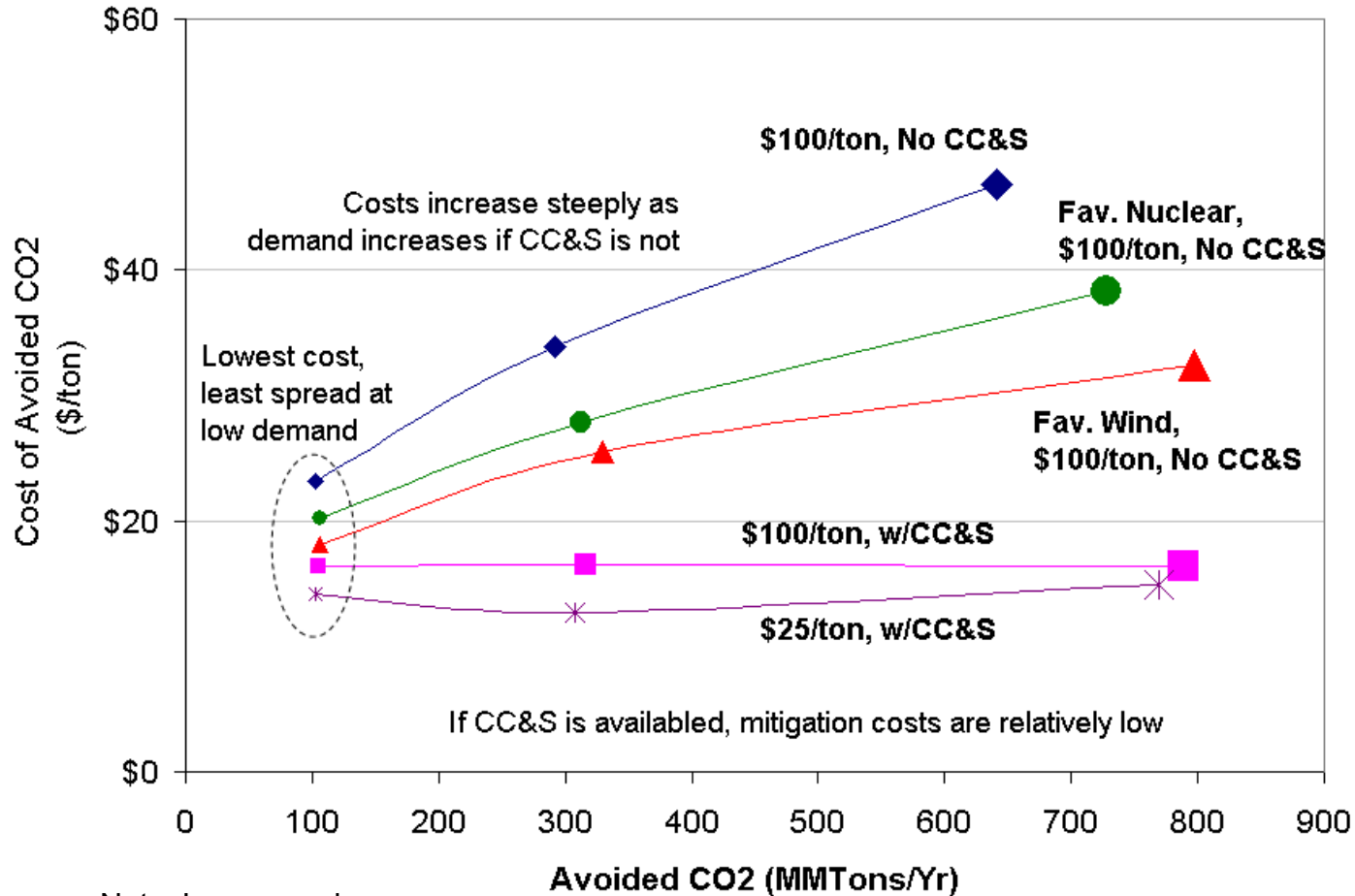
Sensitivity Analysis: Effect of technology improvements and demand on price and resource utilization

Wind, nuclear, and STCH achieve significant market penetration if CC&S is not available



Comparison of CO₂ Mitigation Costs

CO₂ mitigation costs vary from about \$10 per ton to nearly \$50/ton depending on the level of hydrogen demand and whether carbon capture is utilized or not.



Note: Larger marker corresponds to higher demand scenario

Collaborations

- National Renewable Energy Laboratory
 - Project Management - Offered guidance in shaping study scope and identifying critical questions
 - Provided feedback on key input assumptions
 - Shared data sources (e.g., GIS, demand, & H2A data)
 - Provided external review of preliminary results
- Fossil and Nuclear Energy
 - Submitted results for review
- Solar Thermal Chemical Hydrogen Team
 - Provided feedback on STCH input assumptions

Proposed Future Work

Current Contract:

- Review results with DOE EERE & Fossil/Nuclear Energy Offices
- Submit final report to DOE & peer-reviewed journals

TIAX proposes to enhance the capability of the Hydrogen Logistics Model to help continue to meet the goals of the Hydrogen Program:

- Include distributed production pathways in the analysis: Allows comparison of centralized and distributed production within the same framework.
- Use a design-of-experiments approach to model hydrogen infrastructure transition and evolution over time.
- Further integrate inputs & outputs with existing Hydrogen program tools (HyDRA, Macro-System Model, etc) or GIS tools (e.g., ArcGIS)
- Introduce additional policy constraints – e.g., renewable portfolio standards, low carbon fuel mandates, production tax credits
- Model competition with alternative end-uses (e.g., electricity)
- Characterize high sensitivity parameters using Monte Carlo analysis

Summary

- **Relevance:** Compare diverse production pathways within a single analysis framework, model future market behavior, and develop a tool that
- **Approach:** Develop a flexible user-interactive tool that estimates the hydrogen selling price and resource utilization at demand centers across the US
- **Technical Accomplishments and Progress:** Completed development of the Hydrogen Logistics Model and performed scenario analysis to model the effects of demand, carbon price, and cost assumptions on the price of hydrogen and resource utilization.
- **Proposed Future Research:** Potential enhancements could improve integration with other models, evaluate forecourt and centralized production pathways within a single framework, and examine the dynamics and economics of a hydrogen transition.

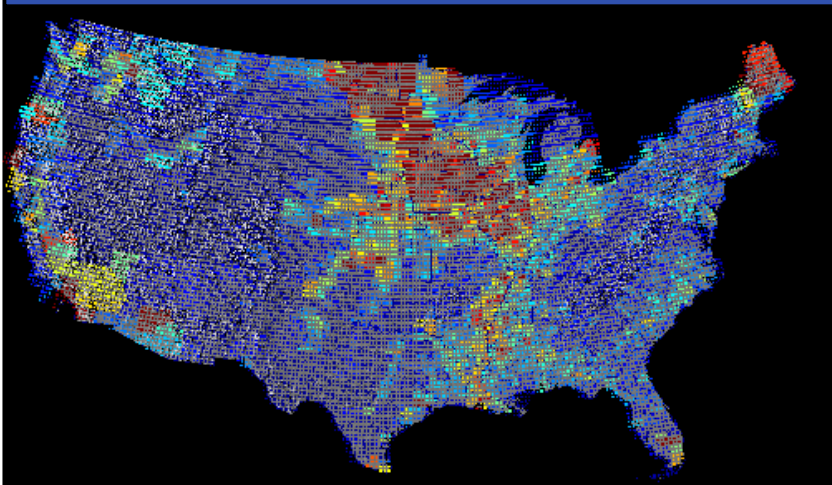
Supplemental Slides

Critical Assumptions & Issues

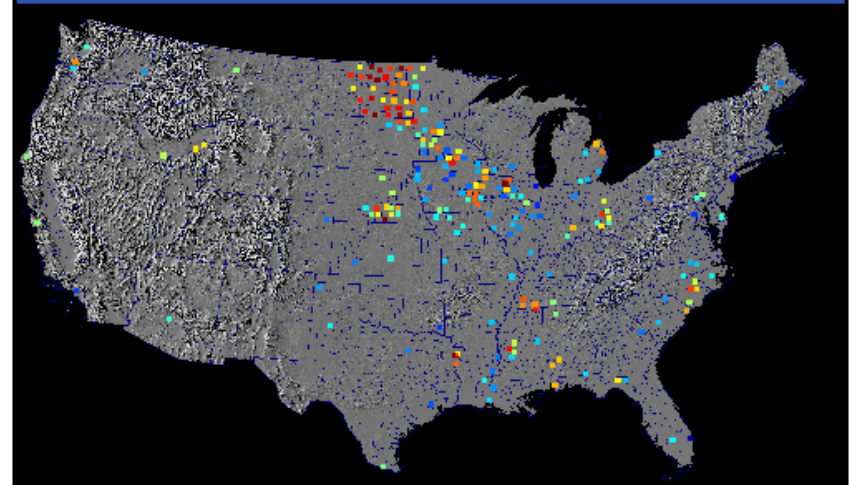
- Competition for alternative feedstock end-uses is addressed exogenously
 - We have not modeled competition between different end-uses for hydrogen feedstocks (e.g., electricity in the case of coal, food or bio-fuel in the case of biomass).
 - Restricted availability of conventional resources to 30% of the total production
 - Based feedstock prices on the “willingness to accept” price of suppliers, which seeks to internalize the opportunity costs of alternative uses.
- Analysis focuses on high volume, centralized production pathways:
 - The results are best interpreted as a representation of a mature hydrogen infrastructure.
 - We have proposed to extend the model to include distributed pathways and transition analysis
- The LFG, NTCH, and STCH pathways are less technologically mature and have not been studied as widely as the other pathways. As such, cost data has not been vetted to the same extent and has a wider uncertainty band than other estimates
 - Reviewed analysis from the solar thermal hydrogen team and nuclear hydrogen initiative to
 - Included sensitivity analysis to reflect key uncertainties

Production plant locations are selected to optimize tradeoffs between supply locations, demand centers, and carbon sinks.

Biomass Feedstock Locations

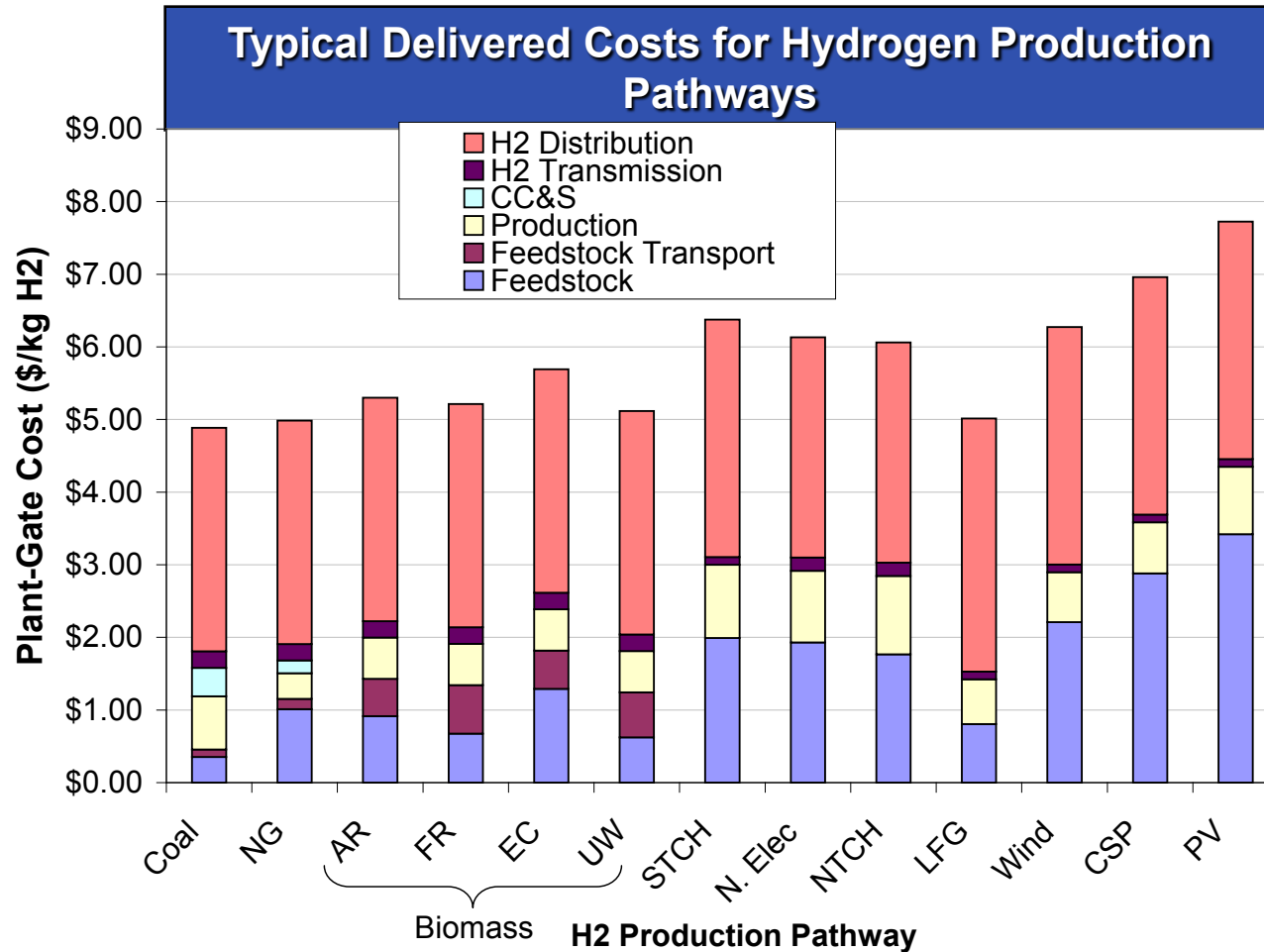


Biomass Production Plant Sites



Biomass sites are selected to balance the reduced production costs of larger plants with the increased costs of feedstock transportation

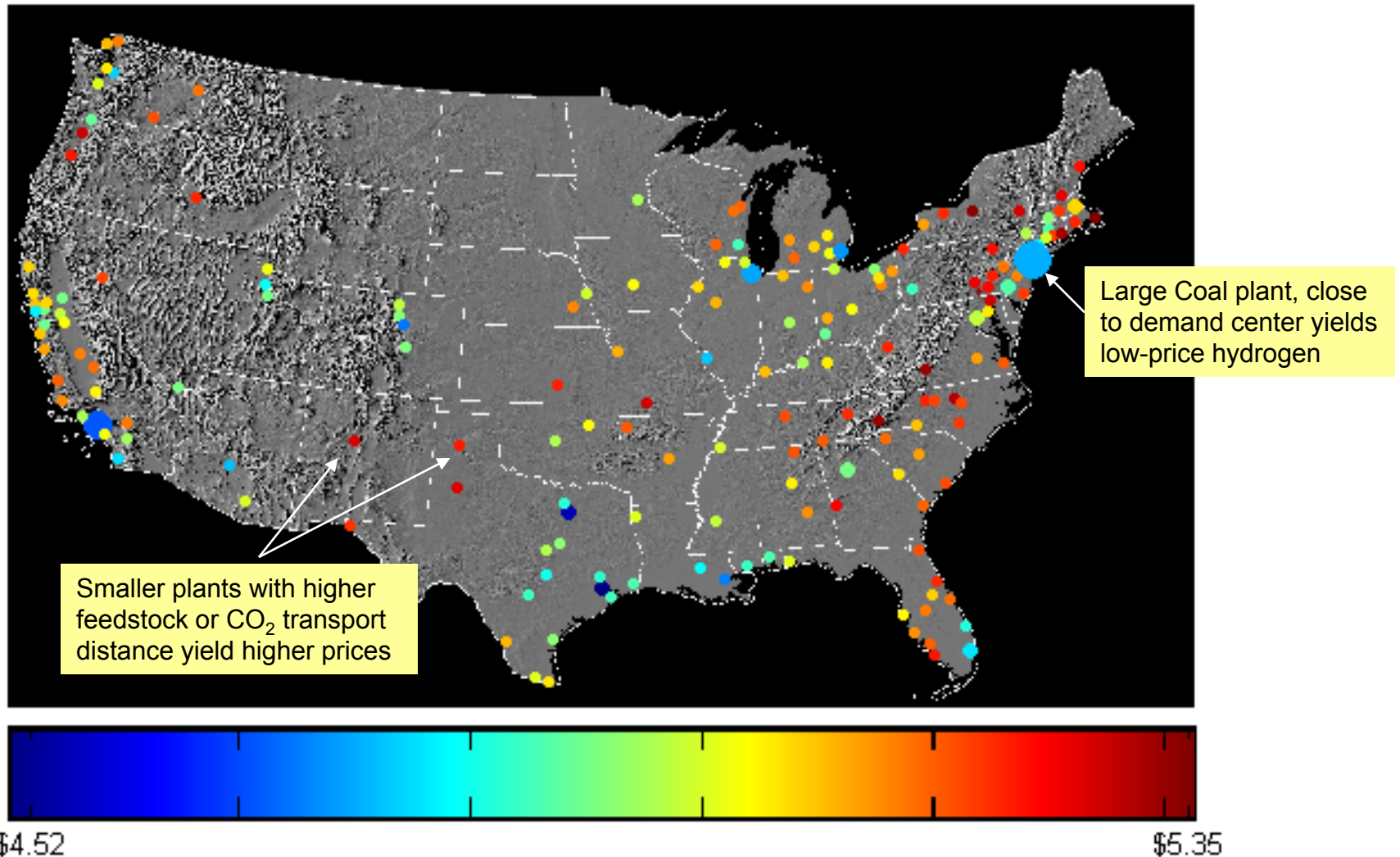
Scoping calculations for plant-gate costs using typical input values suggest that fossil fuels, biomass, and LFG are most likely to be adopted.



Base Case Scenario Assumptions

- Medium demand (~40K TPD) - “H2 Success” Scenario, Year 2040, from NAS H2 study
- Fossil plants equipped with CC&S capability (90% of CO₂ is captured)
- \$25/ton CO₂ tax
- Cost assumptions from H2A defaults (as available)
- LFG is excluded

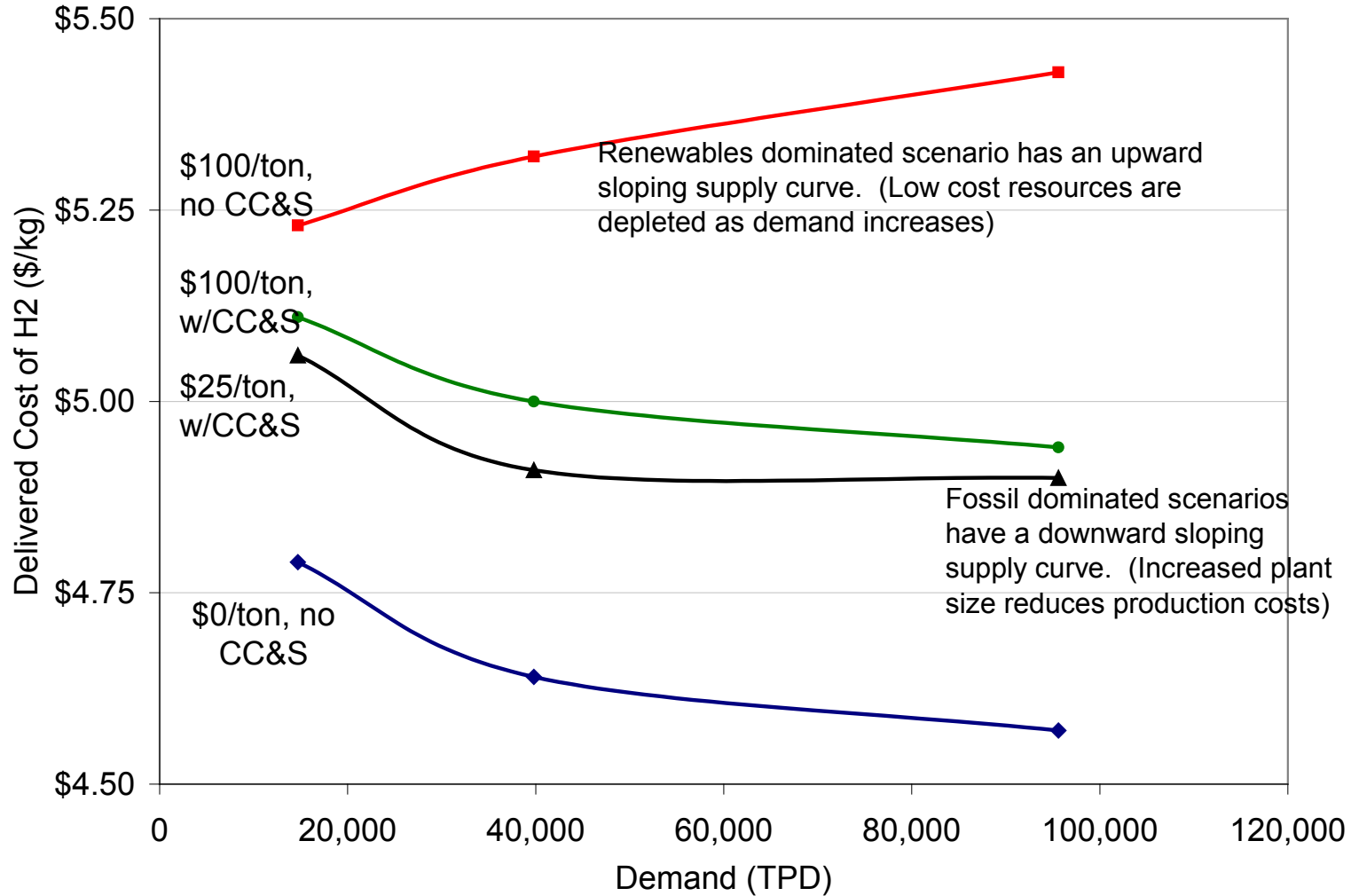
Plant size, location, delivery throughput, and production pathway are primary determinants of the final hydrogen selling price.



Description of Sensitivity Scenarios

Variable	Options	Description
Demand	Low, Medium, High	NAS scenarios – 15K TPD, 39K TPD, 96K TPD
CC&S	Yes or No	0% carbon capture or 90% carbon capture
CO ₂ Tax	None, Low, High	\$0, \$25, \$100 per ton
Wind	Baseline, Favorable	Baseline – Wind turbine costs (\$1,000/kW) and capacity factors from literature; H2A electrolyzer (\$300/kW) Favorable – consistent with DOE MYPP targets (\$700/kW turbine, \$125/kW electrolyzer, higher capacity factor)
Nuclear Electrolysis	Baseline, Favorable	Baseline – H2A high temperature electrolysis (\$0.055/kWh, \$500/kW electrolyzer) & Technology Insights [2007] assumptions Favorable -- \$0.035/kWh electricity, \$300/kW electrolyzer
Solar Thermal (STCH)	Baseline, Favorable	Baseline – DOE target of \$3.00/kg @ 100 TPD H ₂ Favorable – 15% reduction in resource cost (\$80/kW heliostat); increase plant size to 500 TPD
LFG	Unused, Used	Base – LFG is unused Sensitivity case – LFG is included
Delivery	Baseline, Favorable	Baseline – Estimates projected as a function of demand by HDSAM Favorable – Approaches DOE target of \$1.00/kg, including low variable cost

Effect of carbon constraints and demand on the cost of hydrogen



Sensitivity Analysis: LFG has the potential to provide a low-cost renewable alternative to biomass. However, it is severely constrained by the amount of LFG available.

