Impact of Renewables on Hydrogen Transition Analysis

Project ID # ANP1

DOE Hydrogen Program

May 16, 2007

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This presentation does not contain any proprietary or confidential information

Overview

Timeline

- Start date: Oct 2006
- End date: Feb 2007
- 100% Complete (final report to be published by NREL)

Budget

- Total project funding
  - Base Period = $100K
  - No cost share
- FY06 = $40K
- FY07 = $60K

Barriers/Targets

- Systems Analysis Barrier:
  - A. Future Market Behavior
- Targets: 2017 (and beyond)

Renewable Pathway	Cost ($/gge)
Central wind electrolysis	2.00
Solar energy cycles	3.00
Biomass gasification	1.10

Partners

- Collaboration with NREL
- Review by NHA Renewable Hydrogen Working Group

NREL – National Renewable Energy Lab
NHA – National Hydrogen Association

Objectives

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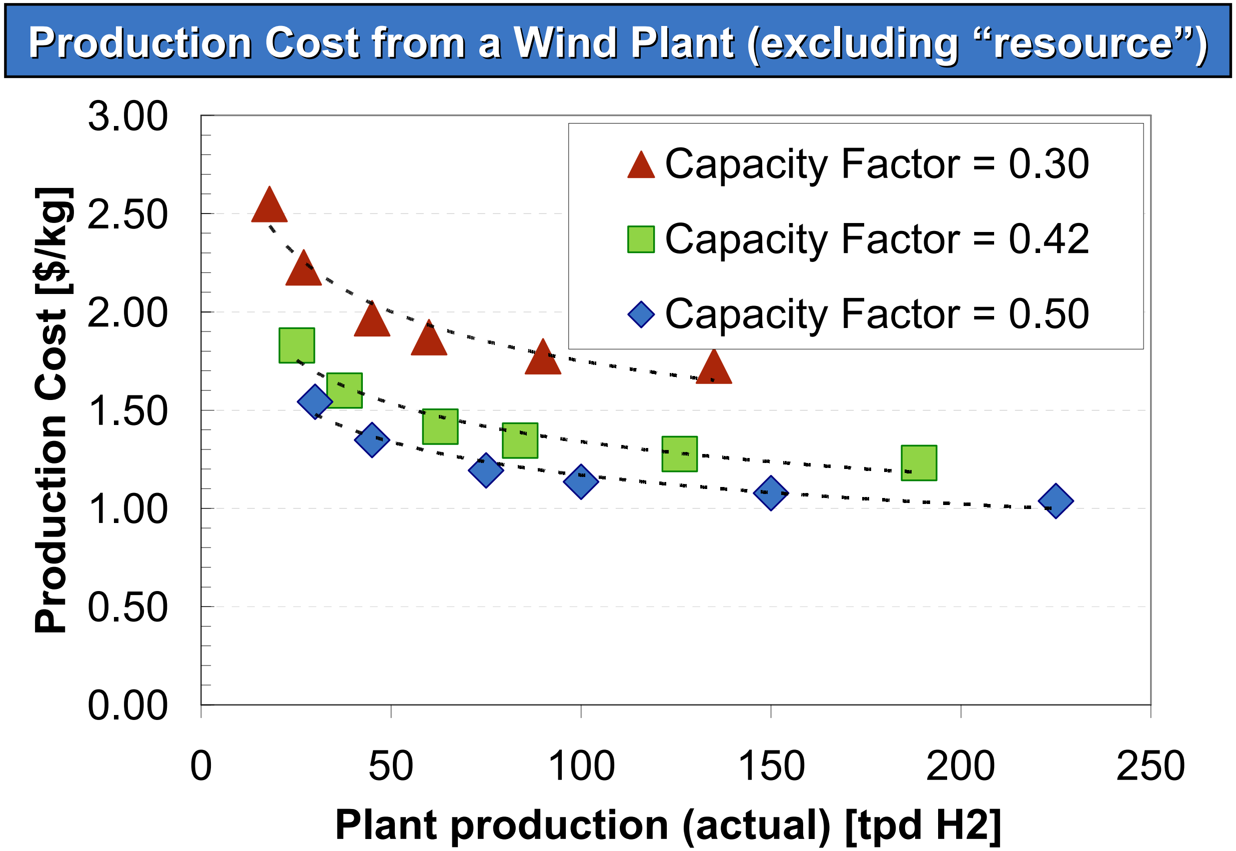
Overall	◆ Predict the most economically attractive renewable resources for producing H_2 for future light-duty vehicles in the U.S.
2006	◆ Identify and down-select the most attractive renewable resources available in the U.S. (Lower 48) ◆ Establish future H_2 light-duty vehicle demand scenarios ◆ Develop Logistics Model to minimize the delivered cost of H_2 by selecting the most economical resources
2007	◆ Determine how competitive renewable-based H_2 options could be compared to fossil fuel-based (i.e. natural gas) production ◆ Find what technical or cost improvements are needed to make renewable-based H_2 more competitive using sensitivity analysis ◆ Investigate H_2 delivery cost reductions by creating a pipeline network from the output of the Logistics Model

The potential for renewable-based hydrogen use by the U.S. automotive sector is investigated using the TIAX H_2 Logistics Model.

- Supply and demand are model results based on location-specific variables, such as population and quality of the local renewable resource
  - GIS data for population and renewable resource quality/availability (from NREL database) are determined for each ~230 mi^2 "node" in the U.S.
- An optimal set of hydrogen production plants and a delivery infrastructure is determined by minimizing the sales-weighted average price of hydrogen
  - Functions for renewable resource, hydrogen production and delivery costs are used to determine the most economically attractive resources
  - We included a population cutoff in order to capture the largest demand centers representing roughly half of the population of the contiguous U.S.
  - Hydrogen is assumed to be delivered via compressed hydrogen pipelines directly from source to sink "as the crow flies"
- After the optimization, a pipeline networking case was developed to investigate the impact of consolidation (higher throughput per mile with fewer overall miles)

[1] Geographic Information Systems (GIS) is a computer-based system used to manipulate, manage, and analyze multidisciplinary geographic and related attribute data (http://www.nrel.gov/gis/).

H2A Production model values for wind electrolysis and biomass gasification are used for cost and efficiency information[1].



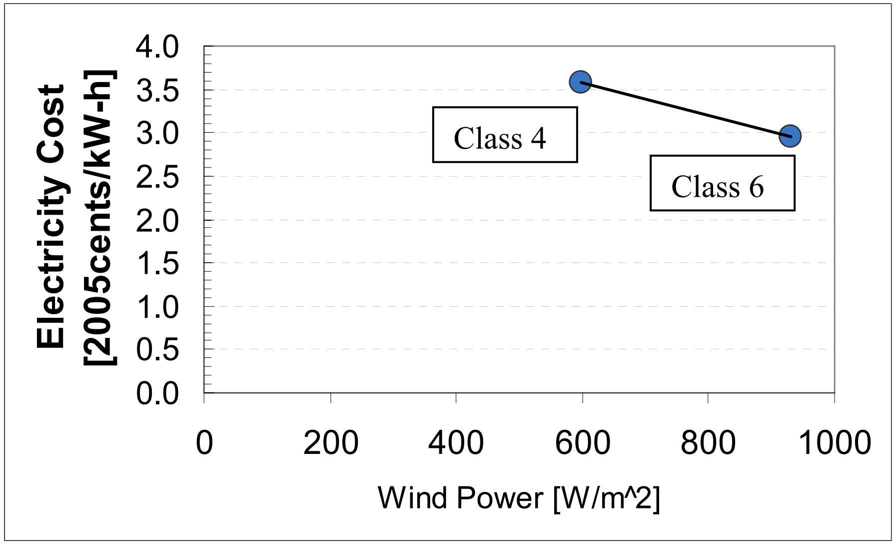
However, unlike H2A, Logistic Model inputs include costs for a range of plant sizes and capacity factors to perform the optimization.

[1] H2A models: "Longer-Term (2020-2030) Hydrogen from Wind" and "Longer-Term (2020-2030) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming". Updated June 7, 2006.

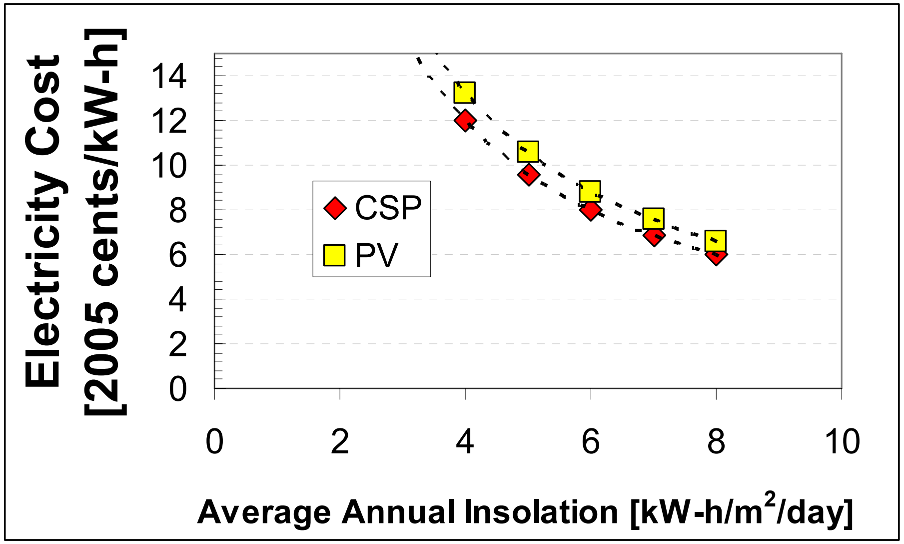
Wind capacity factor and power are both functions of wind speed, thus electricity prices can be tied directly to the wind class.

Similarly, the cost of electricity from solar technologies can be linked to the insolation (normal or global) at a particular location.

Cost of Electricity from Wind Turbines

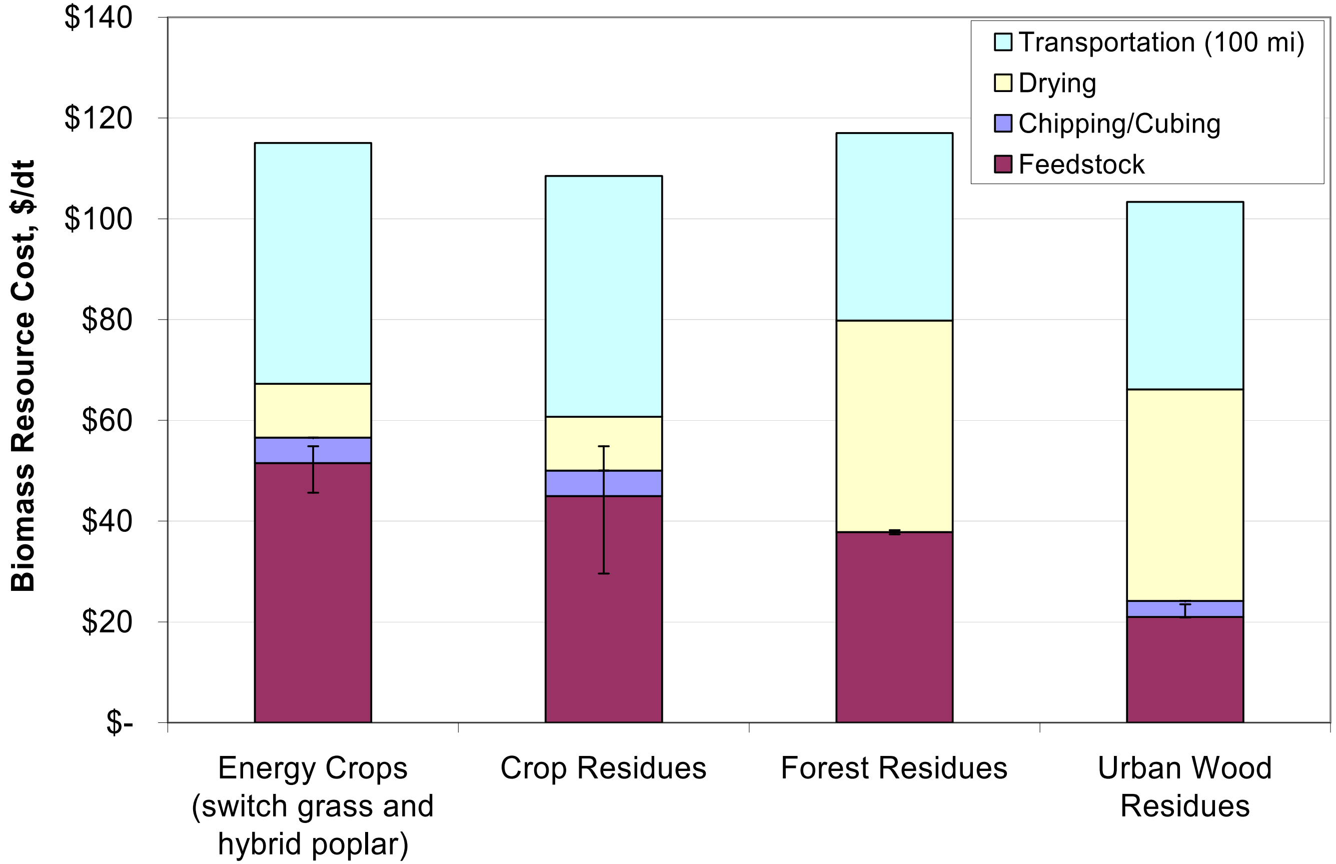


Cost of Electricity from PV and CSP



The cost of biomass is dependent on both the cost of the resource itself and the costs associated with pre-processing and transportation.

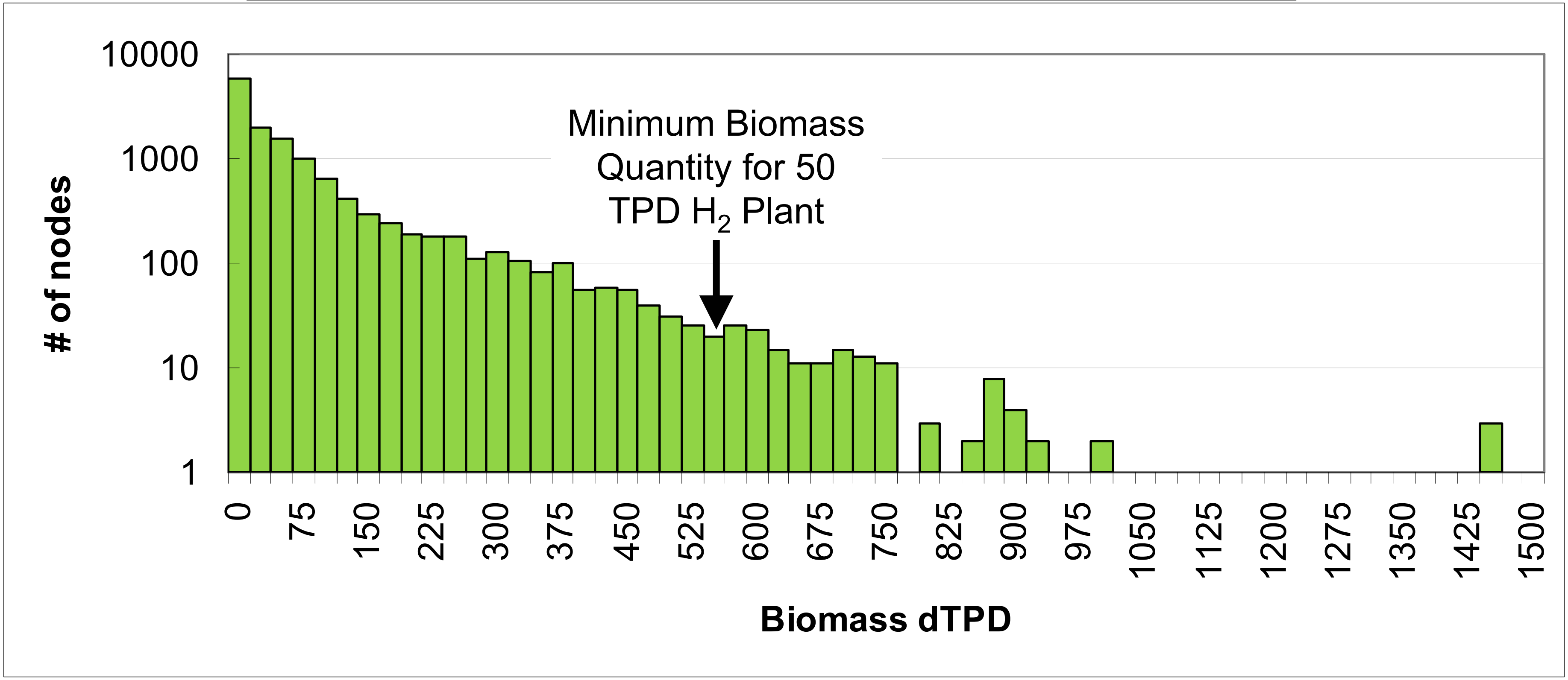
Cost of Biomass[1] – 100 mile transport distance



[1] Resource costs are based ORNL (Walsh 2000) price estimates by state (range given by error bars). Transportation costs are based on NREL (Ringer 2005) estimates and vary by distance in the actual data set used by the model.

Biomass conversion is quite expensive at the small-scale that would result if only a single node's (~230 mi²) worth of biomass were used.

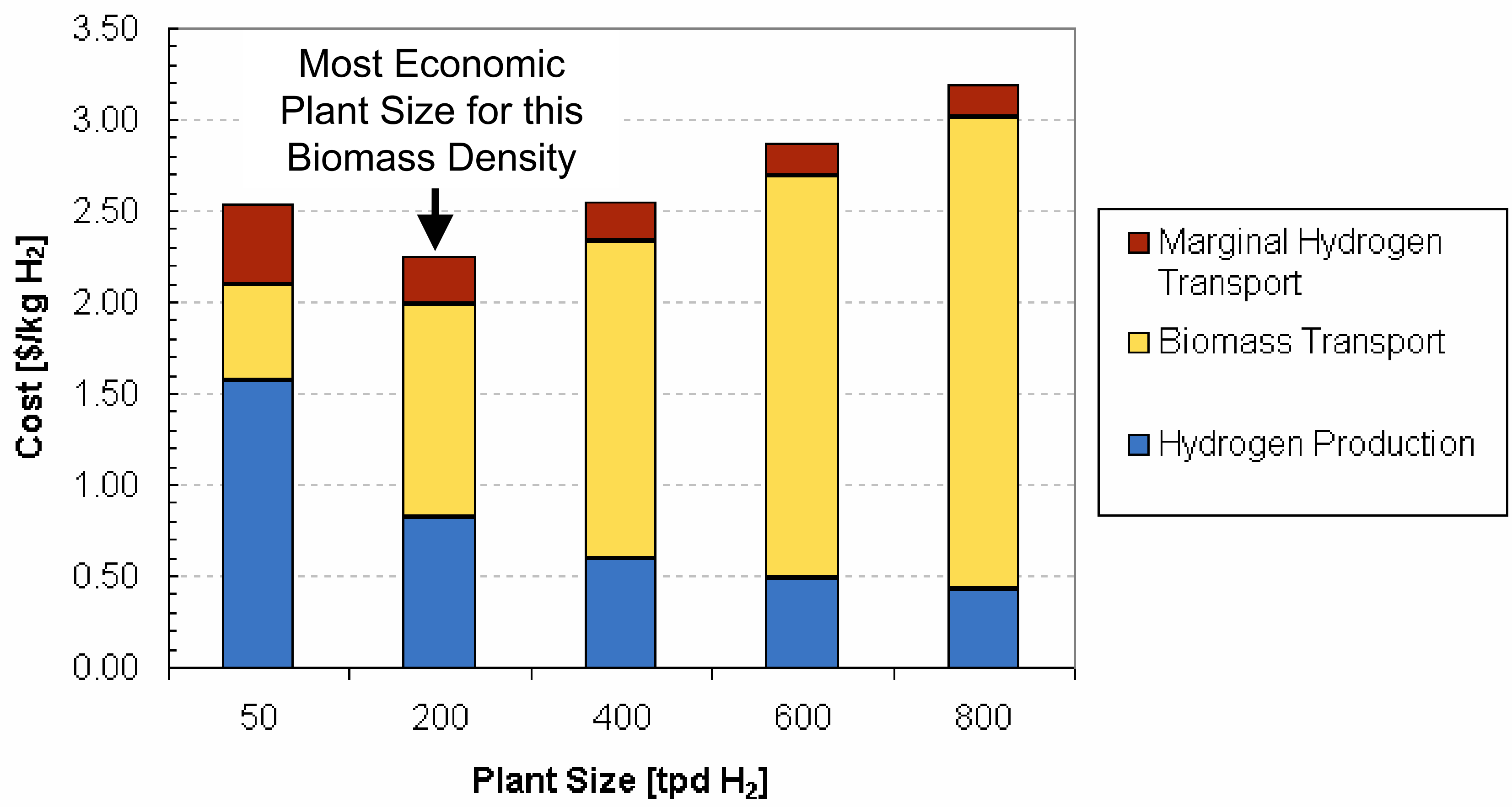
Biomass Distribution in the U.S. (based on nodes)



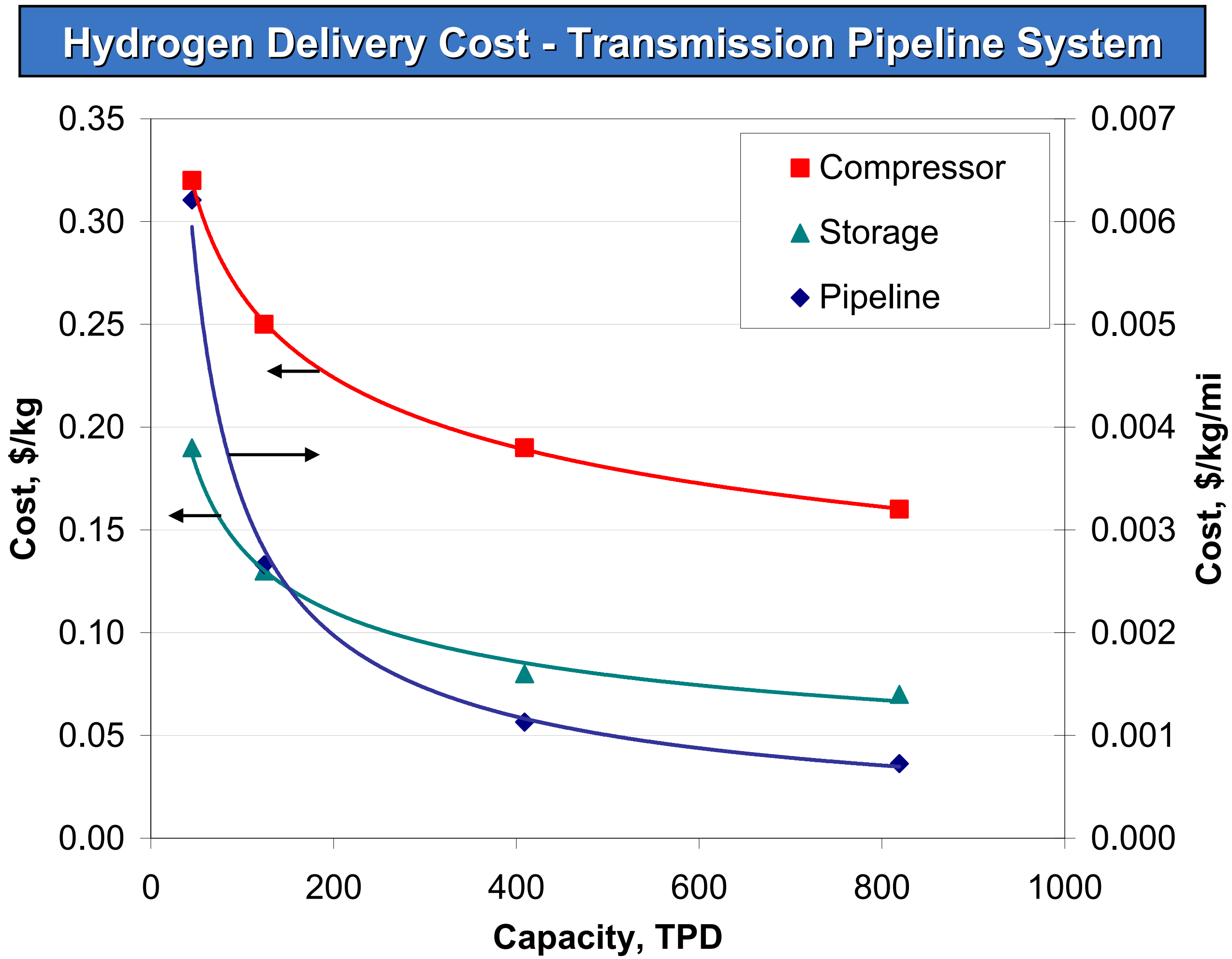
Aggregating the biomass from neighboring or nearby nodes (1 node ≈ 230 mi²) increases the available feedstock.

The economics of biomass aggregation involve a trade-off between improved economies-of-scale and increased transportation costs.

Example of Economics of Biomass Consolidation



Hydrogen delivery cost estimates are based on H2A Delivery model results for a given hydrogen demand.

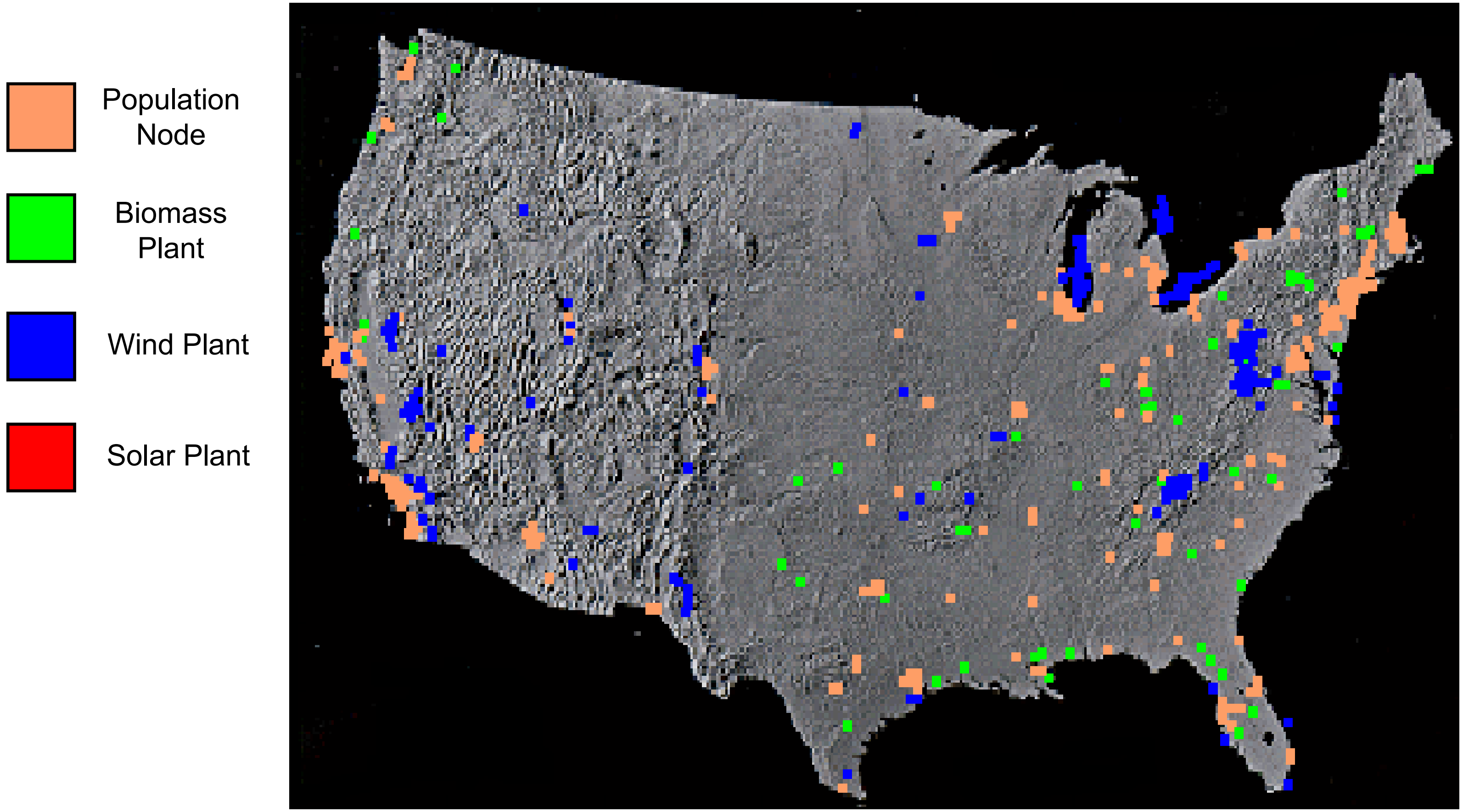


We developed 3 scenarios for H_2 demand from major population centers using DOE projections for H_2 vehicle market penetration.

Assumption	Low Demand	Base Case	High Demand	Comment
Analysis Year	2030	2040	2050	
U.S. Population (Lower 48 only), millions	362	389	438	1% growth per year, U.S. Census Bureau Interim Projection
U.S. Population in Large Cities (Lower 48 only), millions	125	139	158	TIAX Logistics Model based on Census Bureau GIS information
U.S. Population in Medium Cities (Lower 48 only), millions	35	39	49	TIAX Logistics Model based on Census Bureau GIS information
Fraction of U.S. Population in Large and Medium Cities, millions	44%	46%	47%	Cities with >300,000 people
LDV Population in Large and Medium Cities	152	169	197	H2A: large cities = 0.89 LDVs/person; all others = 1.19 LDVs/person
H_2 Vehicles On-Road as Fraction of Total LDVs	40%	80%	98%	Based on DOE H_2 Vehicle Projections (Presidents H_2 Initiative)
Fraction of H_2 Demand met with Renewables	50%	60%	70%	TIAX estimate
Renewable H_2 Demand, TPD	17,600	47,100	78,700	12,000 mi/veh/y; 56.6 mi/kg H_2

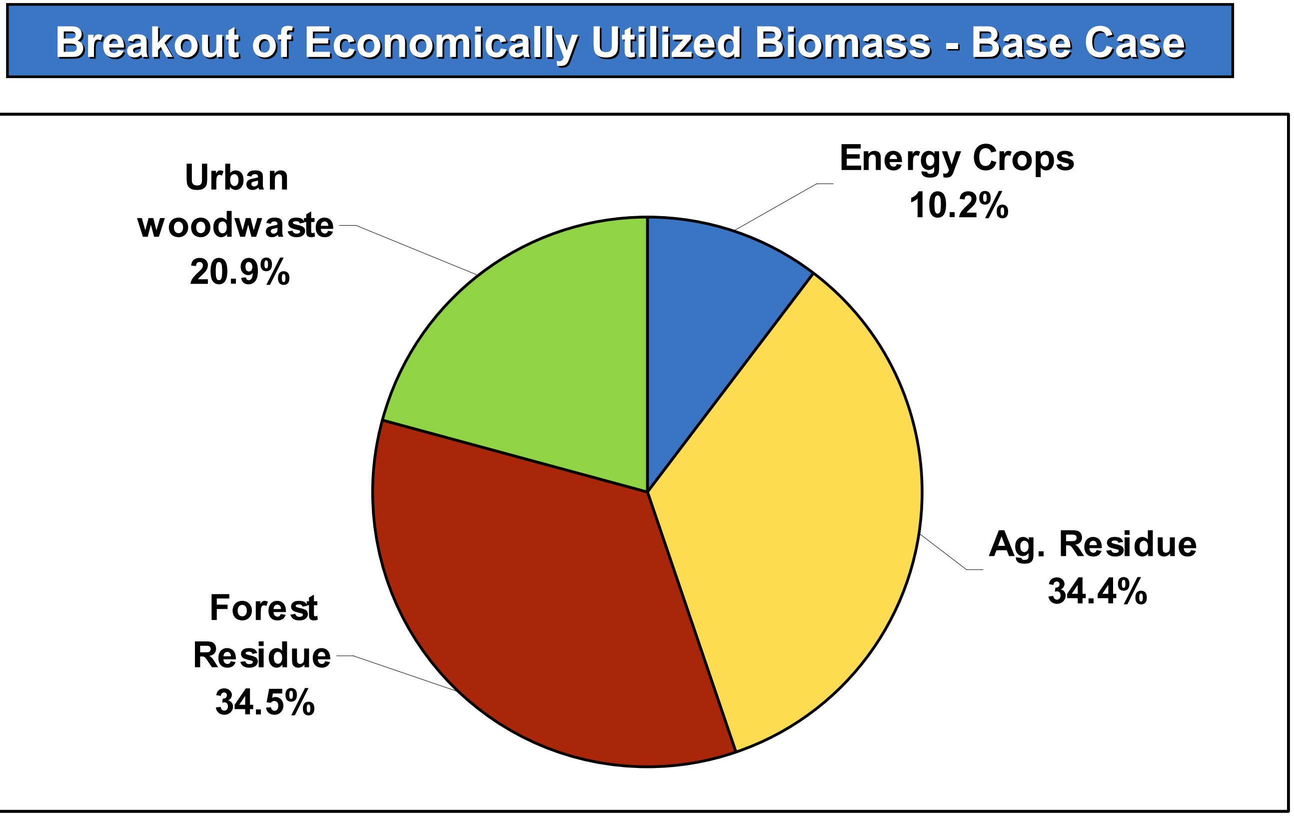
The Logistic Model calculates that biomass and wind resources will be the most economical options in the Base Case.

Location of Economically Utilized Resources - Base Case



Note: Results require details available in the Final Report (to be published soon).

Of the biomass that is used, there is fairly good distribution among the different types of biomass considered.

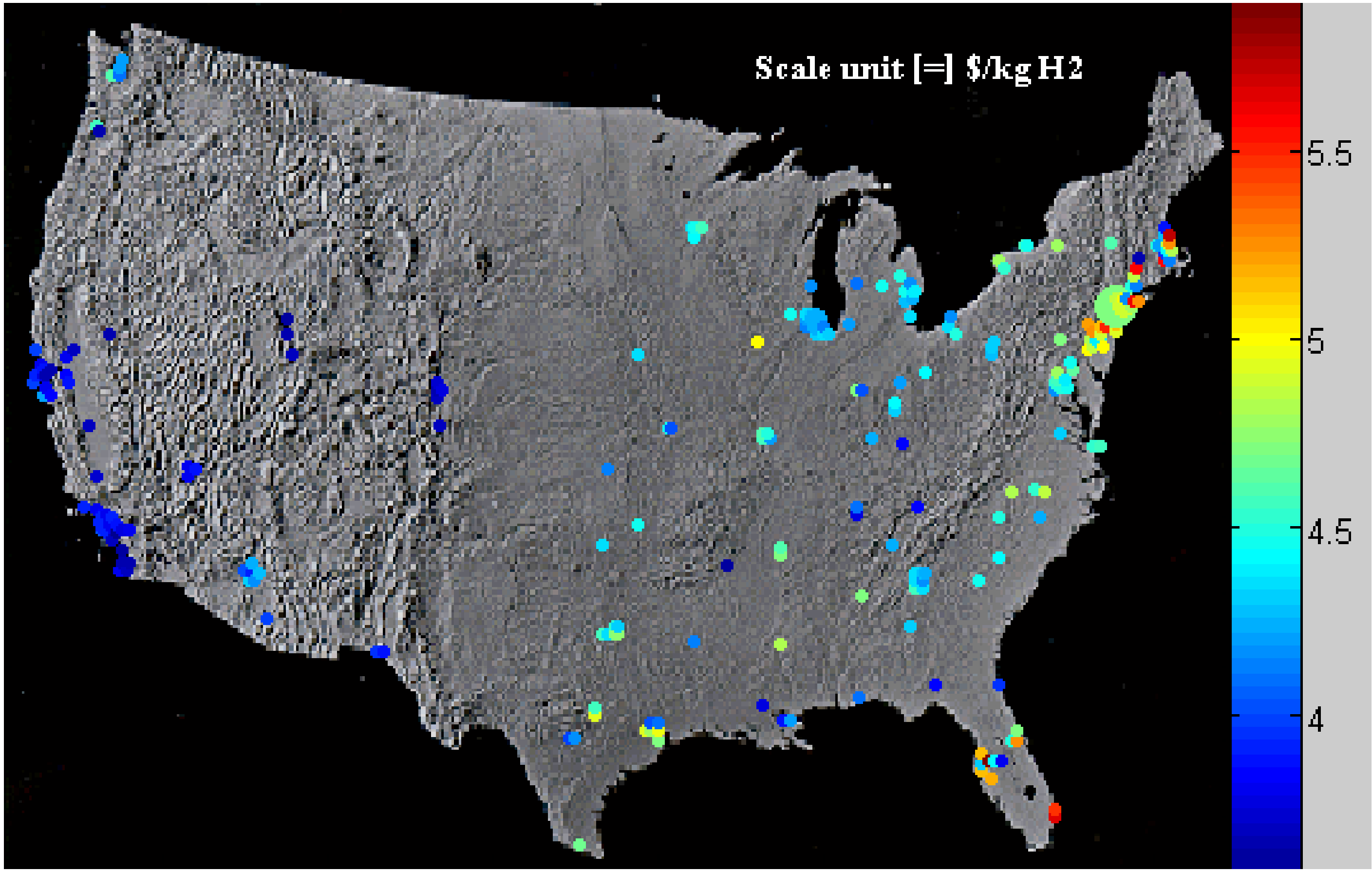


Woody biomass (i.e., forest residue and UWW), while making up less than a quarter of the total available biomass resource, account for over half of the total biomass that can be economically utilized.

Note: Results require details available in the Final Report (to be published soon).

The geographical distribution of hydrogen price shows a distinct trend for increasing from west (~$4.00/kg H_2) to east (>$4.50/kg H_2).

Geographic Price Distribution - Base Case

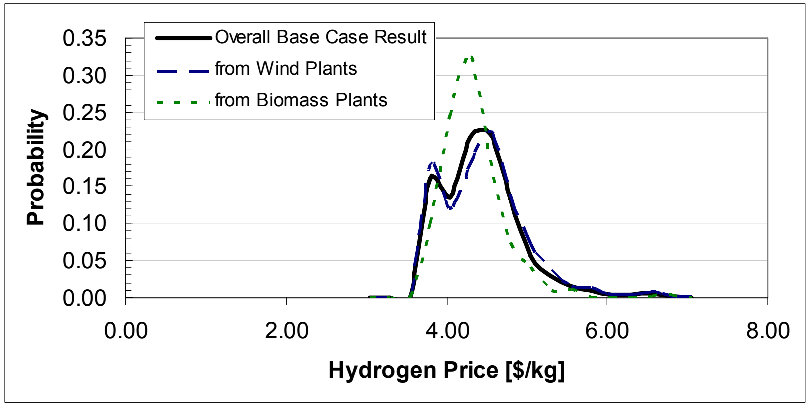


Note: Results require details available in the Final Report (to be published soon).

Employing the Base Case assumptions, the mean price of renewable-based H_2 is predicted by the model to be \$4.35/kg.

Logistics Model Results – Base Case	Wind-Electrolysis	CSP - Electrolysis	PV-Electrolysis	Biomass Gasification
Resource Availability (model input), TW-h/y	31,550	11,228	11,031	1,400
Resource Utilized, TW-h/y	620	0	0	230
H_2 Produced, TPD	38,761	0	0	10,341
Number of H_2 Plants	146	0	0	58
H_2 Throughput per Plant, TPD (ave./range)	222 / 1-798	NA	NA	244 / 28-533
Plant Capacity Factor (ave./range)	0.43 / 0.27-0.48	NA	NA	0.9 (fixed)
H_2 Delivery Distance, mi (ave./range)	198 / 0-694	NA	NA	117 / 0-466
H_2 Selling Price, \$/kg H_2 (ave./range)	4.38 / 3.57-99.48	NA	NA	4.21 / 3.55-15.61
Resource	1.08 / 0.93-1.70	NA	NA	1.14 / 0.76-1.62
Production	1.06 / 0.84-1.57	NA	NA	0.87 / 0.83-1.46
Delivery	1.38 / 0.90 – 96.17	NA	NA	1.34 / 0.91 – 12.93
Forecourt	0.86	NA	NA	0.86

Variation of H_2 Price - Base Case

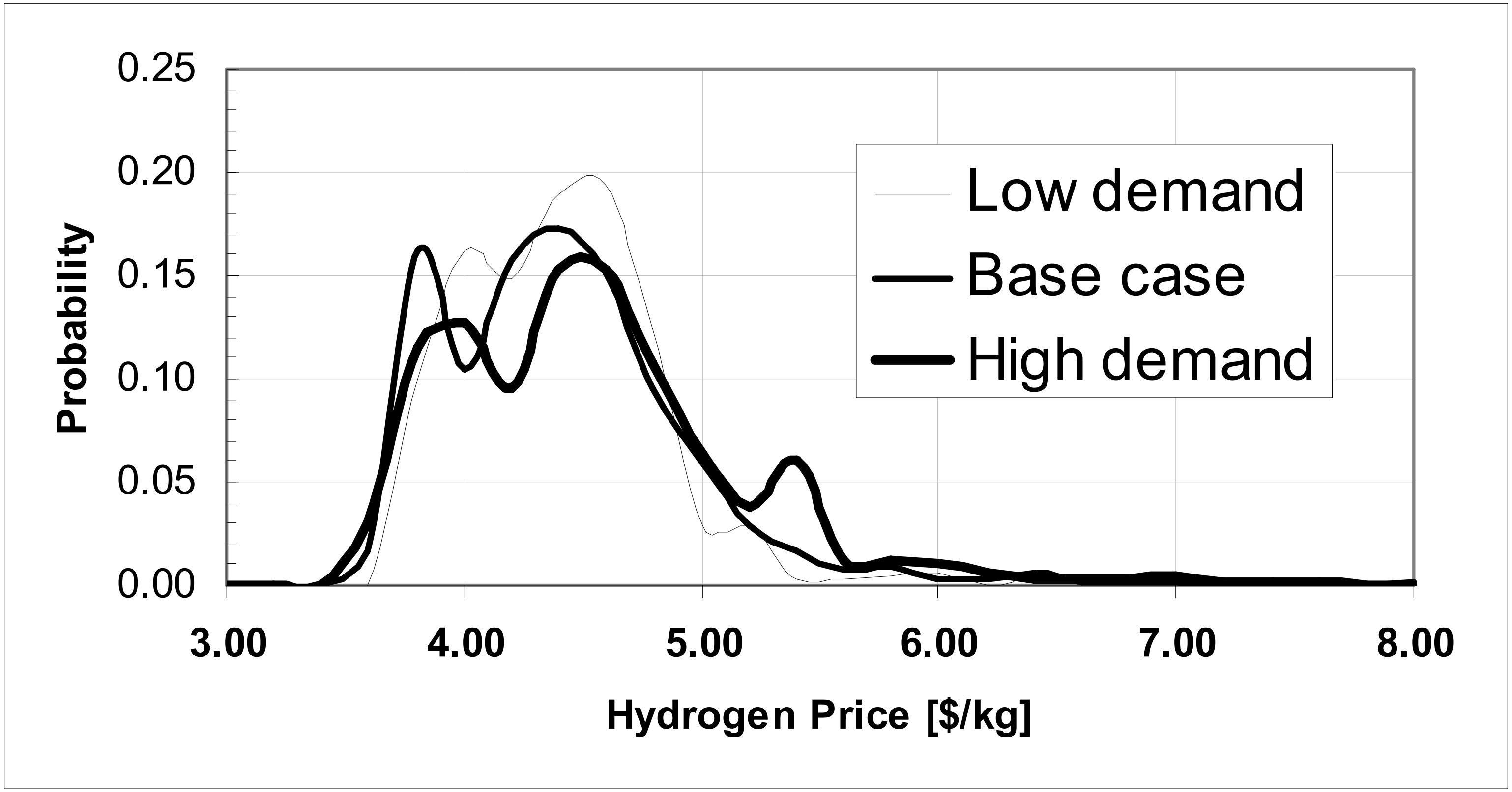


The vast majority of renewable-based H_2 will be more expensive than central natural gas-based H_2, which is projected to be about \$3.50/kg.

Note: Results require details available in the Final Report (to be published soon).

Modeling three different renewable-based hydrogen demand levels shows very little change in the required hydrogen selling price.

Variation of Hydrogen Price - Demand Cases



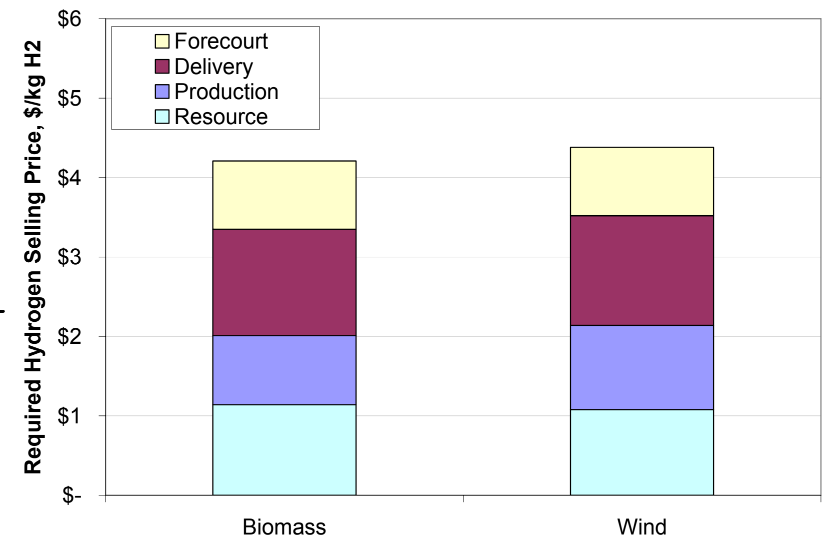
Note: Results require details available in the Final Report (to be published soon).

Costs associated with hydrogen delivery account for approximately a third of the total price for all demand scenarios.

Logistic Model Results – Demand Scenarios

Logistics Model Results	Low Demand	Base Case	High Demand
Year Basis	2030	2040	2050
H_2 Produced, TPD	17,655	49,102	76,994
Number of H_2 Plants	102	222	335
Ave. H_2 Throughput per Plant, TPD	173	221	230
Ave. H_2 Delivery Distance, mi	131	181	284
Ave. H_2 Selling Price, \$/kg H_2	4.33	4.35	4.46
Resource	1.07	1.09	1.09
Production	0.93	1.02	1.04
Delivery	1.47	1.37	1.47
Forecourt	0.86	0.86	0.86

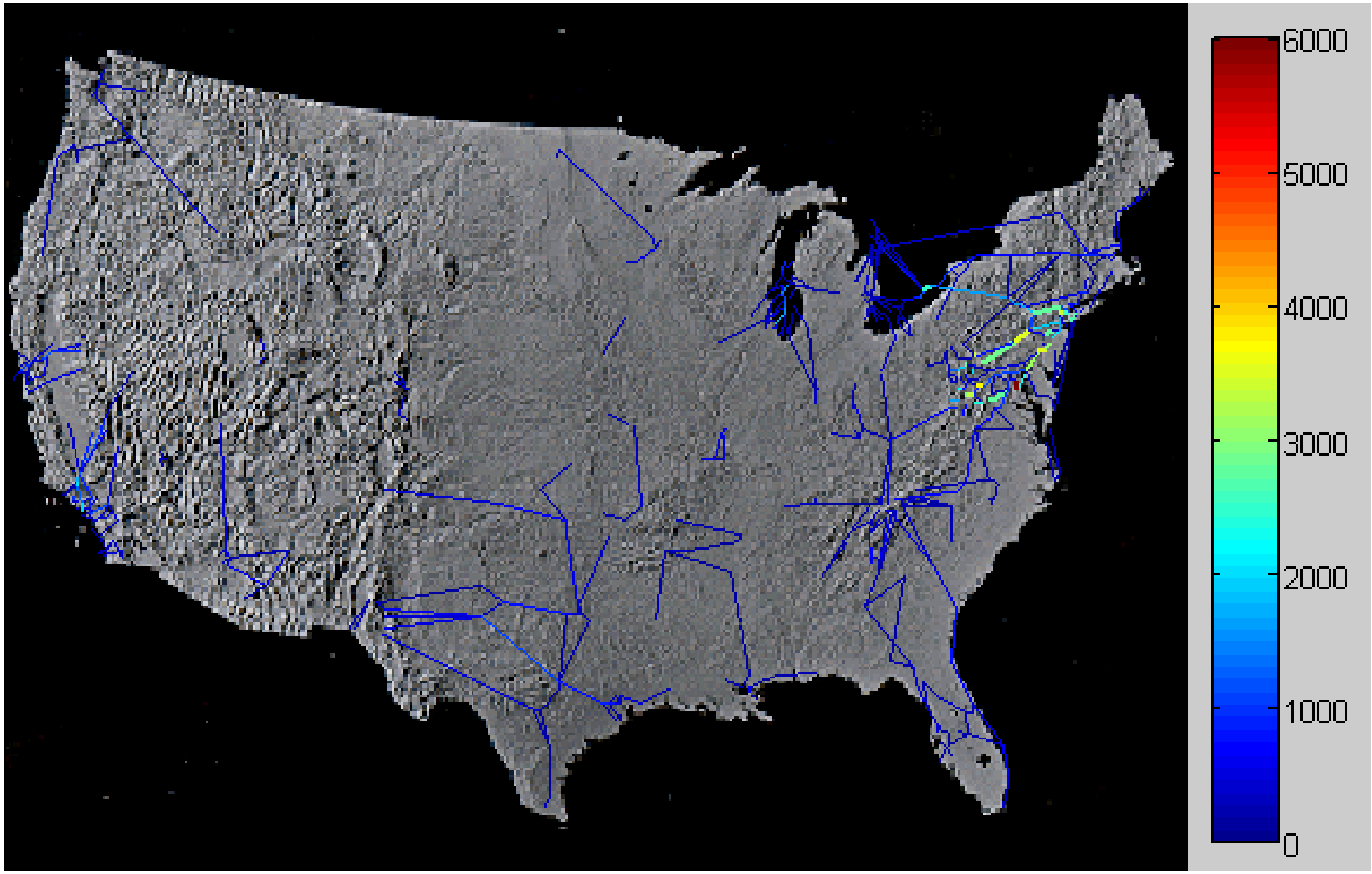
Average H_2 Price - Base Case



Note: Results require details available in the Final Report (to be published soon).

After the initial optimization was conducted assuming direct-route H_2 delivery, we developed a pipeline network consolidation case.

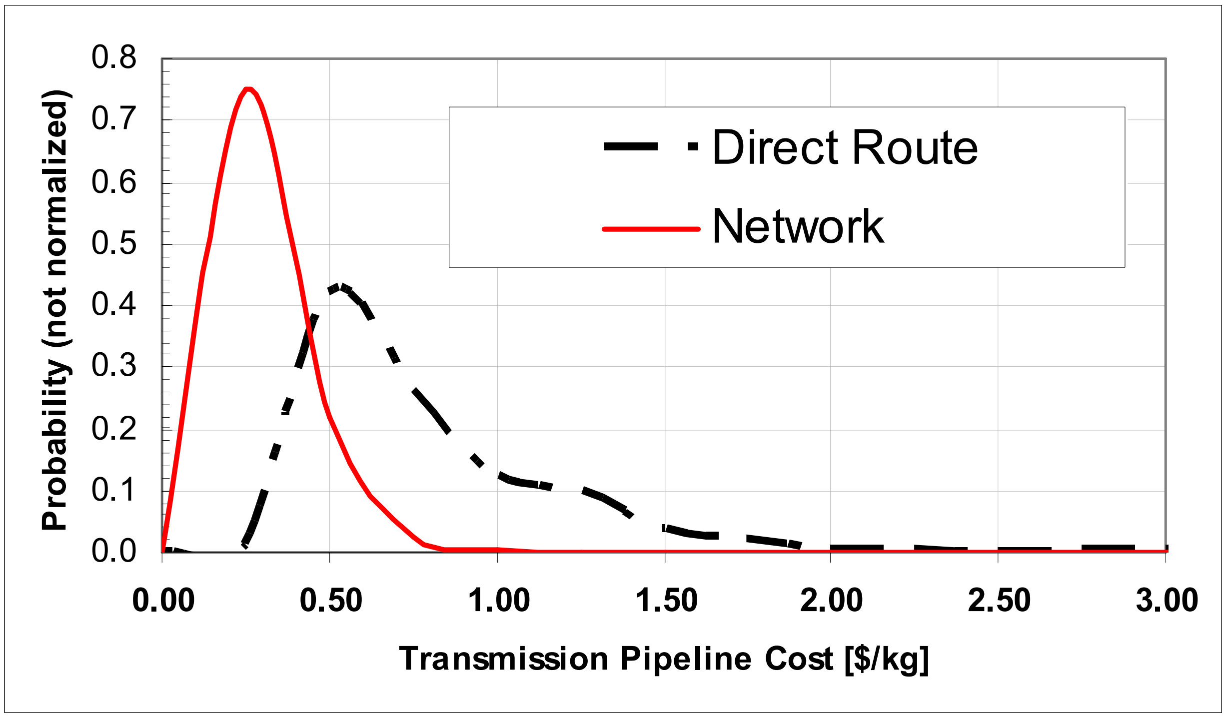
Pipeline Network Consolidation - Base Case



Note: Results require details available in the Final Report (to be published soon).

Consolidation reduced the average delivery cost by $0.49/kg in the Base Case to yield a final average hydrogen selling price of $3.86/kg H_2.

Variation of Delivery Cost for Direct-Route vs. Network



Delivery Parameter	Direct-Route	Network
Miles of pipeline	67,500	27,900
Average pipe throughput, TPD	116	432
Average segment length, miles	181	52
Average transmission cost, $/kg	0.82	0.33

Note: Results require details available in the Final Report (to be published soon).

Answer to primary question: What renewable resources would most likely be developed for hydrogen production in the contiguous U.S.?

- There is good distribution of U.S. wind and biomass resources that can be utilized for hydrogen production
- Biomass Base Case = 10,000 TPD
  - Fairly good distribution throughout the South, East and North West
  - Forest and Agricultural Residues = 70%
- Wind Base Case = 39,000 TPD
  - 4:1 compared to biomass in the Base Case and 6:1 at higher demand levels
  - Good distribution in the Upper Midwest (including Great Lakes), West, Appalachia's and elsewhere
  - But, wind may not be acceptable in all these locations
- There are few solar resources utilized according to the model assumptions and logic, even assuming a low cost of electricity and other favorable inputs
  - Sensitivity analysis for a Favorable Solar Case resulted in 240 TPD from CSP
  - However, hydrogen price from the Favorable Case is only 10% higher than the average biomass and solar prices
  - Solar is likely a more attractive technology option for distributed hydrogen production

Note: Additional conclusions available in the Additional Slides section. Conclusions require details available in the Final Report (to be published soon).

Future Work

We recommend an extension to this study that includes:

- Site-specific resource availability and utilization restrictions
- Other uses for renewable resources (e.g., renewable “grid” power)
- Storing renewable-power in batteries or other energy storage devices
- Water resource availability
- Future carbon tax or renewable-based hydrogen policies
- Distributed H_2 production using local renewable resources (e.g., solar PV)
- Byproducts from renewable-based hydrogen production (e.g., O_2 from electrolysis)
- Non-hydrogen delivery options (e.g., high-power transmission lines, biofuels)
- Right-of-way allowances (including natural or man-made obstacles) for siting pipelines
- Consumer choice projections for hydrogen demand
- State-specific renewable resource and hydrogen demand projections (e.g., detailed biomass availability and costs)
- Other domestic energy options (e.g., nuclear, “clean coal”, byproduct hydrogen)
- Examine integration with coal IGCC/CCS based power plants and other low carbon options that can produce hydrogen as a byproduct
- Re-evaluation of the cost of solar PV technologies
- Re-evaluation of geothermal resources (based on new MIT report)

Additional Slides

We coordinated and reviewed our preliminary results with DOE, NREL, and stakeholders since the last Merit Review.

Audience/ Reviewer	Date	Location
DOE Merit Review	May 06	Washington DC
Task 1 Review Mtg. with DOE and NREL	Dec 06	Washington DC
Renewable Hydrogen Working Group Mtg.	Mar 07	San Antonio TX
NHA Annual Mtg.	Mar 07	San Antonio TX
Several Work-in-Progress Mtgs. with NREL	06-07	Telecon

This study was commissioned to help better understand the most economically viable U.S. renewable resources to produce hydrogen for future vehicles.

- What renewable resources would most likely be developed for hydrogen production for light-duty vehicles (LDVs) in the contiguous U.S.?
- How competitive could renewable-based hydrogen options be compared to fossil fuel-based (i.e., natural gas) hydrogen production?
- What technical/cost improvements are needed for renewable-based hydrogen to be more competitive?
- How would resource and delivery limitations affect renewables utilization, timing and cost?
- How quickly and at what cost (e.g., infrastructure investment, stakeholder cash flow) could a transition to renewable-based hydrogen be accomplished?
- How quickly and by how much could greenhouse gas emissions be reduced?

We did not consider the following impacts in this study:

- Site-specific resource availability and utilization restrictions (however, we did consider global restrictions based on land type)
- Other uses for renewable resources (e.g., renewable "grid" power)
- Storing renewable-power in batteries or other energy storage devices
- Water resource availability
- Future carbon tax or renewable-based hydrogen subsidies
- Distributed H_2 production using local renewable resources (e.g., solar PV)
- Byproducts from renewable-based hydrogen production (e.g., O_2 from electrolysis)
- Non-hydrogen delivery options (e.g., high-power transmission lines, biofuels)
- Right-of-way allowances (including natural or man-made obstacles) for siting pipelines
- Consumer choice projections for hydrogen demand

The nature of this work is predictive and embodies cost/performance assumptions from published studies that we judged to be reasonable.

Several renewable resources have the technical potential to produce quantities of H_2 in excess of projected demand from automobiles (48 MMTPY[1]).

Renewable Potential	Resource[2], TWh/yr	H_2 Supply[3], MMTPY	Source/Comments
Wind	31,600	720	NREL GIS database; performance assumptions from EPRI/DOE, 1997
Solar - CSP	11,200	249	NREL GIS database for normal insolation; performance assumptions from Sargent and Lundy, 2003
Solar - PV	11,000	245	NREL GIS database for global insolation; performance assumptions from EPRI/DOE, 1997
Geothermal	10,900	242	Low-end estimate for enhanced geothermal systems over a 30-year recovery period from MIT, 2006
Biomass	1,400	23	NREL GIS database (http://www.nrel.gov/gis/)
Ocean - Tidal	750	17	Very rough estimate from Black and Veatch, 2004
Ocean - Wave	230	5	Assumes 50% conversion efficiency from 20% of the available resource; Hagerman, 2004; EPRI, 2005
Ocean Thermal Energy Conversion	Not quantified	--	Most of the roughly 90,000 TWh global capacity lies in tropical oceans outside the U.S.; NREL, 2007

[1] Assuming 230 million light duty vehicles traveling 12,000 miles per year and achieving 57 miles per gallon gasoline equivalent on hydrogen (57 miles/kg H_2).
[2] Represents electrical energy for all resources except biomass. Biomass resource potential is based on the lower heating value (LHV) of the feedstock.
[3] Assumes electrolyzer efficiency (LHV) = 74% and biomass gasification efficiency (LHV) = 54.6%.

Based on review and discussions with DOE, we selected wind, CSP, PV and biomass as the most attractive options for detailed analysis.

Renewable Potential	H_2 Supply[1], MMTPY	Selected	Reason
Wind	720	Yes	Commercial technology
Solar – CSP	249	Yes	Demonstrated technology
Solar – PV	245	Yes	Commercial technology but usually at smaller-scale
Geothermal	242	No	Initial screening indicated poor economics
Biomass	23	Yes	Well distributed, low-cost resource
Ocean – Tidal	17	No	Limited resource in contiguous U.S. (most is in Alaska)
Ocean – Wave	5	No	Limited resource in contiguous U.S. (most is in Alaska and Hawaii)
Ocean Thermal Energy Conversion (OTEC)	Not quantified	No	Limited resource in contiguous U.S. (most is in tropical oceans outside the U.S.)

Screening criteria:

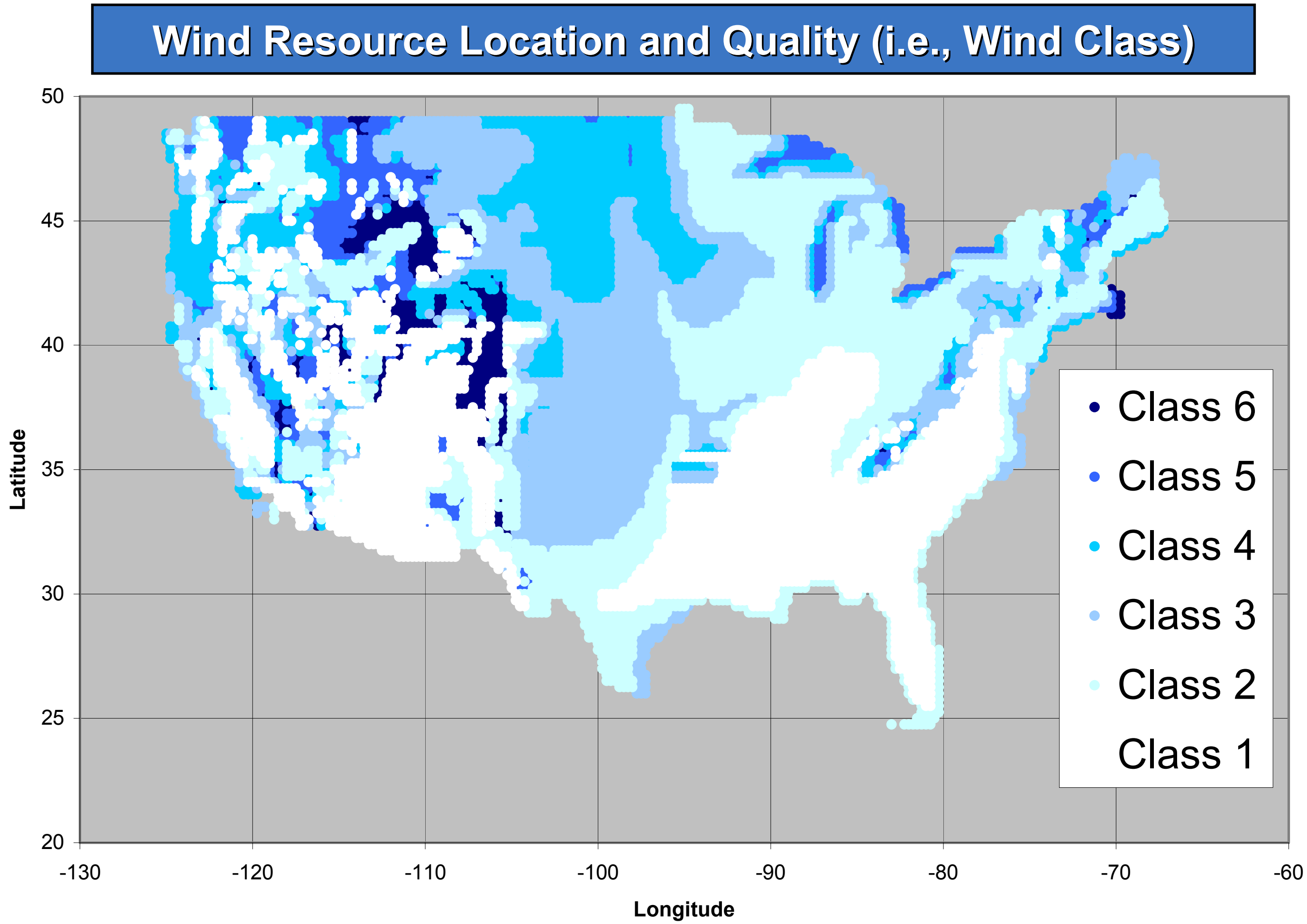
- Quantity of the resource is large enough to potentially meet a significant portion of H_2 demand from light duty vehicles
- Resource could potentially produce H_2 at a cost competitive with other renewable resources within the next 20 years

Each renewable option has different resource and production costs associated with it. Delivery costs include a variable cost based on distance from point of use and fixed costs.

Renewable-H_2 Production	Associated Costs
Wind Power-to-Hydrogen	• *Resource*: Renewable Power, $/kWh = Converting wind energy to electrical energy (Wind Turbine) depends on wind average speed • *Production*: $/kg H_2 = Converting electrical energy to hydrogen (Electrolyzer) depends on plant size and capacity factor
Solar Power-to-Hydrogen	• *Resource*: Renewable Power, $/kWh = Converting solar energy to electrical energy (CSP or PV) depends on insolation • *Production*: $/kg H_2 = Converting electrical energy to hydrogen (Electrolyzer) depends on plant size and capacity factor
Biomass-to-Hydrogen	• *Resource*: Biomass, $/dt = "Feedstock" (Production, Collection) + Prep (Chipping/Cubing, Drying) + Transportation (bringing resource to a central plant) depends on biomass type, location and distance • *Production*: $/kg H_2 = Converting biomass energy to hydrogen (Gasification) depends on plant size

Hydrogen Distribution	Associated Costs
Hydrogen Pipeline Delivery	• *Transmission*: $/kg H_2 = Variable cost depends delivery distance (Pipeline) plus fixed costs (Storage, Compression) • *Intra-city*: $/kg H_2 = Fixed cost (Trunk and Distribution Pipelines)
Hydrogen Station	• *Forecourt*: $/kg H_2 = Fixed cost

Resource location impacts the calculated hydrogen delivery cost, which has a significant impact on the cost of supplying renewable-H_2 to the U.S. population.



Wind and solar resources are assumed to be used to generate electricity to power water electrolysis-based hydrogen plants.

Representative Power Conversion Assumptions	Resource Conversion Efficiency, %	Capacity Factor[1]	Cost of Electricity[2], $/kW-h	Source/Comments
Central Wind Turbine	81.3	0.479	0.030	Based on Class 6 wind; EPRI/DOE, 1997
Central CSP Tower	17.3 (constant)	0.729	0.064	Based on Cramer Junction, CA (very favorable location); assumes 2-axis tracking concentrating systems; CF includes thermal storage; Sargent and Lundy, 2003
Central PV Array	12.8 (constant)	0.295 (constant)	0.076	Based on a favorable location with high insolation; assumes single-axis tracking, thin-film, flat-plate collectors tilted at latitude; EPRI/DOE, 1997; TIAX estimates

[1] Total electricity generated divided by potential electricity generated if the system operated at full capacity for every hour of the year. Includes daily and seasonal variations.

[2] Based on literature sources but converted to 2005$s.

H2A Production model values for wind electrolysis and biomass gasification are used for cost and efficiency information[1].

Renewable-Hydrogen Production Assumptions, Based on 2025 Technologies

Hydrogen Conversion Technology	Conversion Efficiency, % (LHV)	Min. Plant Size, TPD	Scaling Factor Power	Representative Capacity Factor[2]
Central Water Electrolysis	74.0	50	1.0	Wind = 0.479 CSP = 0.729 PV = 0.295
Biomass Gasification	54.9	50	0.85	0.900 (constant)

[1] H2A models: "Longer-Term (2020-2030) Hydrogen from Wind" and "Longer-Term (2020-2030) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming". Updated June 7, 2006.

[2] Total electricity generated divided by potential electricity generated if the system operated at full capacity for every hour of the year. Includes daily and seasonal variations.

We performed a sensitivity analysis to understand how critical variables impact the resource utilization assessment.

Wind Sensitivity Variable	Base Case	Unfavorable Case	Favorable Case	Comment/Source
Cost of Electricity, $/kW-h	0.030	0.038	0.030	Assumes Class 6 wind. Base and unfavorable cases from EPRI/DOE, 1997. Favorable case from DOE Wind Program 2012 Goal.
Electrolyzer Capital, $/kW	360	500	250	H2A Sensitivity Analysis: Longer-Term (2020-2030) Hydrogen Generation from Wind. Updated June 7, 2006.
Electrolyzer Efficiency, % (LHV)	74	64	79	H2A Sensitivity Analysis: Longer-Term (2020-2030) Hydrogen Generation from Wind. Updated June 7, 2006.
Capacity Factor	0.479	0.410	0.491	Assumes Class 6 wind. Base and favorable cases from EPRI/DOE, 1997. Unfavorable case from EIA, 2006.

Solar Sensitivity Variable	Base Case	Unfavorable Case	Favorable Case	Comment/Source
Cost of Electricity (CSP), $/kW-h	0.064	0.080	0.041	Sargent & Lundy, 2003
Cost of Electricity (PV), $/kW-h	0.076	0.100	0.050	Base and unfavorable case from EPRI/DOE, 1997. Favorable case from DOE Solar Program 2015 Goal.
Electrolyzer Capital, $/kW	360	500	250	H2A Sensitivity Analysis: Longer-Term (2020-2030) Hydrogen Generation from Wind. Updated June 7, 2006.
Electrolyzer Efficiency, % (LHV)	74	64	79	H2A Sensitivity Analysis: Longer-Term (2020-2030) Hydrogen Generation from Wind. Updated June 7, 2006.
Capacity Factor (CSP)	0.729	0.600	0.760	Base and favorable cases from Sargent & Lundy, 2003. Unfavorable case from DOE Solar Thermo-chemical Hydrogen (STCH) Program analyses.
Capacity Factor (PV)	0.295	0.210	0.295	Base and favorable cases assuming single-axis tracking case from EPRI/DOE, 1997 and TIAX estimates. Unfavorable case from EIA, 2006.

Even assuming a low cost of electricity and other favorable inputs for the solar cases, sensitivity results continue to show a strong bias toward wind- and biomass-based hydrogen production.

Logistics Model Results – Sensitivity Analysis	Number of Plants / H_2 Produced (TPD)			
	Wind	Biomass	CSP	PV
Base case	146 / 38,761	58 / 10,341	-	-
Favorable Wind	154 / 39,710	52 / 9,393	-	-
Favorable Biomass	146 / 33,781	87 / 15,321	-	-
Favorable Solar	146 / 38,520	58 / 10,341	2 / 241	-
Favorable Delivery	147 / 39,354	54 / 9,748	-	-

Logistics Model Results – Sensitivity Analysis	$/kg Hydrogen, sales weighted average			
	Wind	Biomass	CSP	PV
Base case	4.38	4.21	-	-
Favorable Wind	4.24	4.20	-	-
Favorable Biomass	4.37	3.64	-	-
Favorable Solar	4.38	4.21	4.79	-
Favorable Delivery	3.35	3.24	-	-

How competitive could renewable-based hydrogen options be compared to fossil fuel-based (i.e., natural gas) hydrogen production?

- Most renewable-hydrogen is \$3.50-5.50/kg (w/out pipeline consolidation)
- Average of 10-25% higher in the Base Case (\$3.85 - \$4.35/kg H_2 w/ and w/out pipeline consolidation) compared to central natural gas production (\$3.50/kg H_2)
- Costs associated with hydrogen delivery account for roughly a third of the total
- The modeling of three different renewable-based hydrogen demand levels shows very little change in the required hydrogen selling price

What technical/cost improvements are needed for renewable-based hydrogen to be more competitive?

- Pipeline networking reduces average price by 11%
  - Pipeline consolidation reduces pipeline mileage from 67,500 miles in the direct-route case to 27,900 miles in the networked case
- Favorable biomass and delivery assumptions reduces average price by 13% and 23%, respectively
- Central solar needs significant improvements (e.g., <\$0.04/kWh, higher capacity factors) to be competitive with wind and biomass

Note: Conclusions require details available in the Final Report (to be published soon).