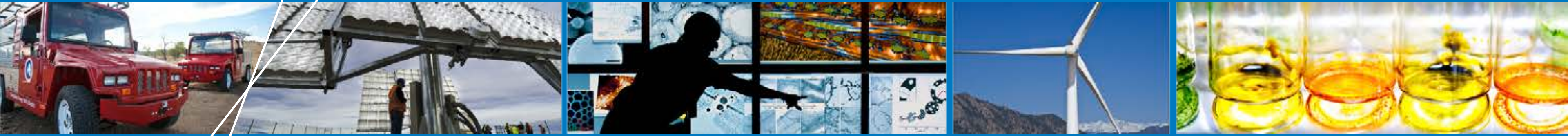
NREL
NATIONAL RENEWABLE ENERGY LABORATORY

AN036

Pathway Analysis: Projected Cost, Well-to-Wheels Energy Use and Emissions of Current Hydrogen Technologies



DOE Annual Merit Review
Crystal City, VA

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May 14, 2013

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Overview

Timeline

- Start: January 2012
- Finish: May 2013
- 100% Complete

Budget

- Total Funding: $170K
  - 100% DOE funded
- FY12 Funding: $110K
- FY13 Funding: $60K

Barriers Addressed

- Stove-piped/siloed analytical capability (B)
- Inconsistent data, assumptions & guidelines (C)
- Insufficient suite of models and tools (D)

Partners

- Alliance Technical Services
- U.S. DRIVE Fuel Pathways Integration Technical Team (FPITT)
- Sandia National Laboratory (SNL)

Project Objective

Hydrogen Pathways Analysis Project Objectives	
Detailed understanding of hydrogen production and delivery pathways	Conduct cost and life-cycle energy and emissions analyses of the complete supply chain of 10 hydrogen pathways using the Macro-System Model (MSM) to evaluate hydrogen cost, energy requirements & greenhouse gas (GHG) emissions
Document and review data, assumptions, and models used for analysis	• Provide detailed reporting of assumptions & data used to analyze hydrogen (H_2) technologies, enabling consistent & transparent understanding of results • Obtain industry review of input parameters and MSM & component models
Reporting	• Provide detailed reporting of hydrogen cost and capital costs of the complete hydrogen supply chain to support fuel cell electric vehicles (FCEVs) • Report on upstream energy & feedstock usage and GHG emissions on a full life-cycle basis, including vehicle cycle and well-to-wheels fuel cycle • Total FCEV cost of ownership reported including fuel and vehicle cycle

Relevance	
Support Fuel Cell Technology Office Goals and Activities	• Evaluate potential of current technologies to meet $2-4/kg cost target • Validate MSM and component models through industry review • Conduct lifecycle analyses of costs, energy & GHG emissions • Assist DOE's Fuel Cell Technology Office with goal setting and R&D decisions by providing a detailed understanding of H_2 technologies using consistent basis • Overcome stove-piped analysis and inconsistent data by providing a framework for modeling using consistent data and assumptions

Project Overview

Well-to-Wheels Energy & Emission Analysis of H_2 Production, Delivery & Dispensing Pathways

Analysis Framework

- Macro System Model
- Design parameters from the H_2 Delivery Scenario Analysis Model (HDSAM) & H_2 Prod. Analysis model (H2A)
- GREET (GHG, Regulated Emissions & Energy in Transportation) data
- Annual Energy Outlook (AEO) 2009 energy & feedstock data
- H_2 Analysis Resource Center (HyARC) data

Models & Tools

- Macro-System Model
- H2A Production
- HDSAM
- GREET 1 fuel cycle
- GREET 2 vehicle cycle
- Vehicle Cost Per Mile tool

Studies & Analysis

Cost, Energy Use & Emissions of H2 Production & Delivery Pathways

- Hydrogen cost
- Lifecycle energy & emissions analysis
- Lifecycle vehicle cost

Outputs & Deliverables

- Report
- Pathway input & output spreadsheets

Detailed understanding of H2 production & delivery pathways

System for documenting assumptions & data for well-to-wheels analysis of hydrogen pathways

National Labs

NREL – MSM & H2A
Argonne – GREET/HDSAM
SNL - MSM

Collaboration

Alliance Technical Services
USDRIVE FPITT

NREL, DOE Fuel Cell Technologies Office & USDRIVE Reviews

Key Input Parameters & Assumptions

The Macro-System Model (MSM) is being used to link H2A, HDSAM, GREET1, GREET2, and the Cost-Per-Mile tool and as the I/O interface

Modeling Assumptions

- Current technologies for H_2 production, delivery and dispensing
- Urban demand area, 1.25 million population (Indianapolis)
- 15% FCEV penetration
- Station size of 1000 kg/d for delivered hydrogen
- Station size of 1330 kg/d for distributed hydrogen
- 62 mi. delivery distance

Analysis Assumptions

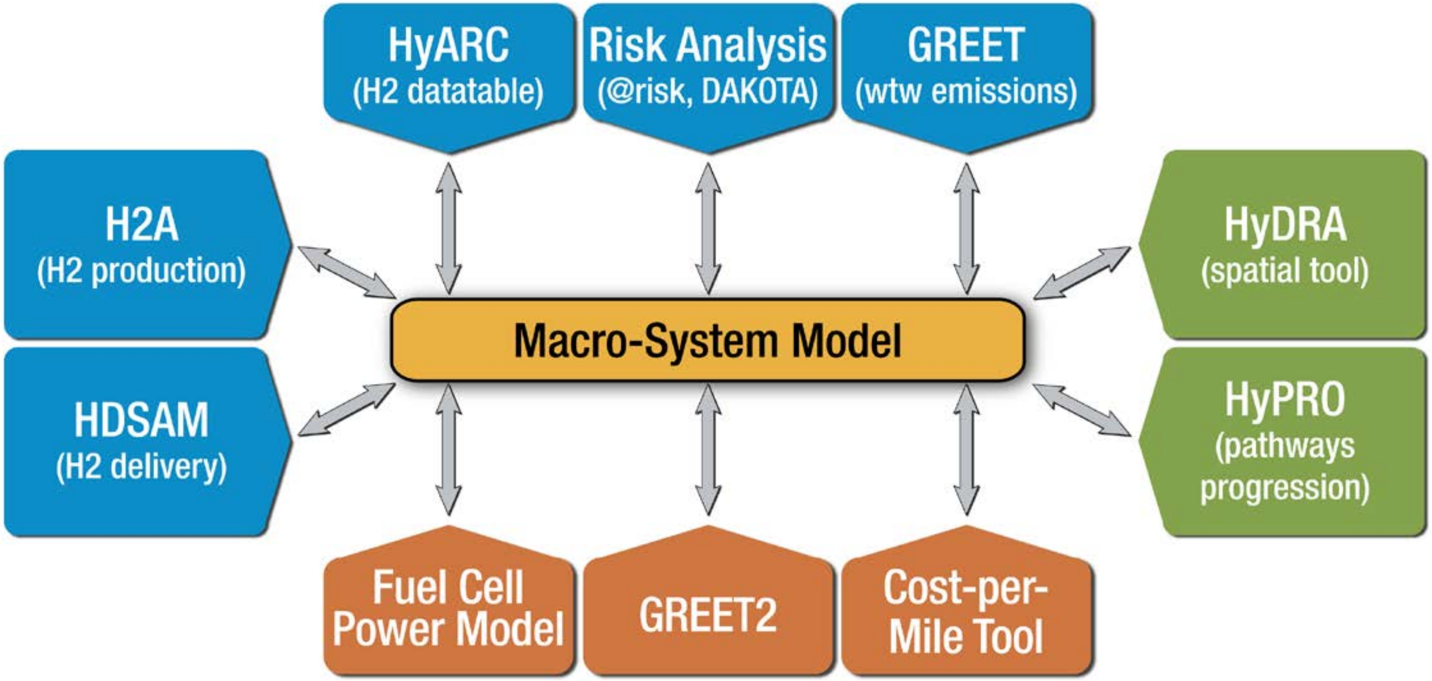
- 2015 start-up year
- 2007$
- 40-year analysis period for central production
- 20-year analysis period for distributed production
- Feedstock & utility costs from the 2009 annual energy outlook (AEO) based on national averages

Vehicle Assumptions

- 2015 FCEV purchase
- 15,000 miles/yr VMT; 160,000 mile lifetime
- Conventional materials (not light-weighted)
- Mid-size FCEV with 48 mpgge (miles per gallon gasoline equivalent) on-road fuel economy; sensitivity at 68 mpgge
- Vehicle cost with five-year ownership period

Pathway Analysis Conducted Using the MSM

The MSM is a cross-cutting tool that acts as a central transfer station, linking other hydrogen models to provide consistency in multi-model simulations



The MSM is well suited to the H_2 pathways analysis since it:

- Enables rapid cross-cutting analysis that utilizes and links other models
- Provides levelized cost at the pump for the entire pathway
- Outputs well to pump, pump to wheels and well-to-wheels (WTW) efficiencies, GHG emissions & energy use

Pathways Analyzed in 2012/2013

10 current-technology production, delivery & dispensing pathways analyzed

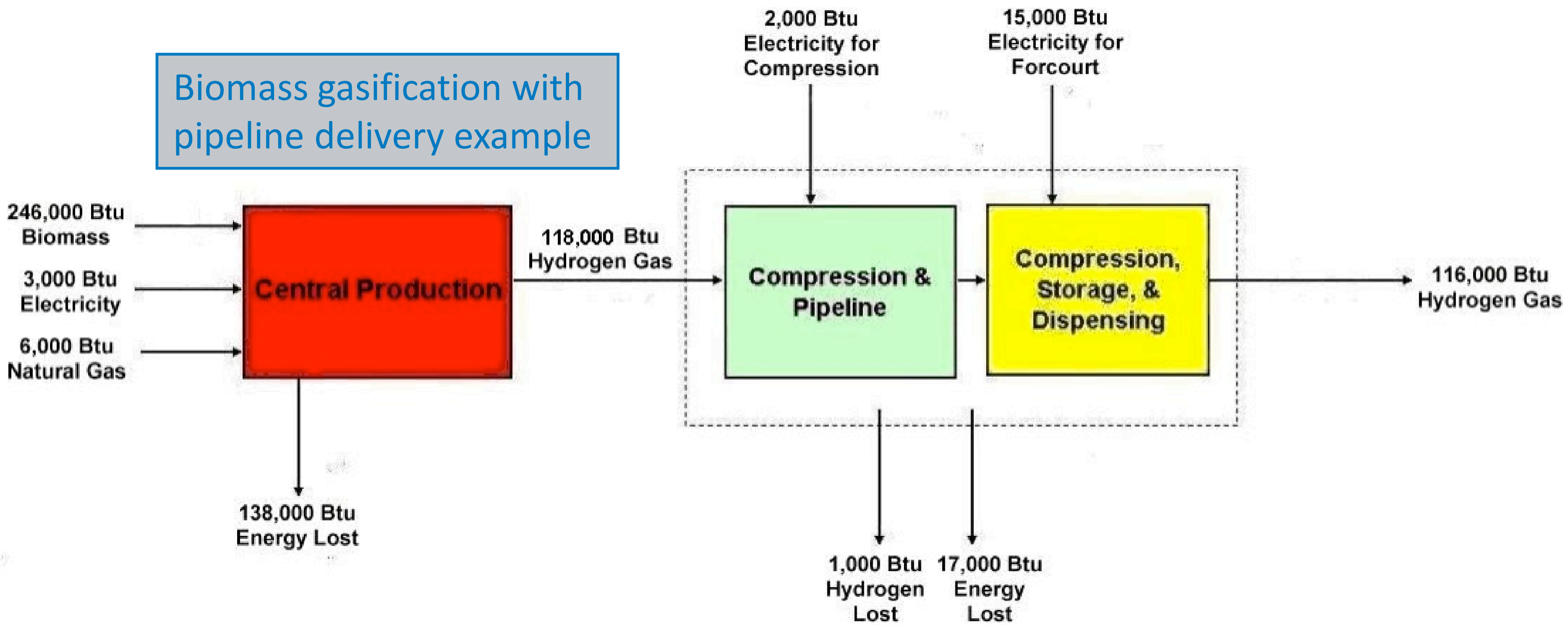
	Production Feedstock / Technology	Delivery Mode	Dispensing Mode	Total Ownership Cost Results Reported
1	Natural Gas Reforming	Distributed Production	700 bar	Yes
2*	Ethanol Reforming	Distributed Production	700 bar	No
3	Electrolysis	Distributed Production	700 bar	No
4	Biomass Gasification	Pipeline	700 bar	No
5*	Biomass Gasification	Gas in Truck	700 bar	No
6	Biomass Gasification	Liquid in Truck	700 bar	No
7*	Biomass Gasification	Liquid in Truck	Cryo-compressed	No
8	Natural Gas Reforming	Pipeline	700 bar	No
9	Wind Electrolysis	Pipeline	700 bar	Yes
10	Coal w/ carbon capture	Pipeline	700 bar	No

* New technologies in this analysis

Pathway Composition – Example

H2 supply chain evaluated for WTW costs, energy use & GHG emissions

Biomass gasification with pipeline delivery example



- Analyzed the **complete hydrogen supply chain pathway**, including production, delivery, and on-site compression, storage, and dispensing (CSD)
- Hydrogen production **includes upstream energy use** required for feedstock production, processing, and delivery
- Pathways analyzed for **levelized cost, energy requirements & GHG emissions**

Documented Parameters, Data & Assumptions

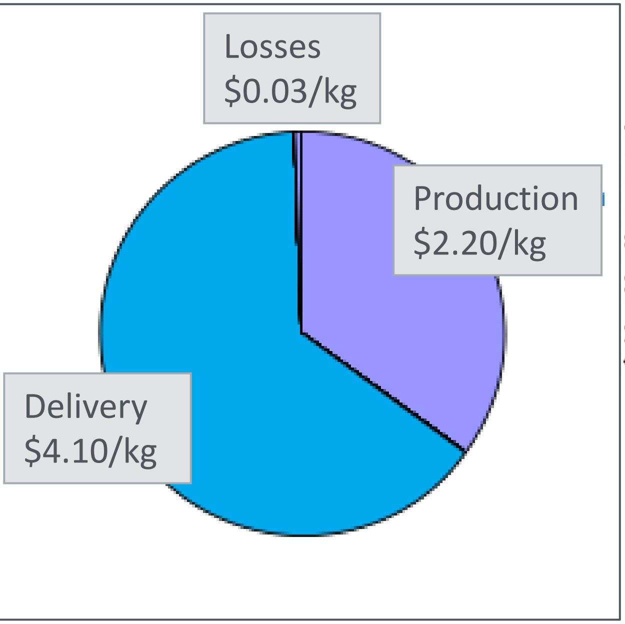
Detailed documentation & industry review of all modeling parameters

- Detailed documentation developed for every pathway, including in-depth report and multi-tab spreadsheets documenting each pathway
  - All modeling parameters, assumptions, and input & output data captured for all pathways
  - Reporting provides consistent and transparent understanding of analysis & results
- Key assumptions, modeling parameters, and analysis inputs reviewed by industry partners through the U.S. DRIVE Fuel Pathways Integration Technical Team (FPITT)
- FPITT review included a review of the MSM and component H2A, HDSAM, and GREET models
  - Feedback on models provided to DOE and national lab model developers

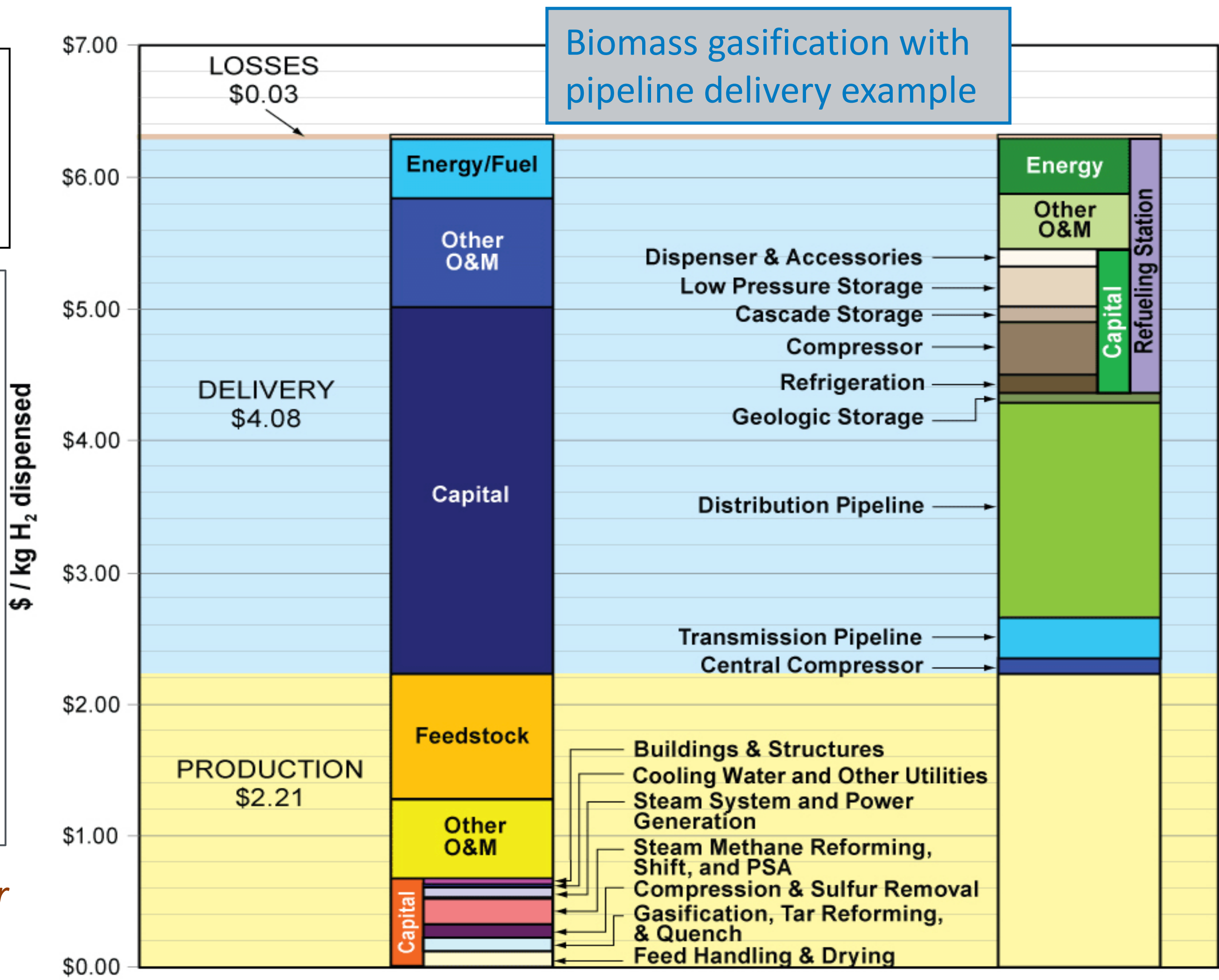
Dispensed Hydrogen Cost Results

H_2 costs, including losses and production & delivery shares, shown for all pathways, with detailed breakdown of capital and operating cost elements

Biomass-Pipeline Pathway
Levelized Cost: $6.32/kg
H_2 per mile: $0.13/mile



Similar results available for 9 other H_2 pathways



Total Cost Per Mile Results – Vehicle & Fuel

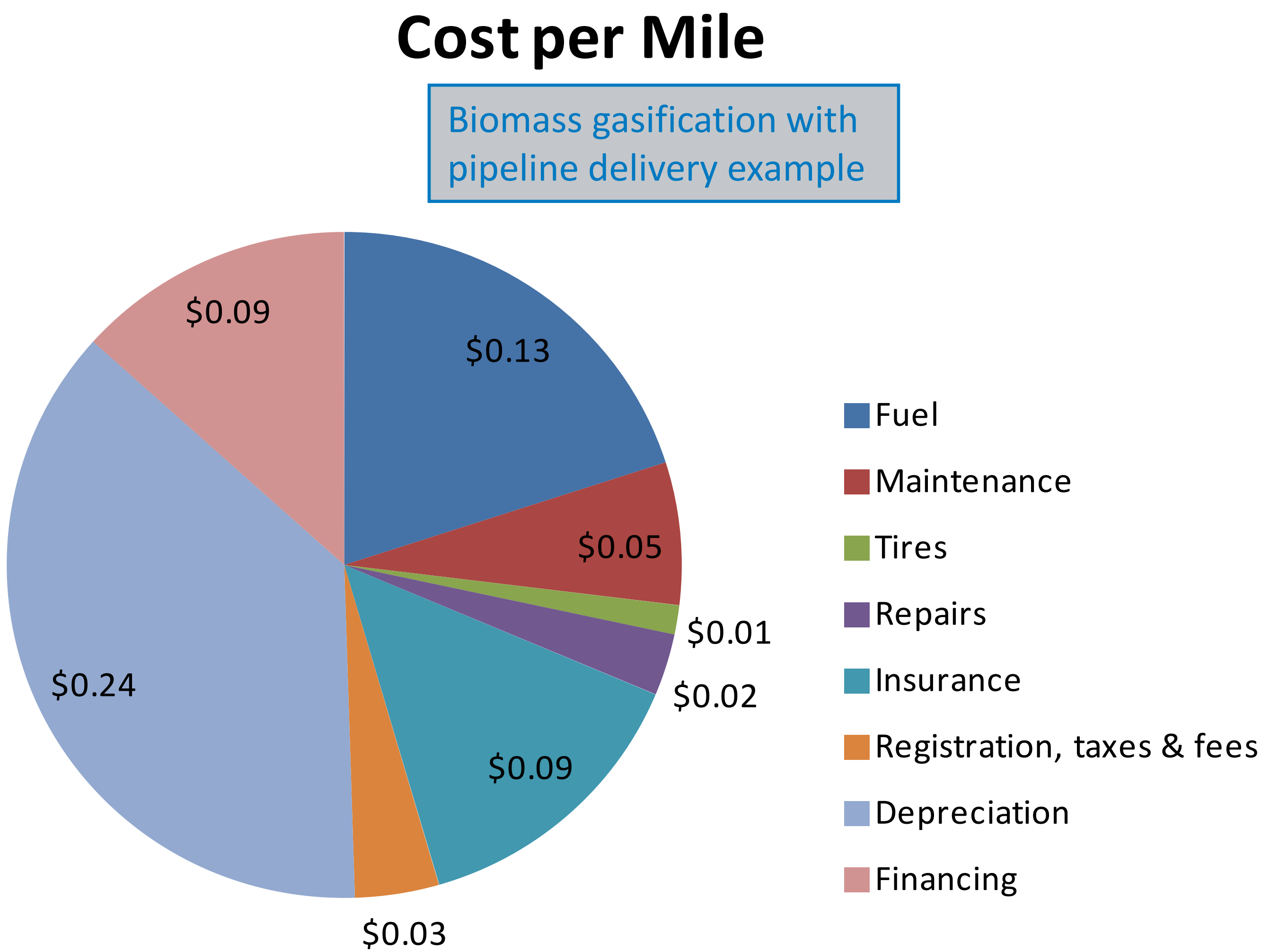
H_2 fuel costs represent 20% of ownership costs
FCEV depreciation & financing represent 50% of costs

Biomass-Pipeline Pathway

H_2 cost per mile: $0.13/mile

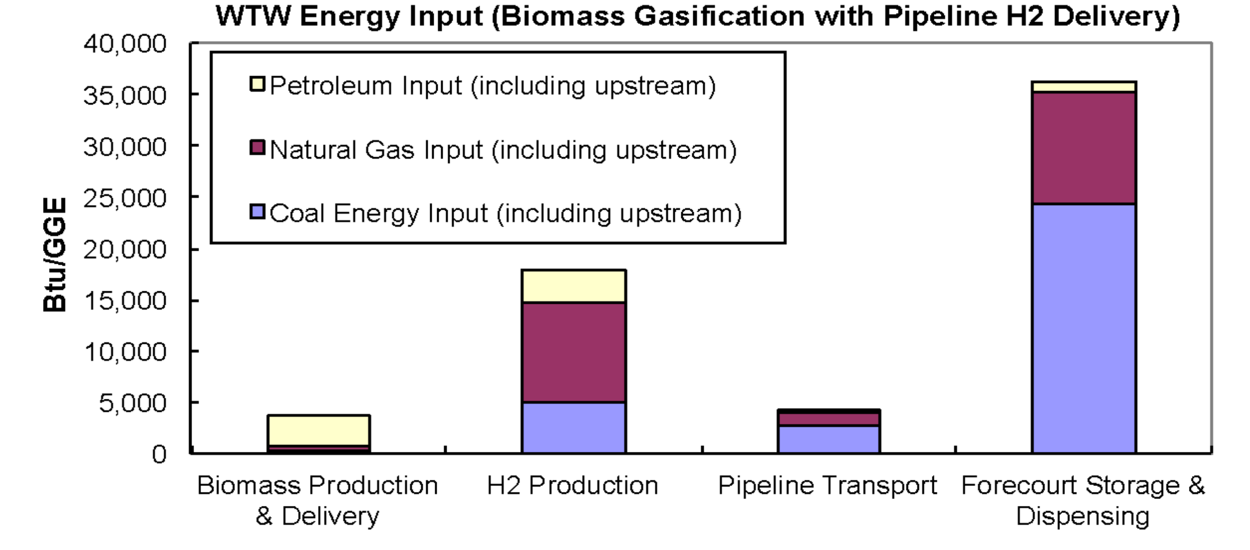
Cost per mile: $0.66/mile

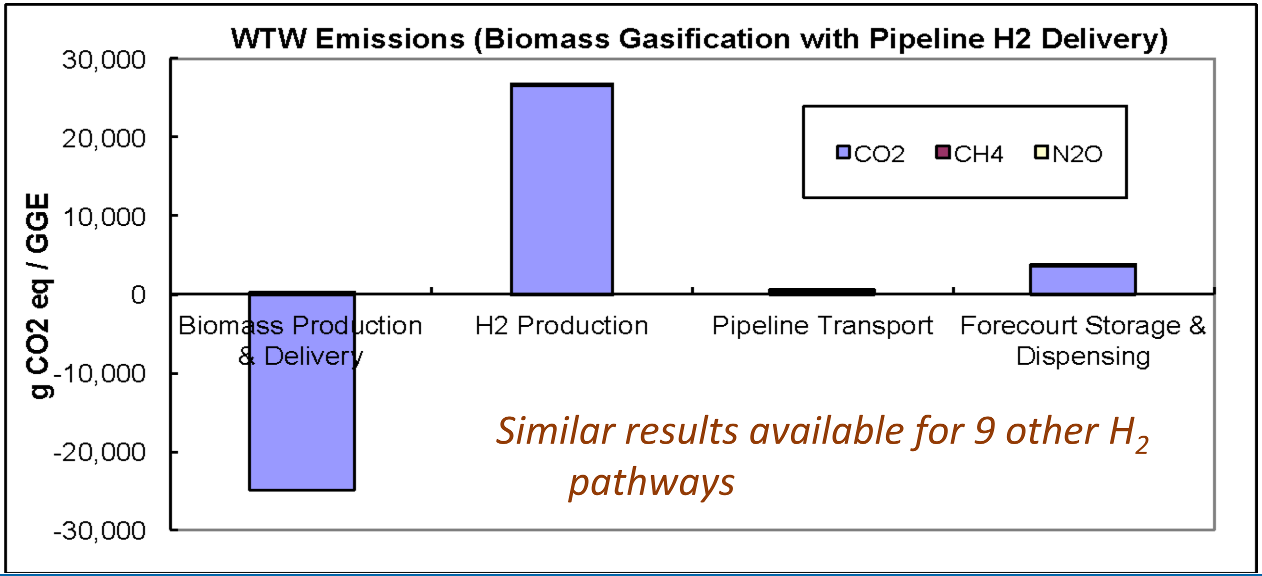
Total cost results reported for distributed natural gas & central wind-pipeline pathways



WTW Energy and Emission Results

Compression, storage & dispensing accounts for most GHG emissions





Similar results available for 9 other H_2 pathways

WTW Energy

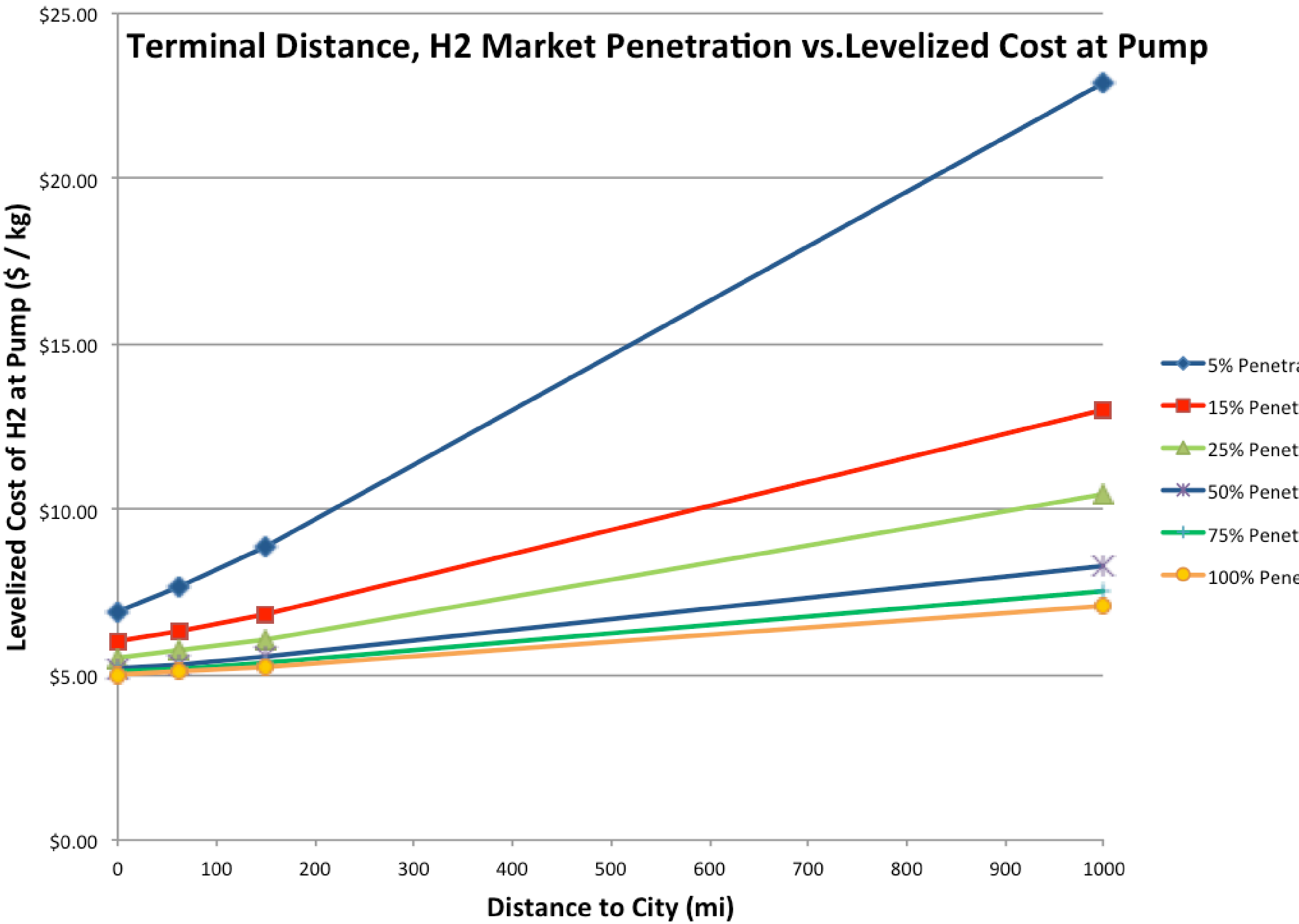
- Total energy req't calculated, only fossil energy shown
- Station requires significant energy due to 700 bar compression/cooling

WTW Emissions

- Biomass production provides CO_2 "sink"
- CO_2 then released during H_2 production, leading to small net CO_2 emissions

Detailed Sensitivity Results

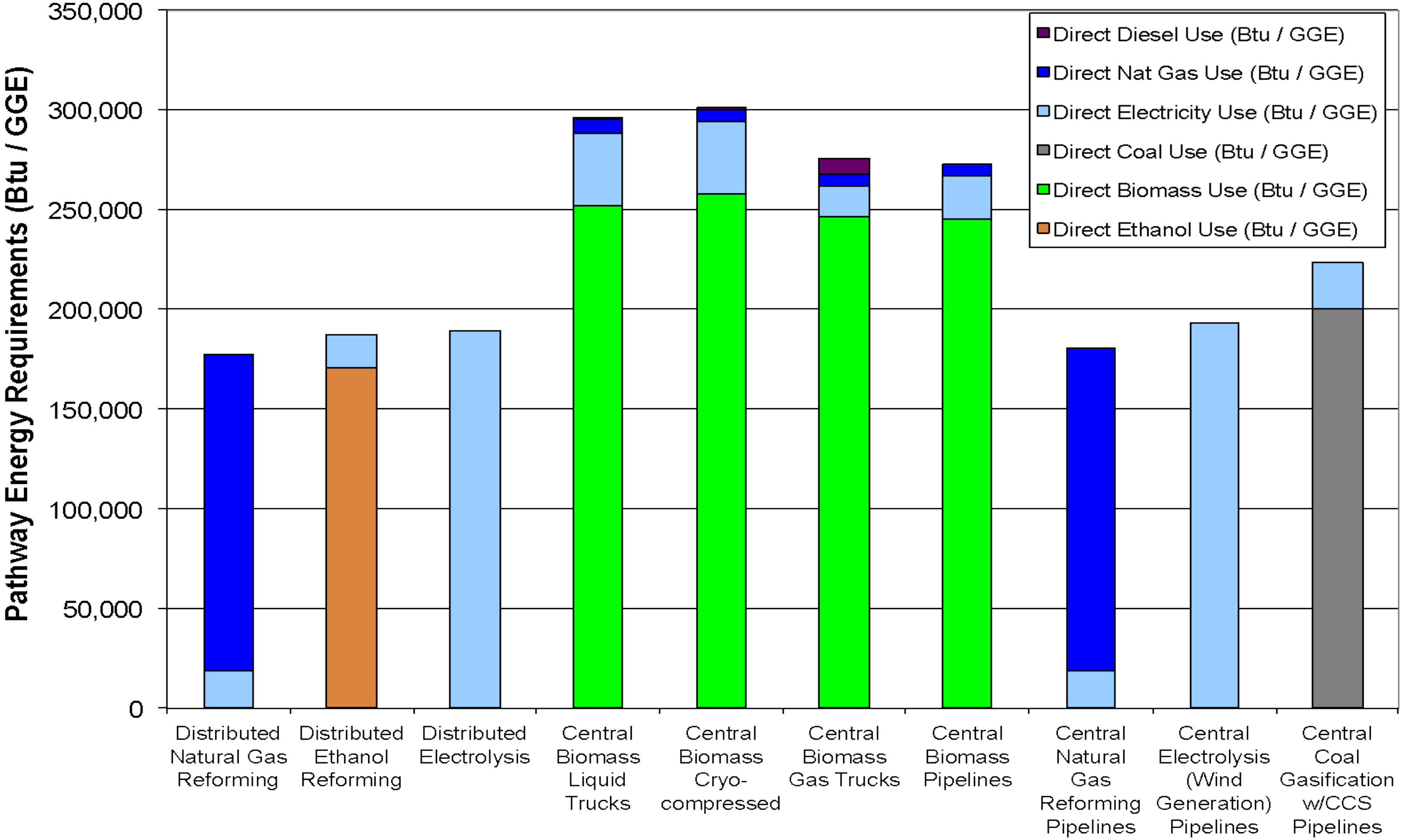
Detailed sensitivity results developed for all hydrogen pathway analyses



- Effects of feedstock and capital on production cost
- Effects of fuel economy on GHG emissions and cost
- Effects of FCEV penetration, delivery distance, forecourt size, and population on H_2 cost and delivery emissions and energy use

Comparative Results – Energy Use

Natural gas pathways use the least total energy, biomass pathways the most



All 10 Pathways Analyzed:

3 Forecourt

7 Central

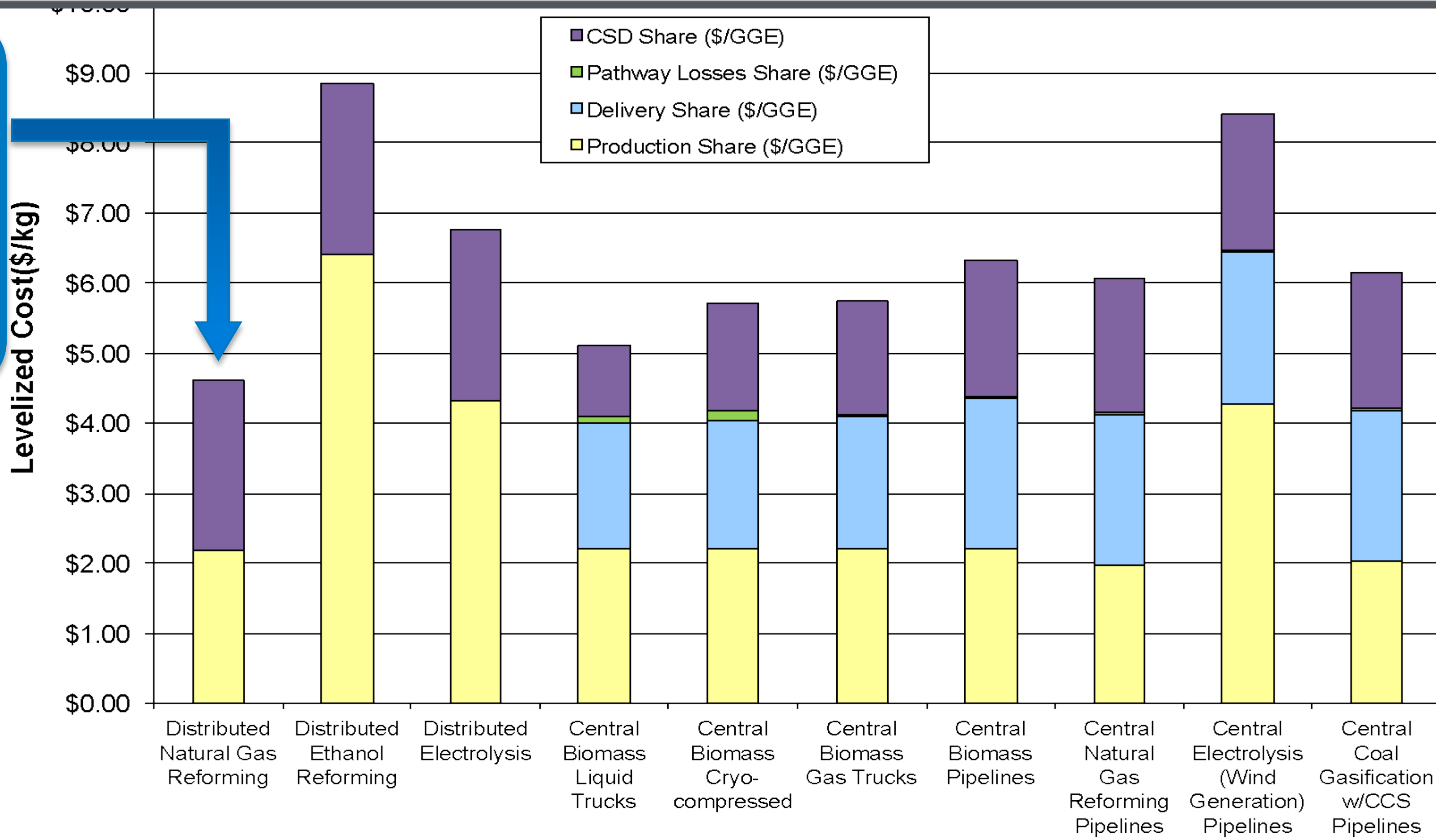
4 Biomass cases showing all delivery types

Stacked bar results show energy requirements for each pathway, including the contributions of input electricity, fossil energy, and renewable biomass and ethanol feedstocks.

Comparative Results – H2 Cost Breakdown

Central pathways generally have lower dispensed H_2 costs. Significant CSD costs show that CSD is a critical area for research to achieve H_2 cost targets.

Distributed natural gas is the lowest cost pathway (~$4.50/kg)

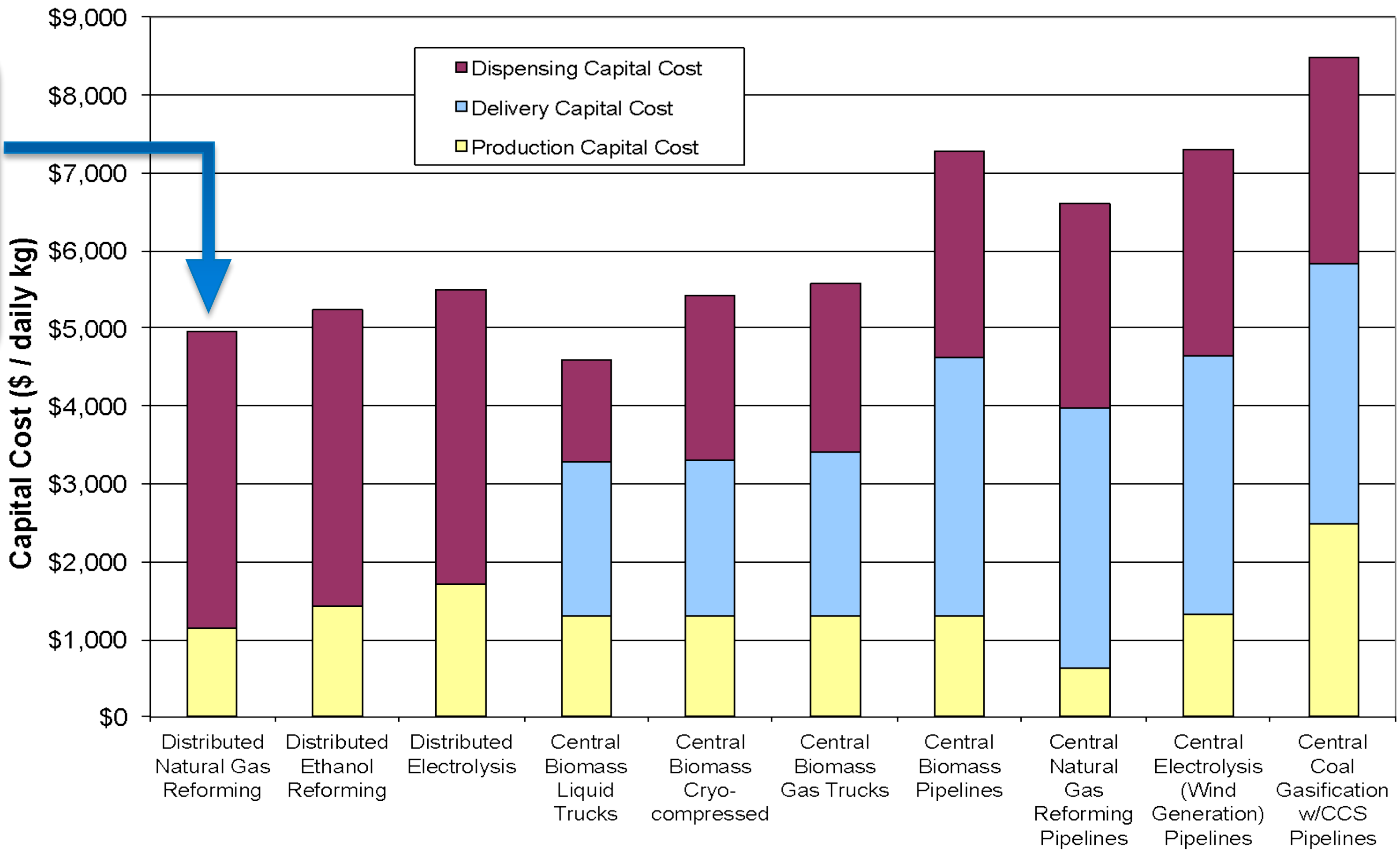


- 4 pathways nearly meet production target of $2/kg, though analysis is for mature market
- $1.50-2.50/kg CSD costs (vs. $2/kg target for H_2 delivery and CSD)

Comparative Results – Capital Cost

Total capital costs are an important hurdle reflecting the investment needed for a FCEV market, e.g. pipelines represent a significant up-front investment

$5,000 /daily kg capital cost means $5M for a 1000 kg/d station

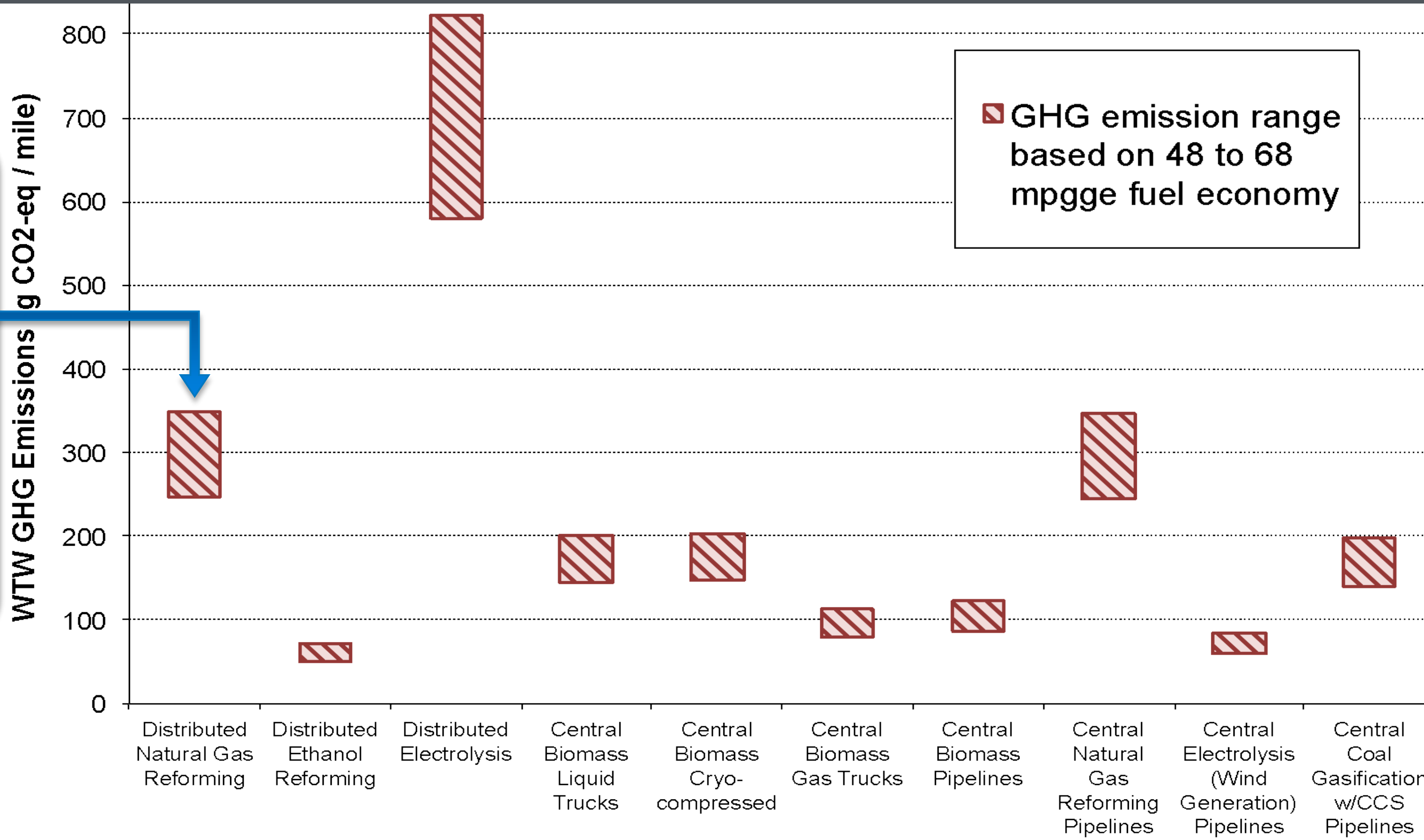


All pathways have significant delivery & CSD capital requirements: $2B-4B per million FCEVs

Comparative Results – WTW GHG Emissions

Low energy use pathways not always low GHG pathways, due to the carbon intensity of the energy feedstocks (e.g., central biomass pathways)

Natural gas reforming is a low cost production pathway, but has high GHG emissions

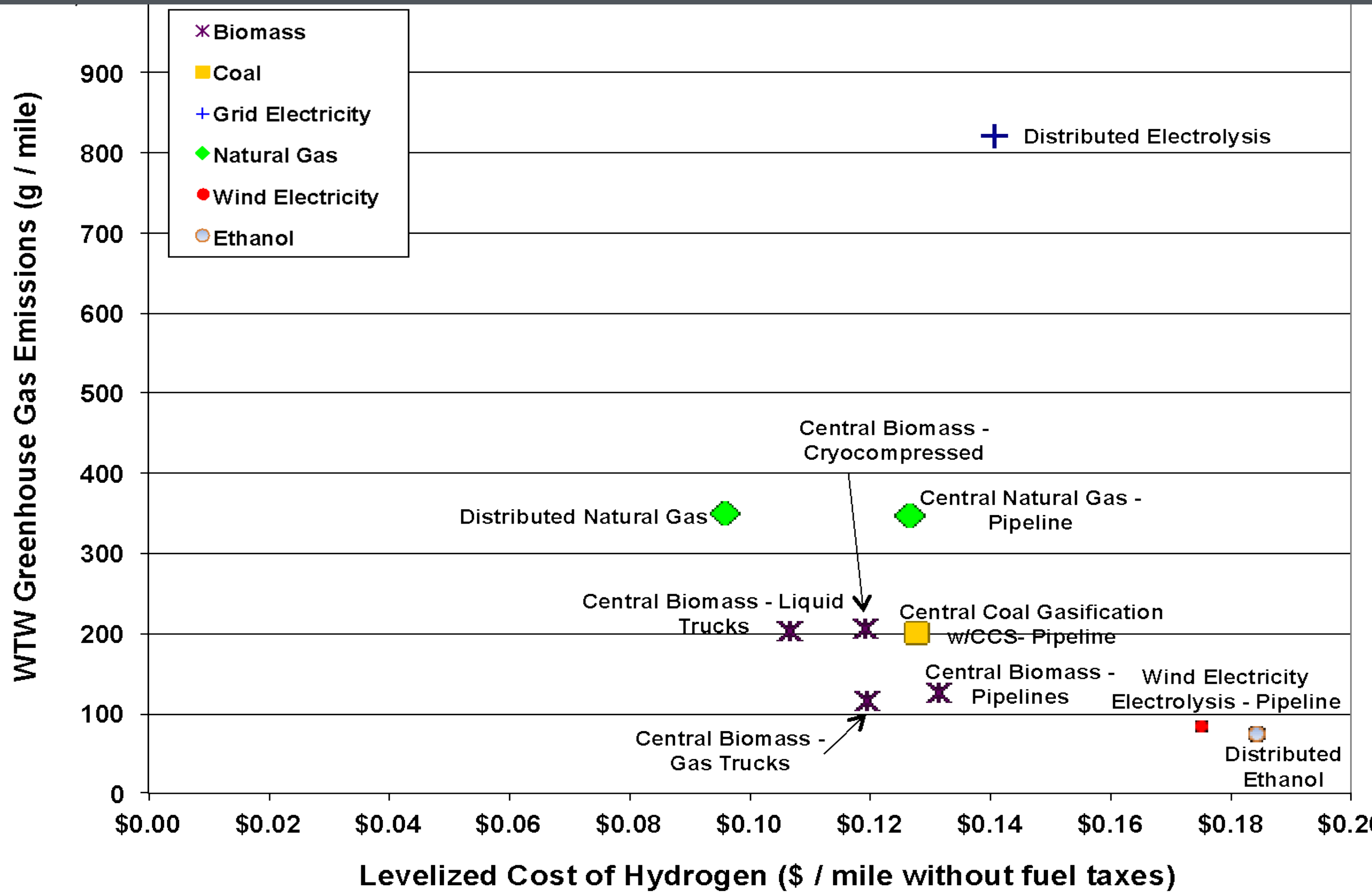


- **Electrolysis emissions depend on grid mix** (wind electricity vs U.S. mix)
- **Liquid hydrogen delivery has higher GHG emissions** due to liquifaction energy required

Comparative Results: GHG vs Fuel Cost

Results reflect the need for a portfolio approach – no clear winner

48 mpgge fuel economy results

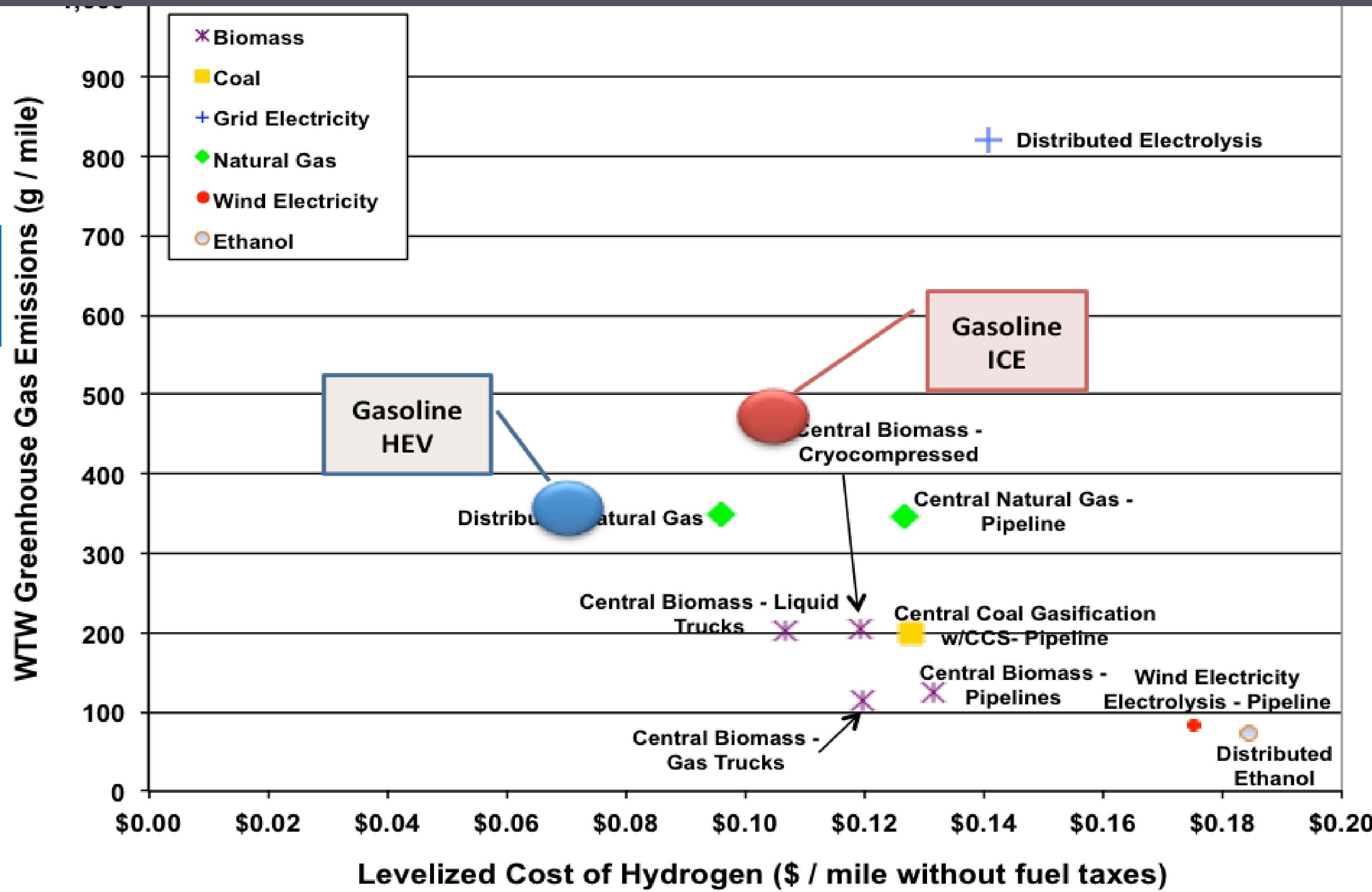


- Biomass and wind electrolysis have low GHGs, but high cost; dist. NG low cost, but high GHG
- Dist. electrolysis shows high GHG emissions using US grid mix, likely a regional solution only

Comparative Results: GHG vs Fuel Cost

Can compare results to conventional gasoline & hybrid electric vehicles

48 mpgge fuel economy results

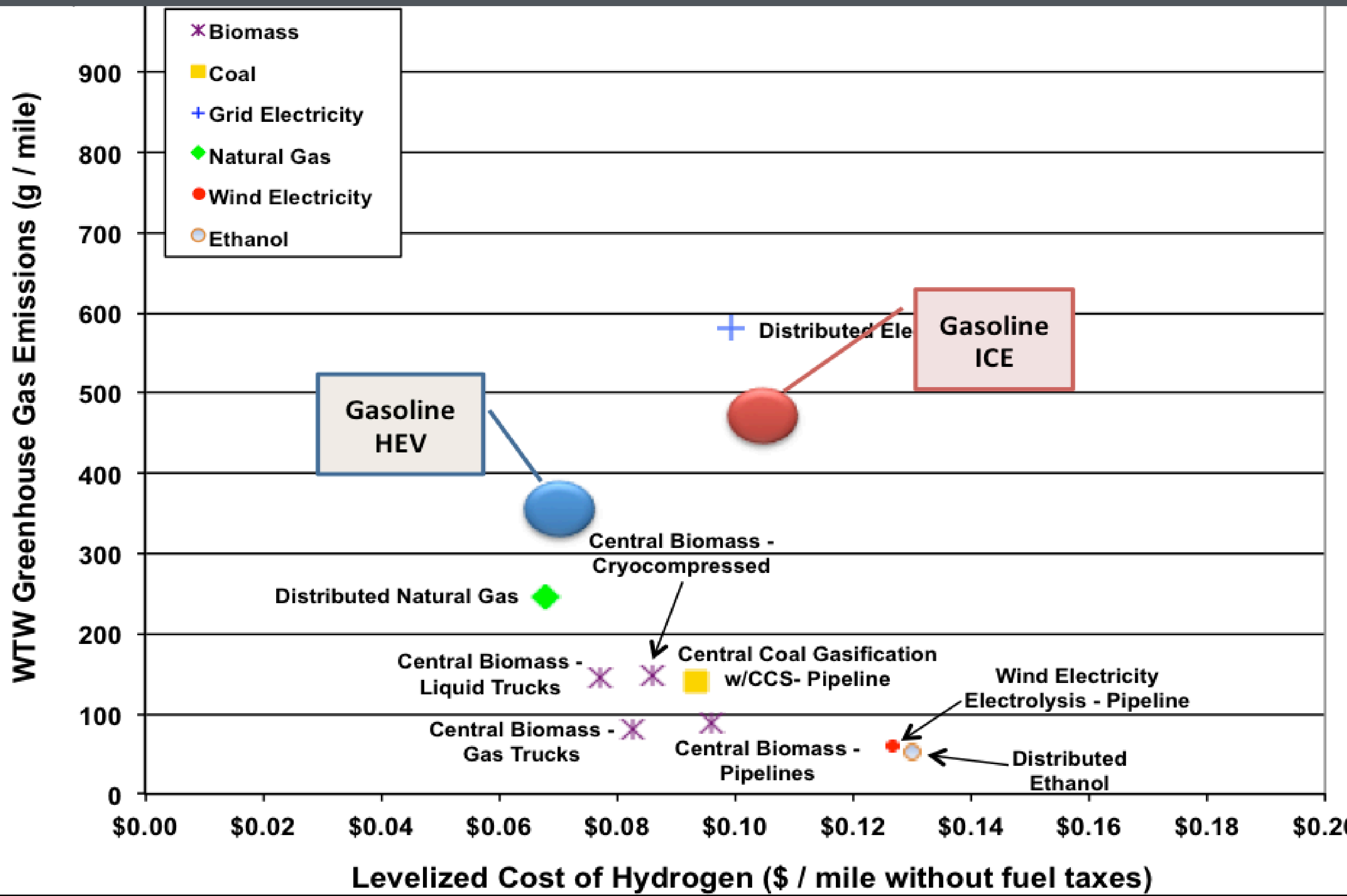


- FCEVs cannot currently match hybrid vehicles on per mile fuel cost
- FCEVs better than both conventional vehicles and hybrids on GHG emissions (one exception)

Comparative Results: GHG vs Fuel Cost

At higher 68 mpgge, FCEVs become comparable on cost to hybrid vehicles

68 mpgge fuel economy results



- FCEVs fueled with hydrogen from distributed NG stations better than hybrid on cost & GHGs
- Most pathways yield significant GHG reductions for FCEVs compared to hybrids

Next Steps and Future Work

Near-Term: Publish WTW pathways analysis results for current technologies

FY13:
- Conduct companion WTW pathways analysis for future production, delivery and dispensing technologies expected to be commercially available in 2025

	Production Feedstock / Technology	Delivery Mode	Dispensing Mode
1	Natural Gas Reforming	Distributed Production	700 bar
2	Ethanol Reforming	Distributed Production	700 bar
3	Grid Electrolysis	Distributed Production	700 bar
4	Central Natural Gas Reforming	Pipeline	700 bar
5	Central Natural Gas Reforming	Gas in Truck	700 bar
6	Central Natural Gas Reforming	Liquid in Truck	700 bar
7	Central Natural Gas Reforming	Liquid in Truck	Cryo-compressed
8	Central Wind Electrolysis	Pipeline	700 bar

Potential Future Work: Investigate advanced technology pathways
- Production: photo-electrochemical, photo-biological, solar thermo-chemical
- On-board storage technologies other than 700 bar compressed gas
- Novel delivery technologies (e.g., dual phase tankers, high pressure tube trailers)
- Investigate WTW energy & emissions of build-out scenarios, not mature market

Project Summary

Hydrogen Pathways Analysis Project Summary	
Approach	Conduct well-to-wheels (WTW) analyses of the complete supply chain of 10 hydrogen pathways using the Macro-System Model (MSM) to evaluate hydrogen cost, energy input requirements & GHG emissions
Relevance	• Evaluate potential of current technologies to meet $2-4/kg cost target • Validate MSM and component models through industry review • Conduct lifecycle costs, energy & emissions of H2 technologies
Technical Accomplishments	• Developed detailed documentation of all input & output parameters enabling consistent and transparent understanding of results and modeling • Industry review of input parameters, MSM & component models • Detailed hydrogen cost and capital costs developed for all H2 pathways • Pathway upstream energy & feedstock usage and GHG emissions reported • Total FCEV cost of ownership reported including fuel cycle and vehicle cycle
Collaborations	• Analysis support from Alliance Technical Services • MSM development support from Sandia National Laboratory • Industry review of modeling assumptions and input parameters through USDRIVE Fuel Pathways Integration Technical Team
Future Work	• Conduct companion WTW pathway analyses of future hydrogen technologies expected in 2025 • Pathway analyses of advanced development hydrogen technologies

Questions & Discussion

THANKS!

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BACK-UP SLIDES

Parameters, Data & Assumptions – Summary

Biomass Production & Delivery

Inputs

Energy Use for Farming Trees	234,964	Btu / dry ton
Coal Input from "Well"	203	Btu / 116000Btu to Pump
Natural Gas Input from "Well"	623	Btu / 116000Btu to Pump
Petroleum Input from "Well"	2,912	Btu / 116000Btu to Pump

Modeling Parameters & Assumptions

Fraction of Woody Biomass (Remaining is Herbaceous)	100%	
LUC GHG changes	0	g / dry ton
Average dist from farm to H_2 production	40	miles

Outputs

Biomass moisture content	25%	
Woody biomass LHV	16,013,234	Btu / dry ton
Biomass price at H_2 production	$75.02	2007 $ / dry ton
Biomass Share of Levelized Co:	$0.97	2007$ / kg H_2 dispensed
WTG CO_2 Emissions	-24,829	g CO_2 eq./ 116000 Btu
WTG CH_4 Emissions	13	g CO_2 eq./ 116000 Btu
WTG N_2O Emissions	35	g CO_2 eq./ 116000 Btu
WTG GHG Emissions	-24,782	g CO_2 eq./ 116000 Btu

Hydrogen Production

Inputs

Biomass consumption	13.5	kg (dry) / kg H_2 produced
Natural gas consumption	0.0059	MMBtu / kg H_2 produced
Electricity consumption	0.98	kWh / kg H_2 produced
Process Water Consumption	1.32	gal / kg H_2 produced
Cooling Water Consumption	79.3	gal / kg H_2 produced
Total Capital Investment	$181,079,846	2007$
Coal Input from "Well"	5,126	Btu / 116000Btu to Pump
Natural Gas Input from "Well"	9,498	Btu / 116000Btu to Pump
Petroleum Input from "Well"	3,390	Btu / 116000Btu to Pump

Modeling Parameters & Assumptions

Central plant design capacity	155,236	kg / day
Capacity factor	90%	
Number of production facilities necessary	0.87	
Process energy efficiency	46.0%	
Electricity Mix	US Mix	
After-tax IRR	10%	
Assumed Plant Life	40	

Outputs

Hydrogen Output Pressure	300	psi
Hydrogen Outlet Quality	99.9%	
Total capital investment	$1,296	2007$ / daily kg H_2 (effective capacity)
Levelized Cost of Capital	$0.64	2007$ / kg H_2 dispensed
Fixed O&M Costs	$0.23	2007$ / kg H_2 dispensed
Variable O&M Costs	$0.40	2007$ / kg H_2 dispensed
Total Levelized Cost	$2.24	2007$ / kg H_2 dispensed
SMR CO_2 Emissions	26,511	g CO_2 eq./ 116000 Btu
SMR CH_4 Emissions	138	g CO_2 eq./ 116000 Btu
SMR N_2O Emissions	43	g CO_2 eq./ 116000 Btu
SMR GHG Emissions	26,692	g CO_2 eq./ 116000 Btu

Pipelines for Delivery

Inputs

Electricity consumption for compressor	0.56	kWh / kg H_2 dispensed
Electricity consumption for geo storage	0.01	kWh / kg H_2 dispensed
Total electricity consumption	0.57	kWh / kg H_2 dispensed
Total Capital Investment	$404,341,499	2007$
Coal Input from "Well"	2,825	Btu / 116000Btu to Pump
Natural Gas Input from "Well"	1,253	Btu / 116000Btu to Pump
Petroleum Input from "Well"	107	Btu / 116000Btu to Pump

Modeling Parameters & Assumptions

City Population	1,247,364	people
Hydrogen Vehicle Penetration	15%	
City hydrogen use	121,096	kg / day
Distance from City to Production Facility	62	miles
Geologic storage capacity	1,324,720	kg H_2
Number of trunk pipelines	3	
Service-line length	1.5	miles / line
Number of service lines	122	
Hydrogen losses	0.76%	

Outputs

Total capital investment	$3,339	2007$ / daily kg dispensed
Levelized Cost of Capital	$1.71	2007$ / kg H_2 dispensed
Energy & Fuel	$0.04	2007$ / kg H_2 dispensed
Other O&M Costs	$0.40	2007$ / kg H_2 dispensed
Levelized Cost of Delivery	$2.15	2007$ / kg H_2 dispensed
Delivery CO_2 Emissions	389	g CO_2 eq./ 116000 Btu
Delivery CH_4 Emissions	24	g CO_2 eq./ 116000 Btu
Delivery N_2O Emissions	2	g CO_2 eq./ 116000 Btu
Delivery GHG Emissions	415	g CO_2 eq./ 116000 Btu

Forecourt Dispensing

Inputs

Electricity consumption	4.4	kWh / kg H_2 dispensed
Total Capital Investment per Station	$2,628,512	2007$ / station
Total Capital Investment	$320,678,503	2007$ / all stations
Inlet pressure of hydrogen at stations	294	psi
Coal Input from "Well"	24,443	Btu / 116000Btu to Pump
Natural Gas Input from "Well"	10,837	Btu / 116000Btu to Pump
Petroleum Input from "Well"	928	Btu / 116000Btu to Pump

Modeling Parameters & Assumptions

Average Dispensing Rate per Station	1,000	kg/day
Number of Dispensing Stations	122	
Number of Compression Steps	5	
Usable Low Pressure Storage per Station	367	kg H_2
Usable Cascade Pressure Storage per Station	130	kg H_2
Site storage	42%	% of design capacity
Number of 2-hose Dispensers per Stati	2	
Hydrogen Losses	0.50%	

Outputs

Hydrogen outlet pressure	12,688	psi
Basis -- Hydrogen Quantity	116,000	Btu (116,000 Btu/gal non-oxygenated conventional unleaded gasoline)
Total capital investment	$2,648	2007$ / daily kg H_2 (effective capacity)
Levelized Cost of Capital	$1.08	2007$ / kg H_2 dispensed
Energy & Fuel	$0.41	2007$ / kg H_2 dispensed
Other O&M Costs	$0.43	2007$ / kg H_2 dispensed
Levelized Cost of Dispensing	$1.93	2007$ / kg H_2 dispensed
CSD CO_2 Emissions	3,369	g CO_2 eq./ 116000 Btu
CSD CH_4 Emissions	208	g CO_2 eq./ 116000 Btu
CSD N_2O Emissions	14	g CO_2 eq./ 116000 Btu
CSD GHG Emissions	3,591	g CO_2 eq./ 116000 Btu

Vehicle

Inputs

Vehicle Mass	3,020	lb
Fuel cell size	70	kW
Size of hybridization battery	30	kW

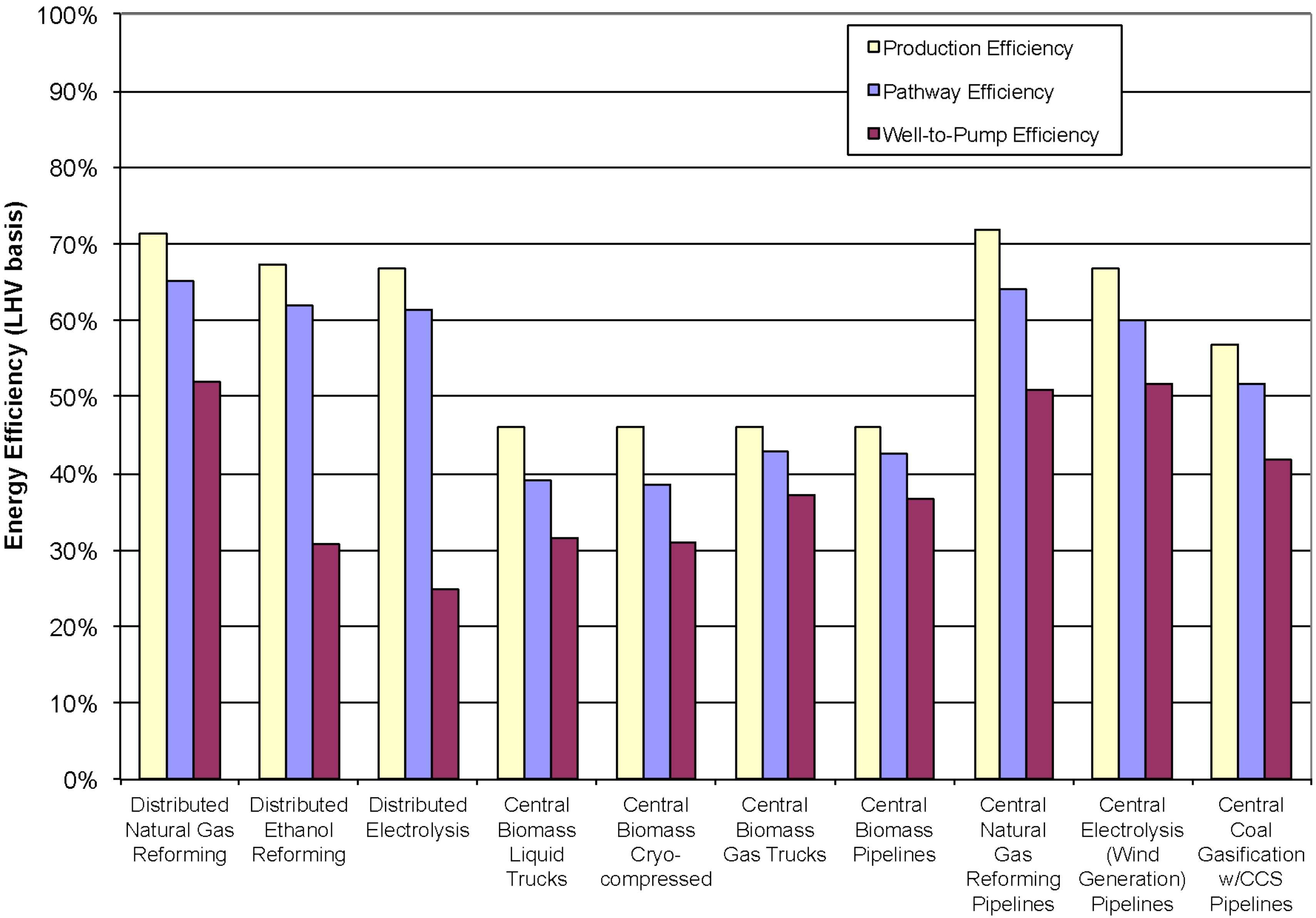
Modeling Parameters & Assumptions

Fuel Economy	48.0	mi / GGE
Vehicle Miles Traveled	15,000	mi / yr

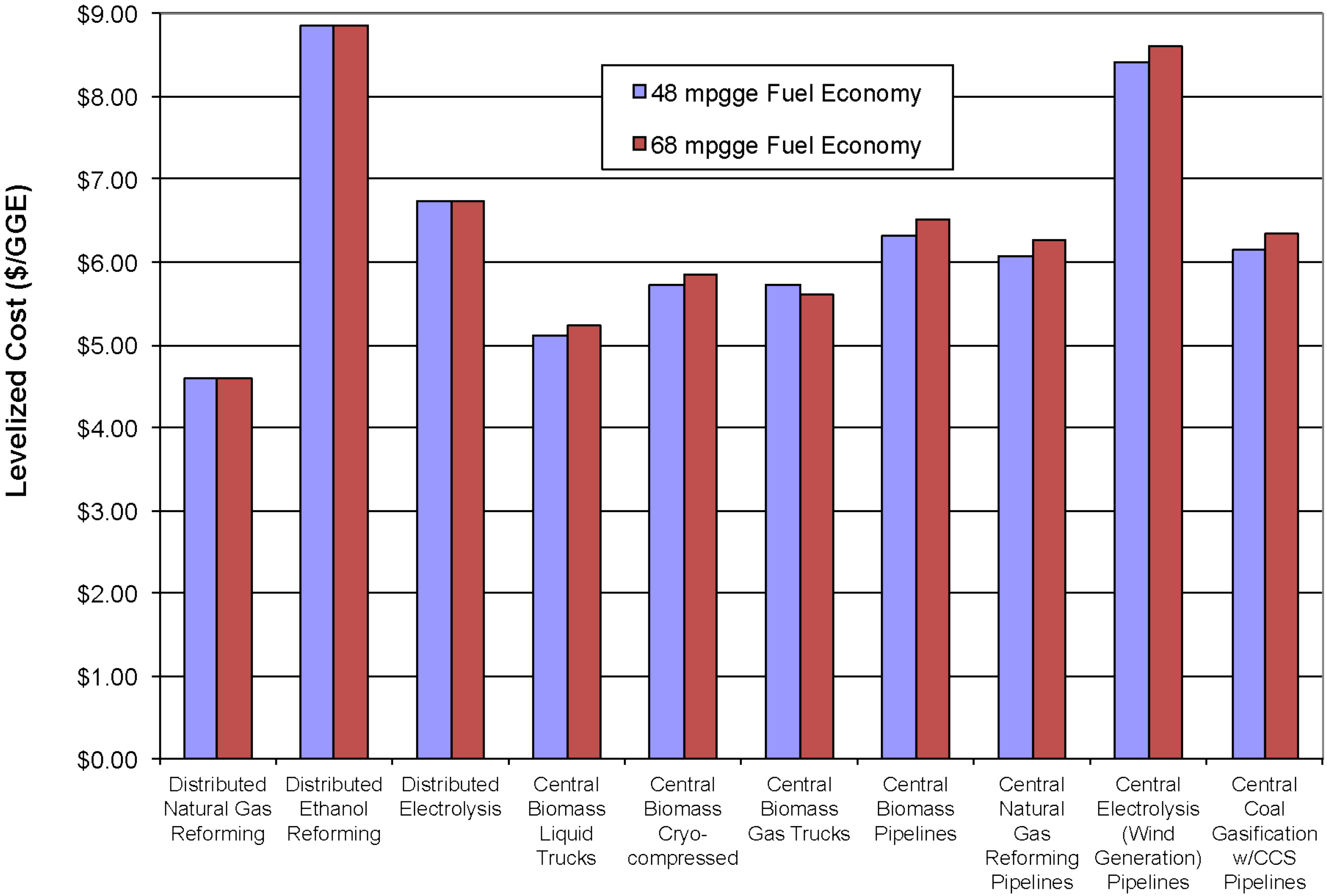
Outputs

Cost Per Mile	$0.66	2007$ / mi
Fuel Share	$0.13	2007$ / mi
Maintenance, Tires, Repairs	$0.07	2007$ / mi
Insurance & Registration	$0.12	2007$ / mi

Comparative Results – Efficiency



Comparative Results – H2 Cost at 48 vs 68 mpgge



Comparative Results – H2 Production Cost