Economic Comparison of Renewable Sources for Vehicular Hydrogen in 2040

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Project Scope

- The Challenge: *How to deliver 10 quads of H_2 from renewable sources in 2030-2050 for the U.S. transportation sector, considering*
  - Resource availability
  - Demand
  - Cost
  - Distribution pathways

10 quads H_2 ~ light-duty U.S. fleet in 2030 if converted to fuel cell vehicles

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Relevance to DOE R&D Plan

- Provides insight about a hypothetical hydrogen infrastructure for vehicles, with the hydrogen supplied from predominantly domestic resources

- Identifies cost (i.e., technical) barriers that must be overcome to achieve high utilization of renewable resources for hydrogen production

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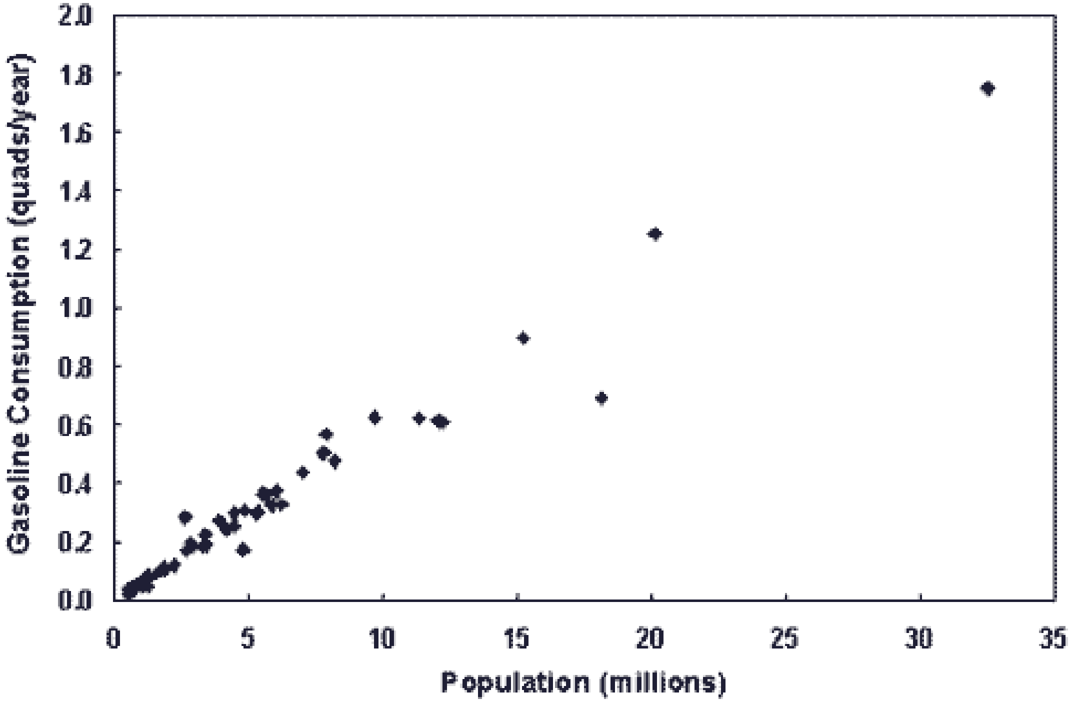
Calculation of H_2 Demand Distribution

- Calculated per capita gasoline energy use from data in chart
- Estimated population in each state for 2040 (based on Census Bureau projections)
- Estimated fraction of national fuel consumption for each state in 2040
- Allocated the 10 quads of H_2 proportional to the 2040 fractional fuel consumption

State Gasoline Consumption by Population (1999-2000)



Source: EIA (gasoline usage), Census Bureau (population)

Renewable Resources Available for H_2

- Biomass availability from ORNL state-by-state analyses and EPA MSW/landfill data. (Includes dedicated energy crops, agricultural residues, wood wastes, MSW, landfill gas, and livestock manure)
- State wind totals from EPRI/DOE, state class breakdown from NREL wind map (Classes 4, 5, and 6 only)
- Solar state-by-state from 10% of BLM land with >6 kWh/m^2-day (annual average insolation)
- Geothermal from Geothermal Energy Association report
- *Nuclear was explicitly excluded*

	H_2 Potential in 2040 Quads/year
Biomass	**2.7**
Wind	**22.9**
PV Solar	**5.9**
Geothermal	**0.4**
Total	**31.9**

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Biomass Cost Assumptions
115 m.t. H_2/day

Hydrogen yield	70 kg/m.t. biomass*
Plant Capital Cost	$117.3 million
Capacity factor	85%
On-stream factor	95%
Plant lifetime/payback period	25 years
Cost of capital	10.8%
Biomass cost	$44/m.t.
Annual operating and maintenance	3% of initial capital
Insurance and taxes	1% of initial capital
Operator labor (12 @ 12 hrs/shift)	$40/hour (loaded)
Corporate overhead	15% of revenues

*58 kg/m.t. for MSW

Feedstock Cost	
Energy crops	$44/m.t.
Wood & Ag Waste	$40/m.t.
Livestock Manure	$22/m.t.
MSW	$22/m.t.
Landfill gas	$1.64/Kscf

Cost of H_2 at Plant ($/kg)	
Energy crops	**1.75**
Wood & Ag Waste	**1.68**
Livestock Manure	**1.32**
MSW	**1.45**
Landfill gas	**1.98***

*** Delivered**

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Wind Turbine Cost Assumptions
50 MW peak, Classes 4, 5, and 6

Plant Capital Cost (\$648/kW$_{peak}$)	\$32.4 million
On-stream factor	98%
Plant lifetime/payback period	25 years
Land lease rate	2.5% of revenue
Cost of capital	10.8%
Annual fixed O&M	2% of initial capital
Annual variable O&M	\$0.005/kWh
Operator labor (3 @ 12 hrs/shift)	\$40/hour (loaded)
Corporate overhead	15% of revenue

Capacity Factor	
Class 4	38.3%
Class 5	41.4%
Class 6	48.7%

	COE (¢/kWh)
Class 4	**4.7**
Class 5	**4.4**
Class 6	**3.8**

Forecourt Electrolysis Cost Assumptions

Plant Capital Cost ($300/kW$_e$)	$510,000
Capacity factor	69%
Plant lifetime/payback period	10 years
Cost of capital	10.8%
Annual fixed O&M	2.5% of initial capital
Water Cost	$2/1000 gal
Operator labor (1 @ 12 hrs/shift)	$20/hour (loaded)
Corporate overhead	15% of revenue

Electrolysis Cost $1.30/kg H_2

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Transmission and Distribution Cost Assumptions

- Hydrogen Pipeline
  - Interstate: 40% higher (energy basis) than recent natural gas pipeline construction $\Rightarrow$ \$0.024/kg H_2-100 miles
  - Local: 40% higher (energy basis) than markup on commercial natural gas from city gate price
- Electricity $\Rightarrow$ \$0.00178/kWh-100 miles
- Compression, forecourt storage, dispensing
  - 920 kg H_2/day capacity
  - 7,000 psi storage, dispense to 5,000 psi
  - \$470,000

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H_2 Pathways and Cost Factors

- All pathways deliver 5,000 psi gas to the vehicle (7,000 psi storage for fast fill)
- Cost factors were calculated from capital and operating costs using discounted cash flow method (8-11% cost of capital, 10-25 year payback)

∗ *Only the lowest cost pathway for each resource was selected*

  – Uneconomical pathways: liquid H_2 transport, pyrolysis oil, centralized electrolysis

- Cost of H_2 calculated from component factors

Electrolysis

$$C_{H2} = \frac{1}{\eta_e (1 - l_T)} (C_G + C_T D) + C_E + C_{CSD}$$

Gasification

$$C_{H2} = C_G + C_{P-L} + C_{P-D} D + C_{CSD}$$

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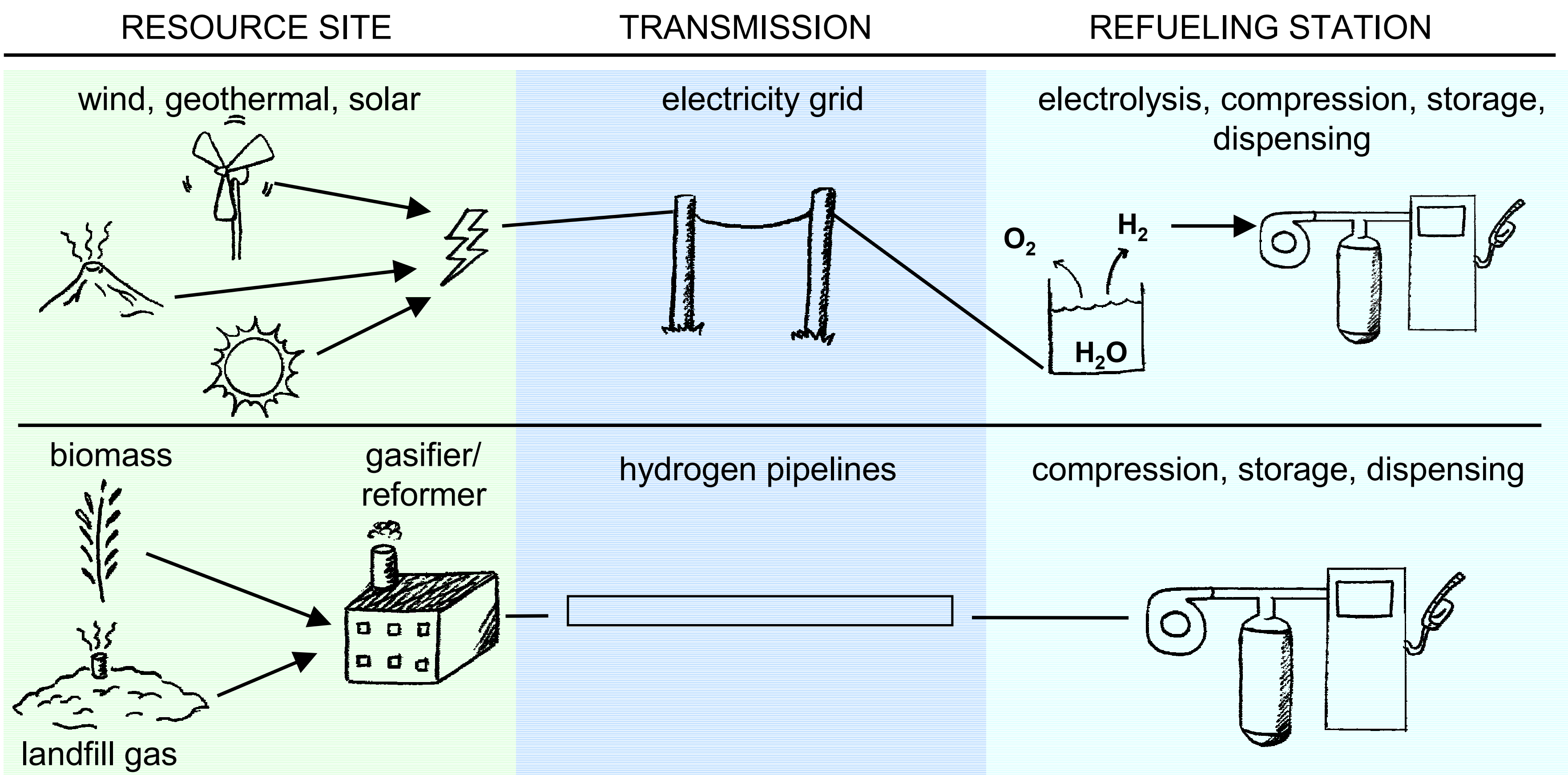
Two Categories of Hydrogen Pathways



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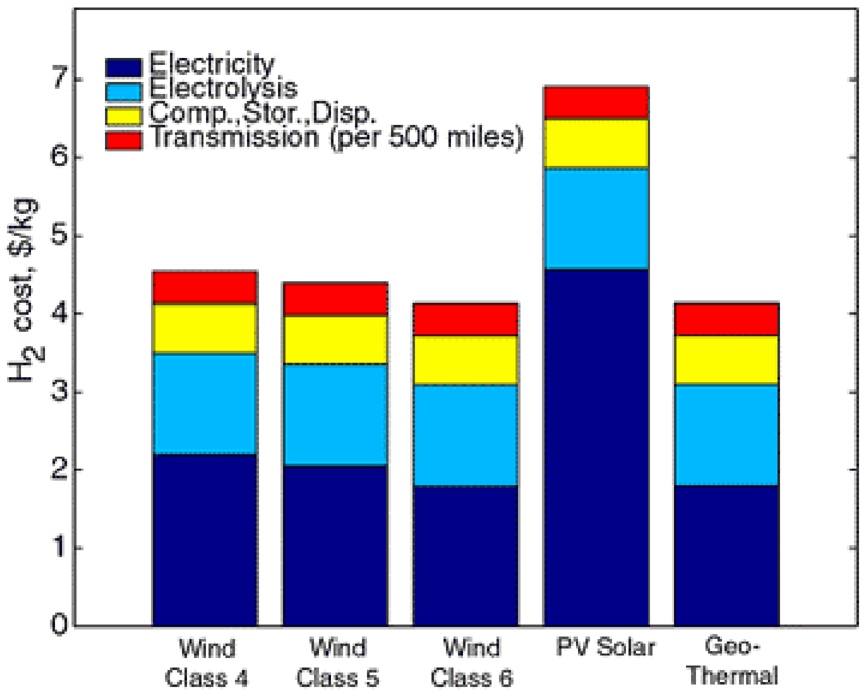
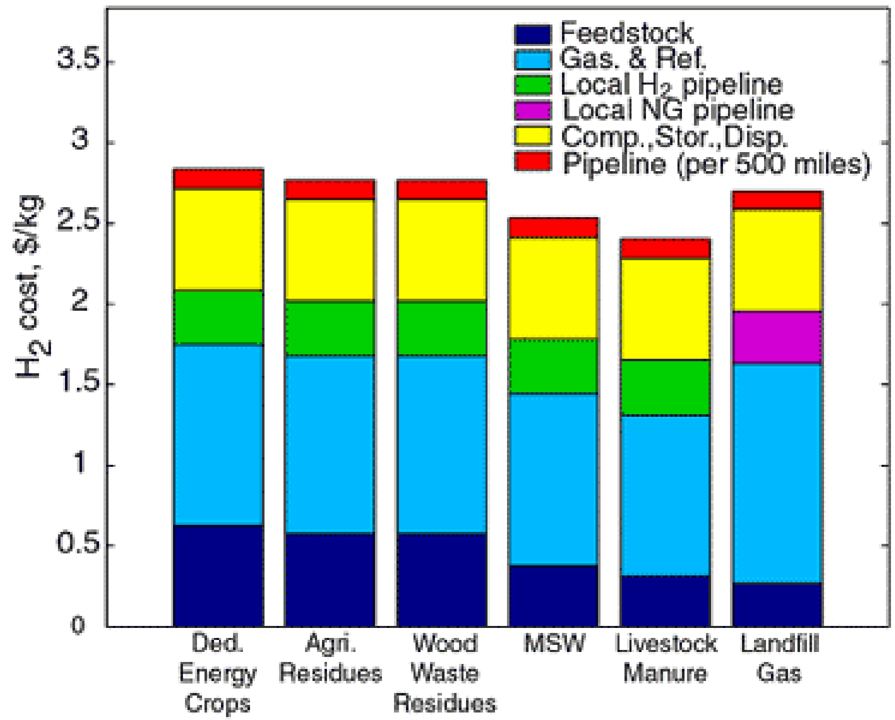
Cost of Hydrogen
(excluding sales taxes and dispensing markup)

Electrolysis Methods



Gasification/Reformation Methods



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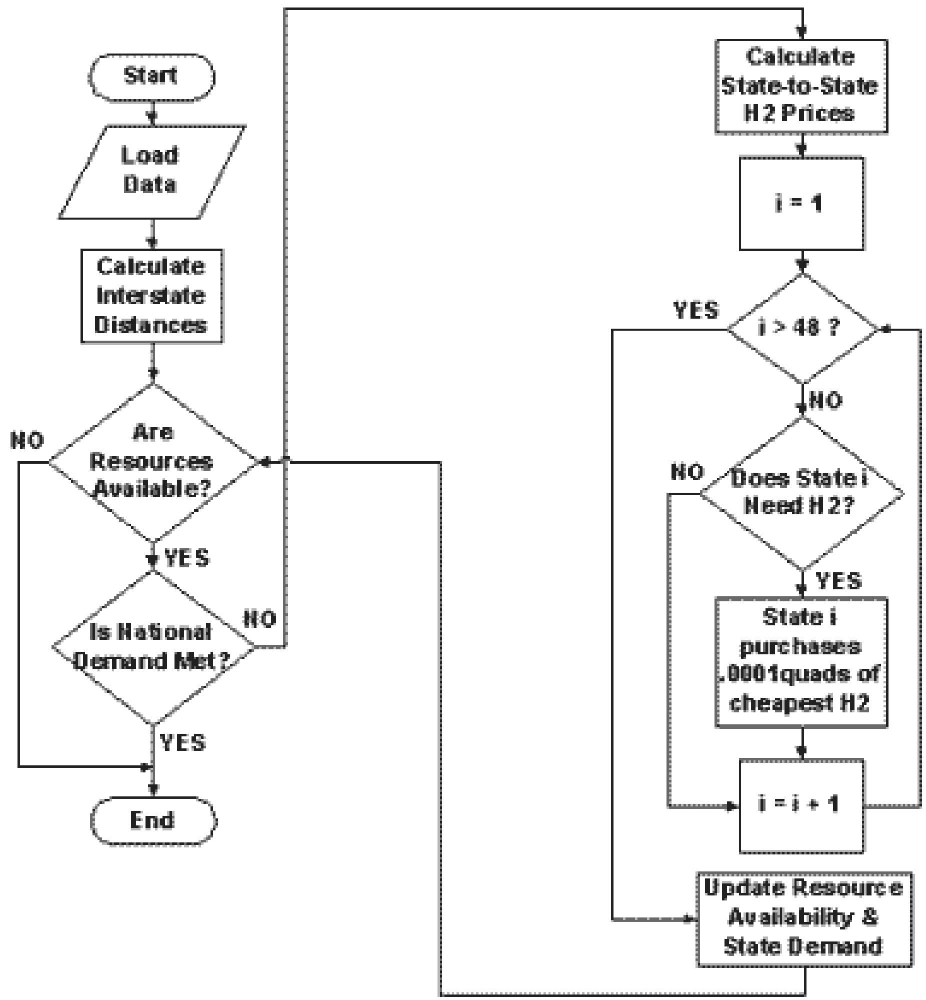
H_2 Distribution Simulation

- Calculate cost of H_2 from each state to each state for each resource (48 contiguous states)
- States purchase H_2 in 0.0001 quad increments over multiple rounds until needs are met
- Lowest cost resources are used first
- Result ~ lowest cost for U.S.



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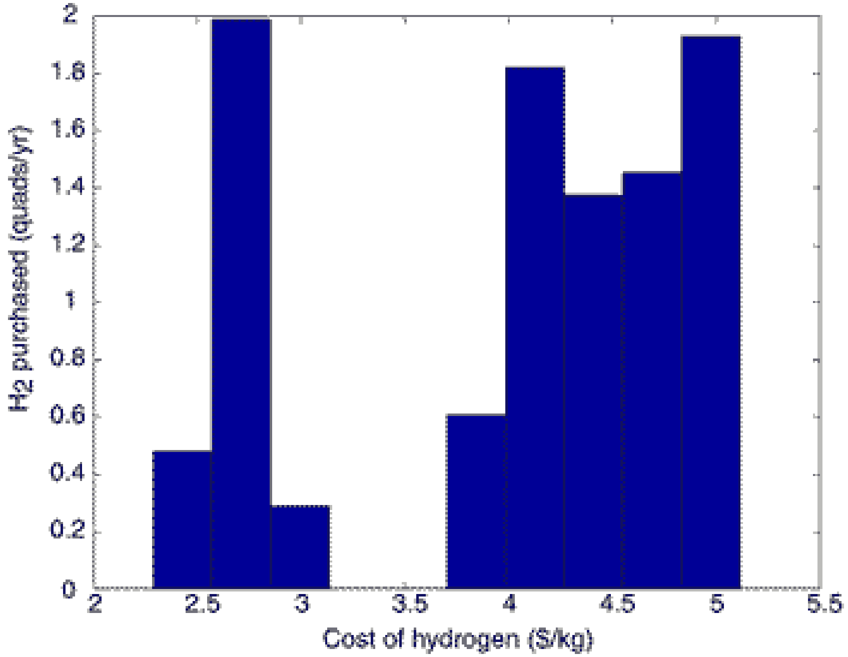
Resource Usage and Model Cost of H_2

	Potential (quads/year)	***Predicted Usage (quads/year)***
Wind Class 4	18.1	5.3 [29%]
Wind Class 5	3.1	0.48 [15%]
Wind Class 6	1.7	0.98 [58%]
Geothermal	0.43	0.43 [100%]
Biomass	2.7	2.7 [100%]
PV Solar	5.9	0 [0%]

NOTE: In general, cheapest feedstocks are used first (Biomass over Wind over Solar). Classes 5 and 6 wind are not fully utilized because of high transmission costs from remote locations.

National H_2 cost distribution



Average Cost of Hydrogen (delivered): $3.98/kg

[$33.24/GJ, $35.04/$10^6$ Btu]

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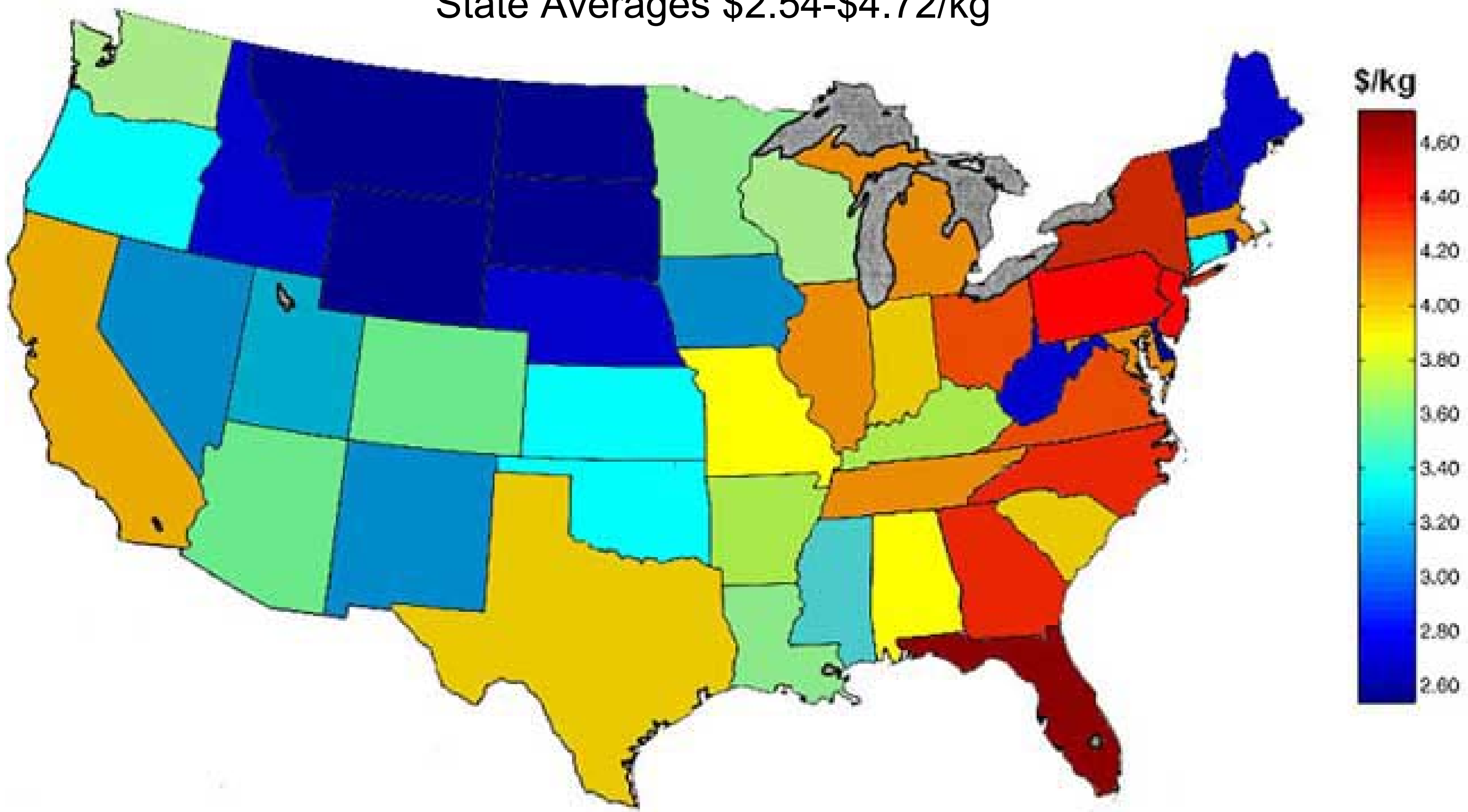
Delivered H_2 Cost by State

Color represents average statewide cost of H_2 without dispensing markup or sales taxes.
State Averages $2.54-$4.72/kg



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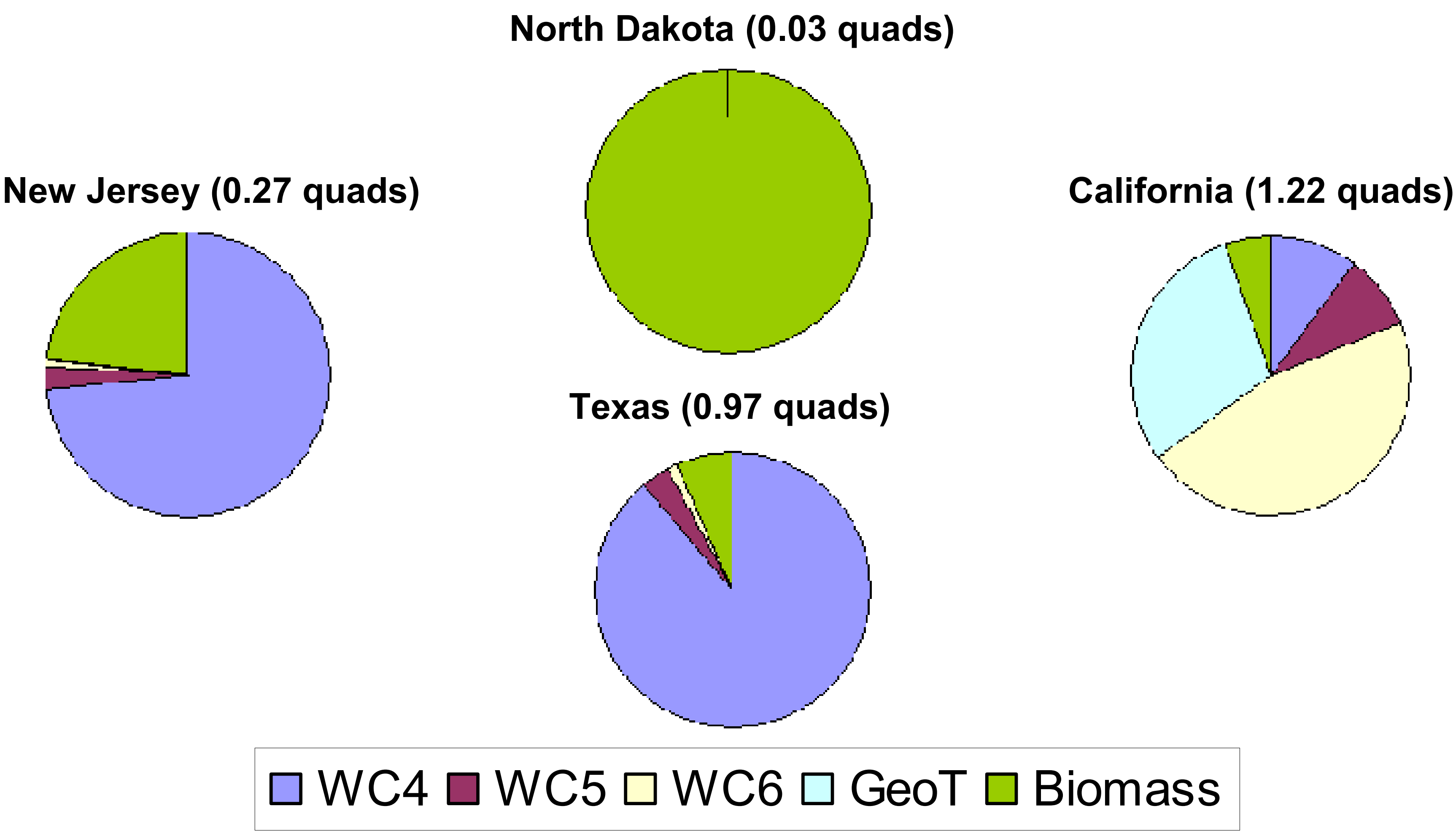
Example States: Resources Used



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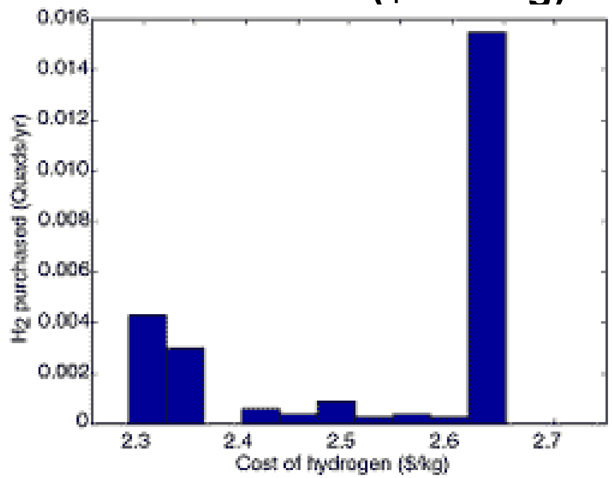
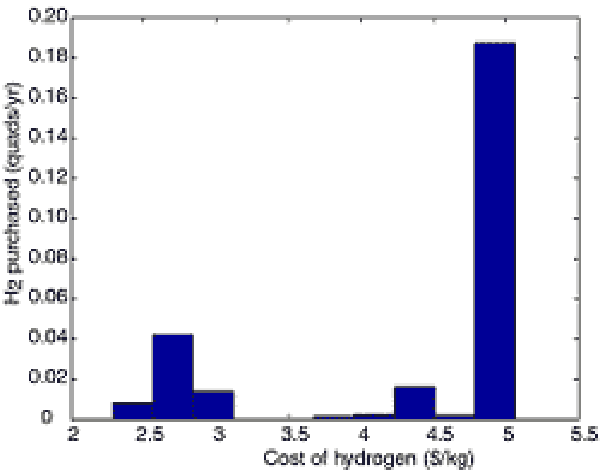
Example States: H_2 Cost

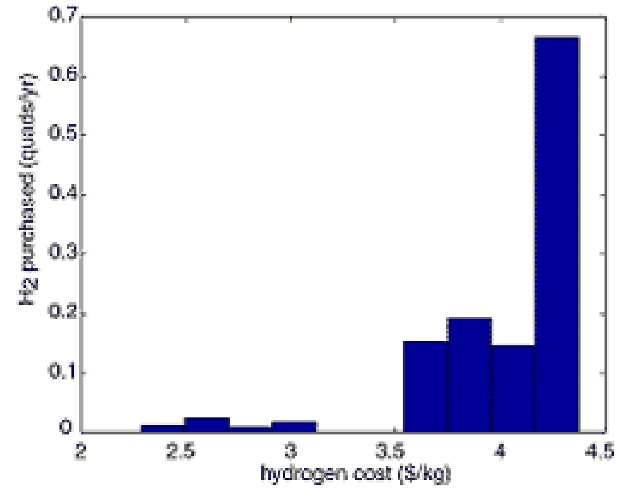
North Dakota ($2.54/kg)



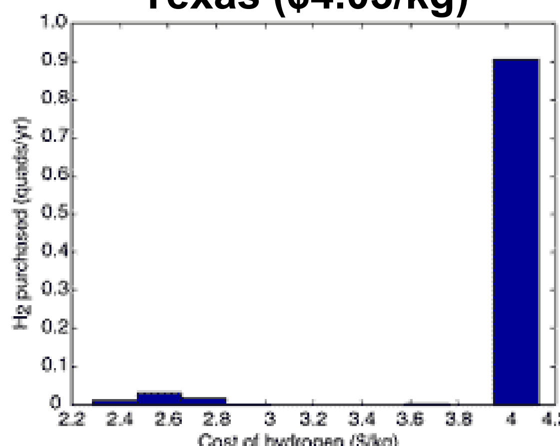
New Jersey ($4.45/kg)



California ($4.09/kg)



Texas ($4.03/kg)



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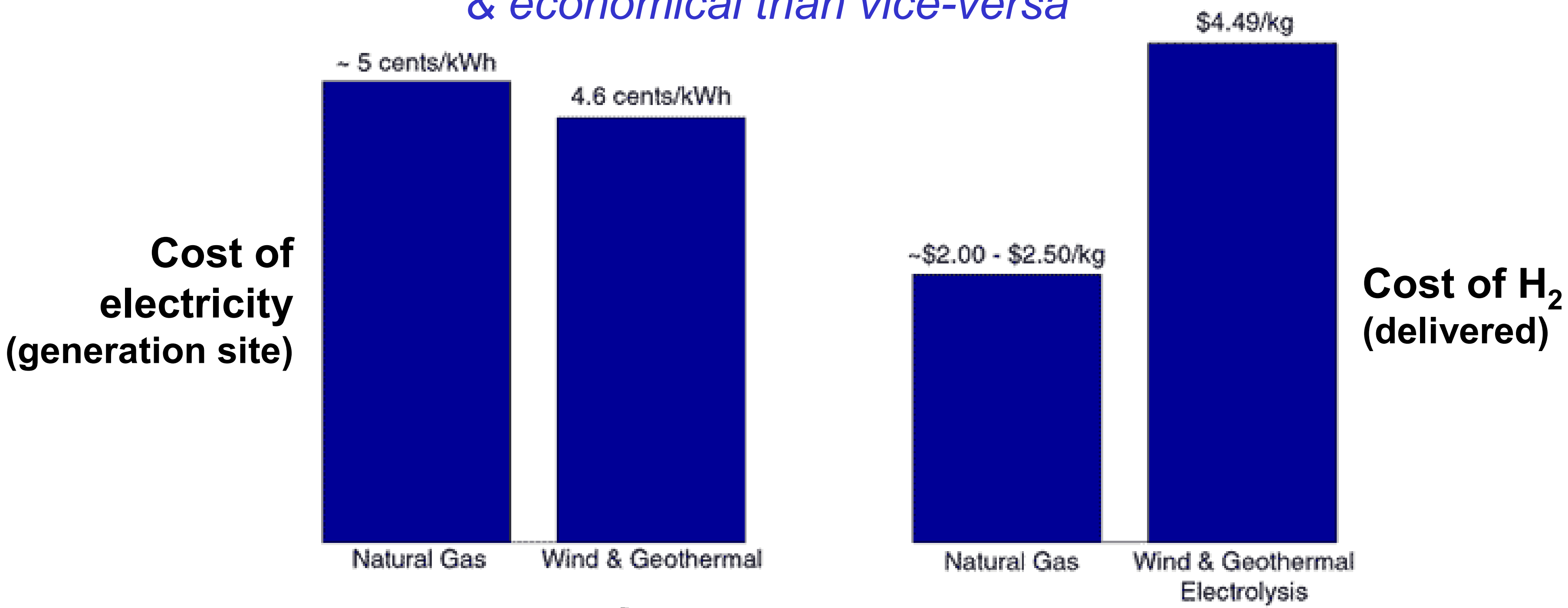
Interesting Aside: Electrolysis is an Uneconomical Use of Wind and Geothermal Electricity

- Electricity cost from wind/geothermal ≈ electricity cost from NG turbine
- H_2 cost from wind/geothermal ~85% more than H_2 cost from NG SR

∴ *Natural gas → H_2, wind/geothermal → electricity is more efficient & economical than vice-versa*



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Conclusions

- 10 quads of H_2 from renewable sources for transportation uses is technically achievable
- Electrolysis is significantly more expensive than biomass gasification
- Relatively abundant wind resources make solar a non-factor
- Significant wind resources are "stranded" due to cost of transmission
- Alternative production and distribution methods may be used, but not on the national scale

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Project Timeline

The work in the past year has been for Task 3 of a three task project.

Task	Title	Status
1	Distributed Hydrogen Fueling Systems Analysis	Complete. Report published October 2000.
2	Cost and Performance of Stationary Hydrogen Fueling Appliances	Complete. Report published April 2002.
3	Hydrogen from Renewable Energy Sources: Pathway to 10 Quads For Transportation Uses in 2030 to 2050	Draft Report issued for review February 2003.

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Collaborations

- Discussed capital cost projections for solar electricity with BP Solar
- Presented results at the 14th Annual U.S. Hydrogen Conference (March 2003, Washington, D.C.)
- Draft Report submitted for review to
  - DOE H2A Working Group
  - NREL

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Acknowledgements

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