AN036

Pathway Analysis: Projected Cost, Lifecycle Energy Use and Emissions of Future Hydrogen Technologies

DOE Annual Merit Review
Washington, DC

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Overview

Timeline

- Start: March 2013
- Finish: September 2013
- 80% Complete

Note: Timeline/completion address only the present pathway analysis; future funding of additional pathway analyses not yet established

Budget

- Total Funding: $180K
  - 100% DOE funded
- FY13 Funding: $60K
- FY14 Funding: $120K

Note: Budget addresses only the future-technologies pathway analysis; completed current-technologies pathway analysis funded at $170K during FY12-13

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 Pathway 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 complete hydrogen production, delivery, and dispensing 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 complete hydrogen fuel pathways 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 cycles

Relevance	
Support Fuel Cell Technology Office Goals and Activities	• Evaluate potential of current technologies to meet \$2-4/kg H_2 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

Lifecycle Energy Emission, & Cost 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

- Pathway Reports
- 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

- Future 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

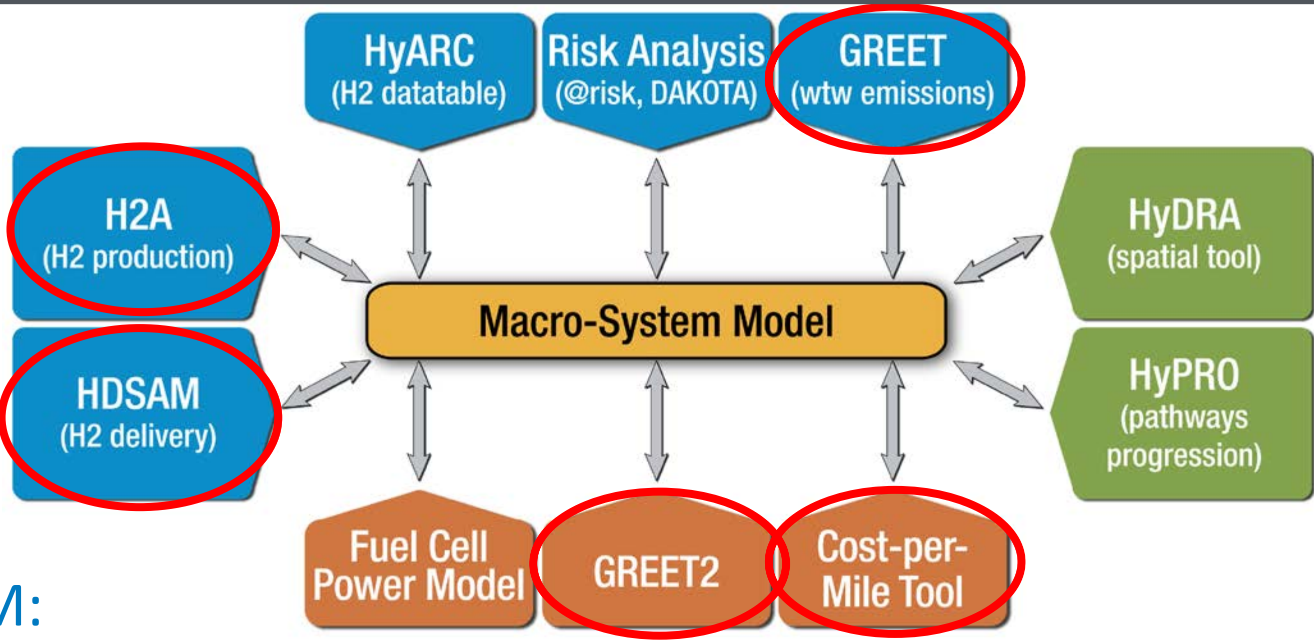
- 2025 start-up year
- Mature market assumed
- 2007$ cost reporting
- 40-year analysis period for central production
- 20-year analysis period for distributed production
- Feedstock & utility costs from the 2009 annual energy outlook (AEO), reflect national averages
- Consider upstream energy

Vehicle Assumptions

- 2020 FCEV purchase
- 15,000 miles/yr VMT; 160,000 mile lifetime
- Mid-size FCEV modeled (chassis comparable to conventional vehicle)
- 58 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:

- Enables rapid cross-cutting analysis that utilizes and links other DOE H_2 models
- Provides levelized cost at the pump for the entire pathway
- Provides well-to-wheels fuel-cycle (WTW) and vehicle-cycle efficiencies, GHG emissions & energy use
- Enables lifecycle cost, energy use, and GHG analysis of H_2 fuel, including analysis of upstream energy use for feedstock production, delivery and processing

Pathways Analyzed in 2013/2014

8 future-technology production, delivery & dispensing pathways analyzed; preliminary analysis of 4 emerging technology pathways

		Production Feedstock / Technology	Delivery Mode	Dispensing Mode
Future technology pathways (analysis completed)	**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**
Emerging technology pathways (preliminary)	*i*	*Central Natural Gas w/ CCS*	*Pipeline*	*700 bar*
	ii	*Central Photo-Electrochemical*	*Pipeline*	*700 bar*
	iii	*Central Photo-Biological*	*Pipeline*	*700 bar*
	iv	*Central Solar Thermo-chemical*	*Pipeline*	*700 bar*

[CCS = Carbon capture and sequestration]

Response to Reviewers' Comments

Study considers hypothetical mature market, not transition, to inform R&D

"The evaluation of pathways using future technologies is essential. There is also a critical need to understand how pathways will evolve and change during a multi-decade transition."

- Though development of hydrogen fueling infrastructure and market transition studies are critical, they are outside the scope of this study.
- This project seeks to understand the performance of cost of hydrogen fuel technologies operating in a mature market, with a focus on informing R&D.
- The evaluation seeks to separate performance of H_2 technologies and the effects of economies of scale on cost.

"It is not clear if the results [of the study] are validated."

- The study results have undergone extensive review by both NREL and FPITT and have been compared to the results of DOE's published models (e.g., H2A, HDSAM and GREET) and have been compared to the results of similar lifecycle assessments, such as those conducted elsewhere by DOE and by the US DRIVE.

"The PI should also consider how the grid might be de-carbonized ."

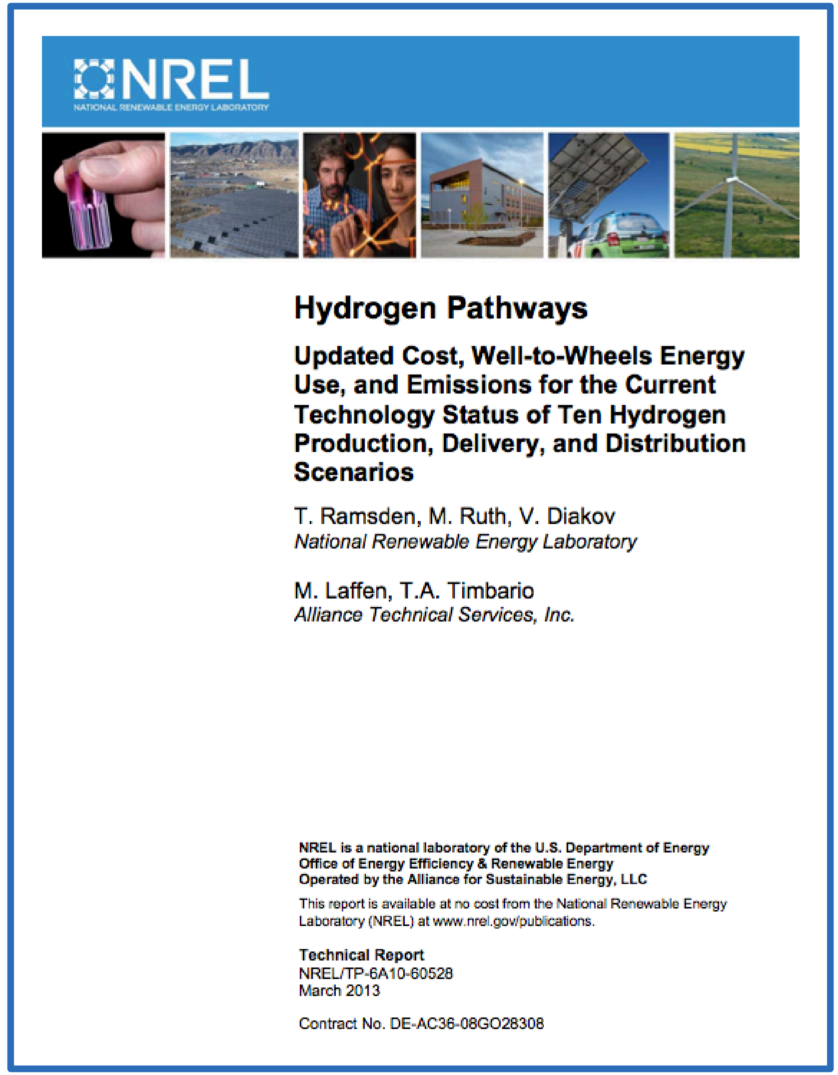
- A "green grid" sensitivity analysis has been conducted for all pathways

Current Technologies Pathway Evaluation Completed

Hydrogen Pathways Evaluation of Current Technologies Published in FY2013

- Lifecycle cost, energy use and GHG emissions evaluation of 10 current- technology hydrogen production, delivery and dispensing pathways completed in FY 2013
- Evaluation considered hydrogen production from biomass gasification, coal gasification, natural gas reformation, and wind electrolysis
- Report published and available on-line at:

http://www.nrel.gov/docs/fy14osti/60528.pdf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Hydrogen Pathways

Updated Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Ten Hydrogen Production, Delivery, and Distribution Scenarios

T. Ramsden, M. Ruth, V. Diakov
National Renewable Energy Laboratory

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NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-6A10-60528
March 2013

Contract No. DE-AC36-08GO28308

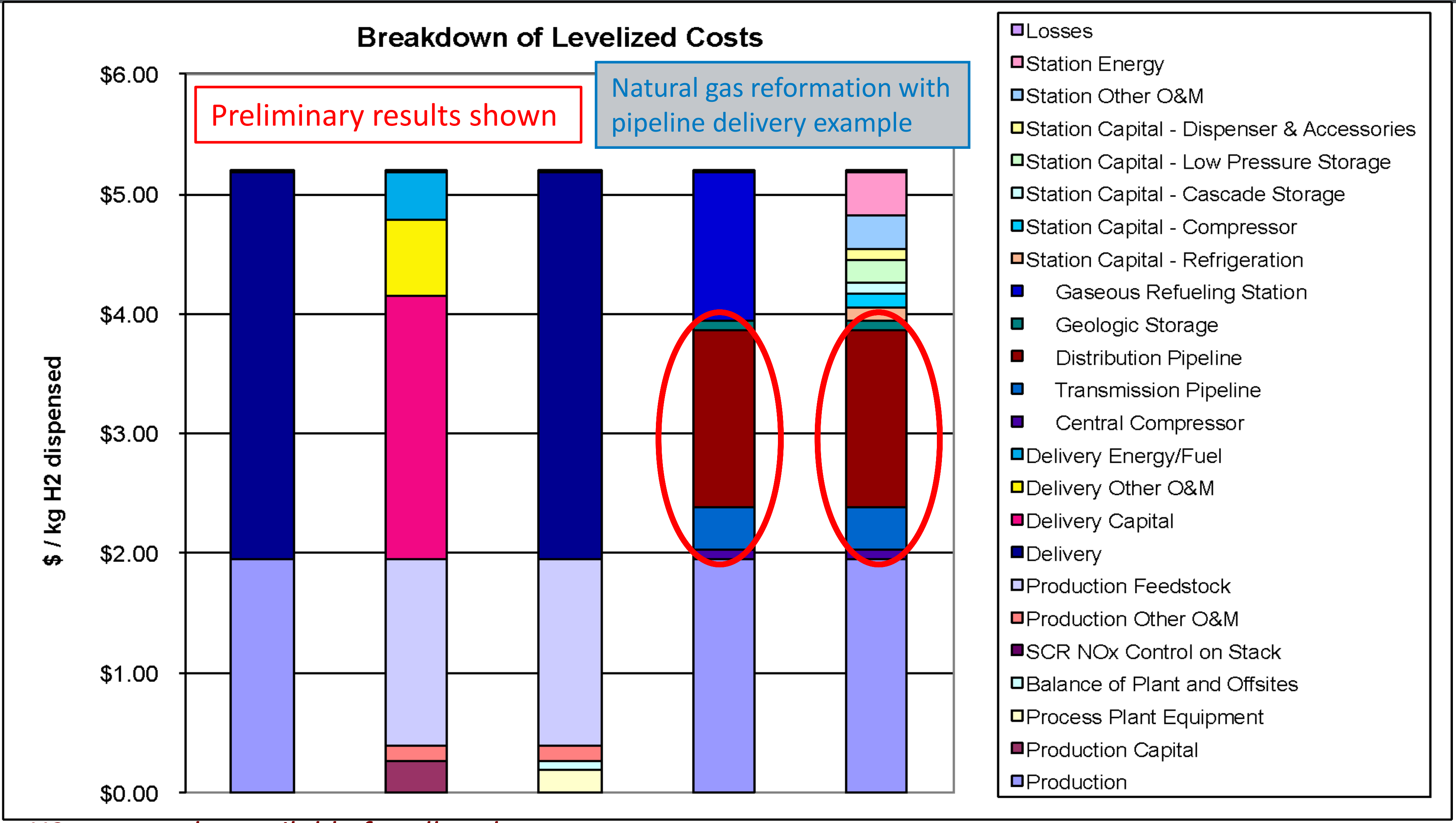
Documented Parameters, Data & Assumptions

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
  - Extensive QA/QC performed comparing MSM modeling results to individual component model results to insure accuracy of findings
- Key assumptions, modeling parameters, and analysis inputs reviewed by industry partners through the U.S. DRIVE Fuel Pathway 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

Detailed H_2 cost breakdown provides insight to major costs. Pipeline delivery case shows significant pipeline capital costs -- $1.80/kg towards pipelines



H2 cost results available for all pathways

Total Cost Per Mile Results

H_2 fuel costs represent 10% of ownership costs
FCEV depreciation & financing represent over 50% of costs

Central Natural Gas Reformation – w/ Gas Truck Delivery Pathway

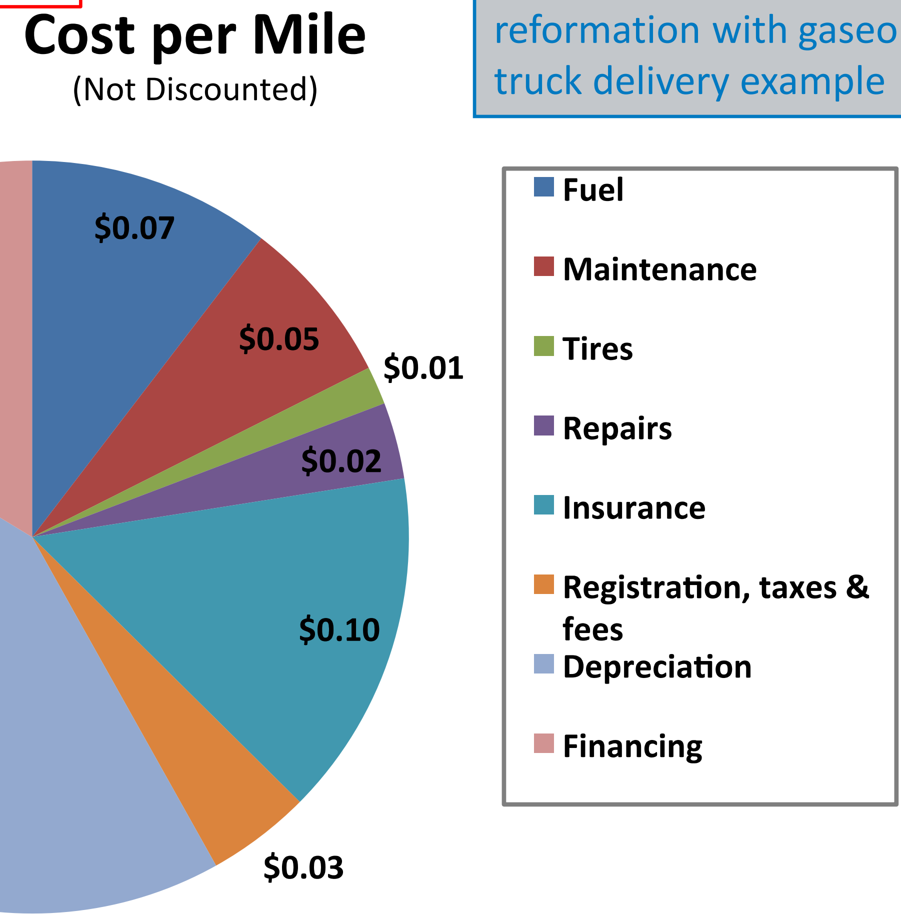
H_2 cost per mile: $0.07/mile

Total ownership cost per mile: $0.70/mile

Total cost results available for all future technologies pathways

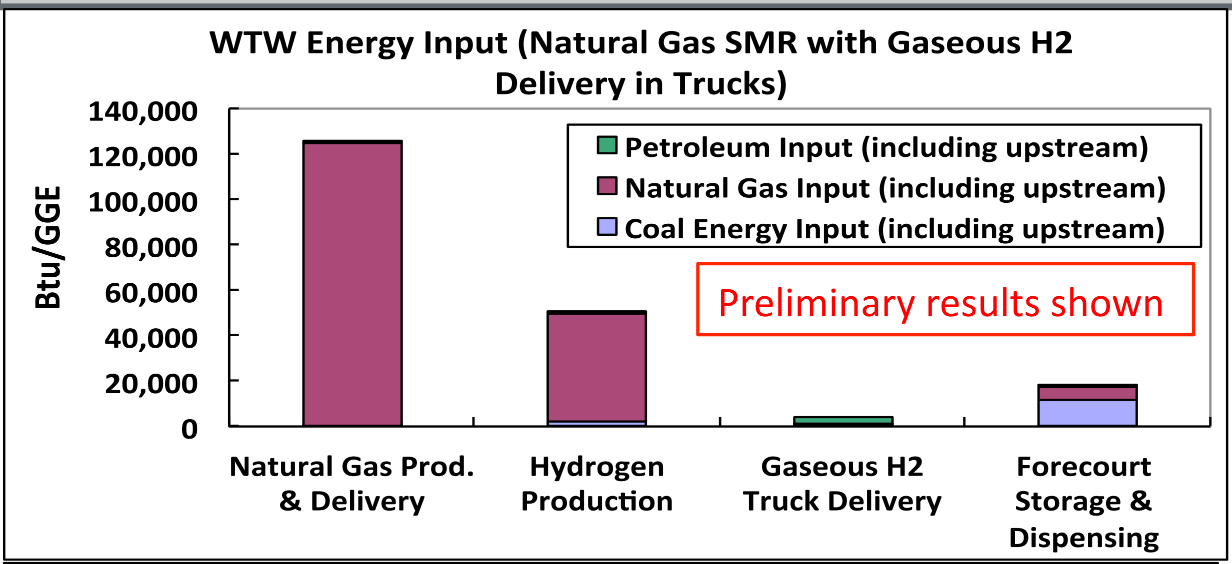
Preliminary results shown

Central natural gas reformation with gaseous truck delivery example

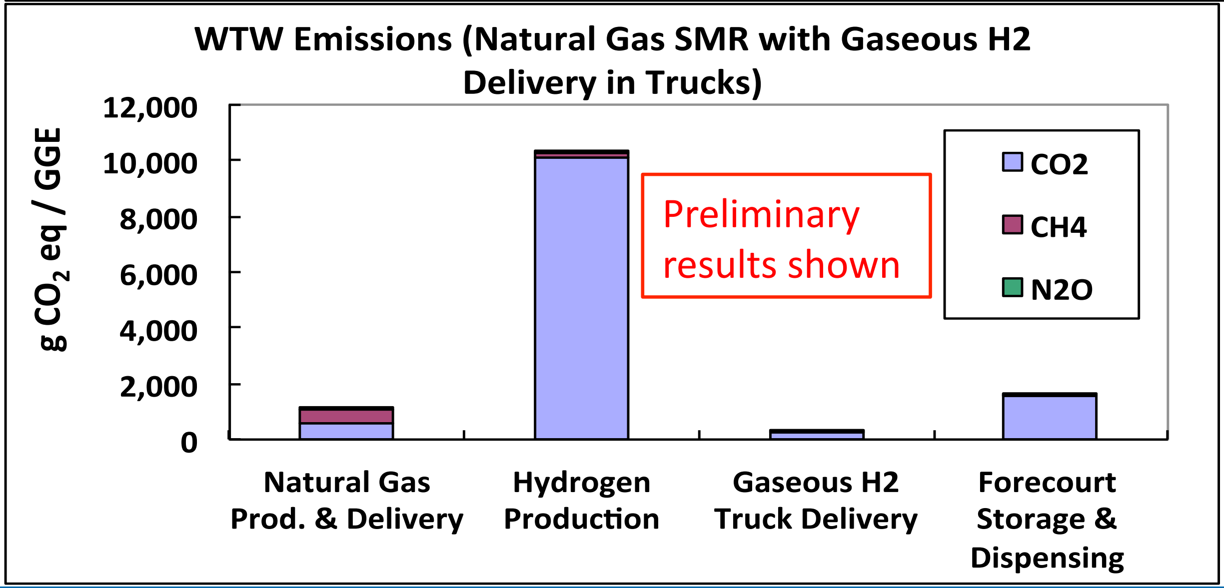


WTW Energy and Emission Results

Hydrogen production accounts for most fuel-cycle GHG emissions



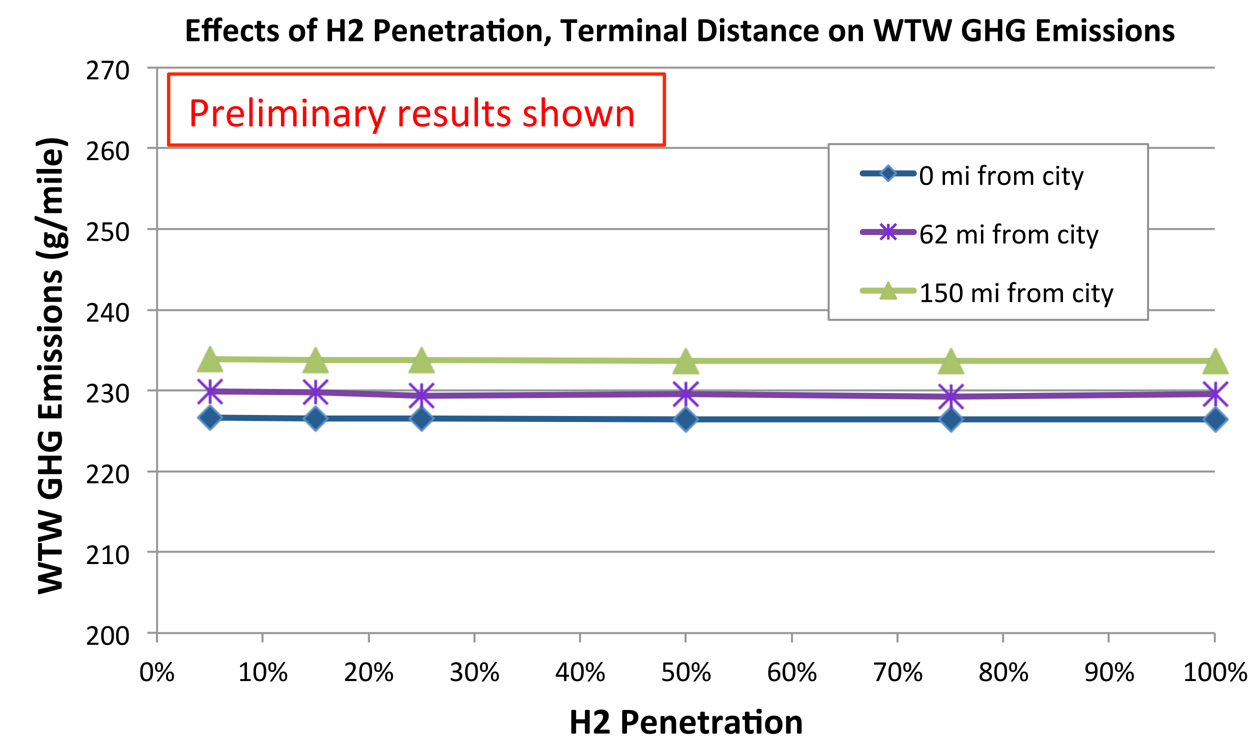
Central natural gas reformation with gas truck delivery example



Similar results available for all future technology H_2 pathways

Detailed Sensitivity Results

Sensitivity analysis show that GHG emissions do not significantly change due to delivery distance (<150 mile) or grid mix in gas truck delivery pathway



Central natural gas reformation with gas truck delivery example

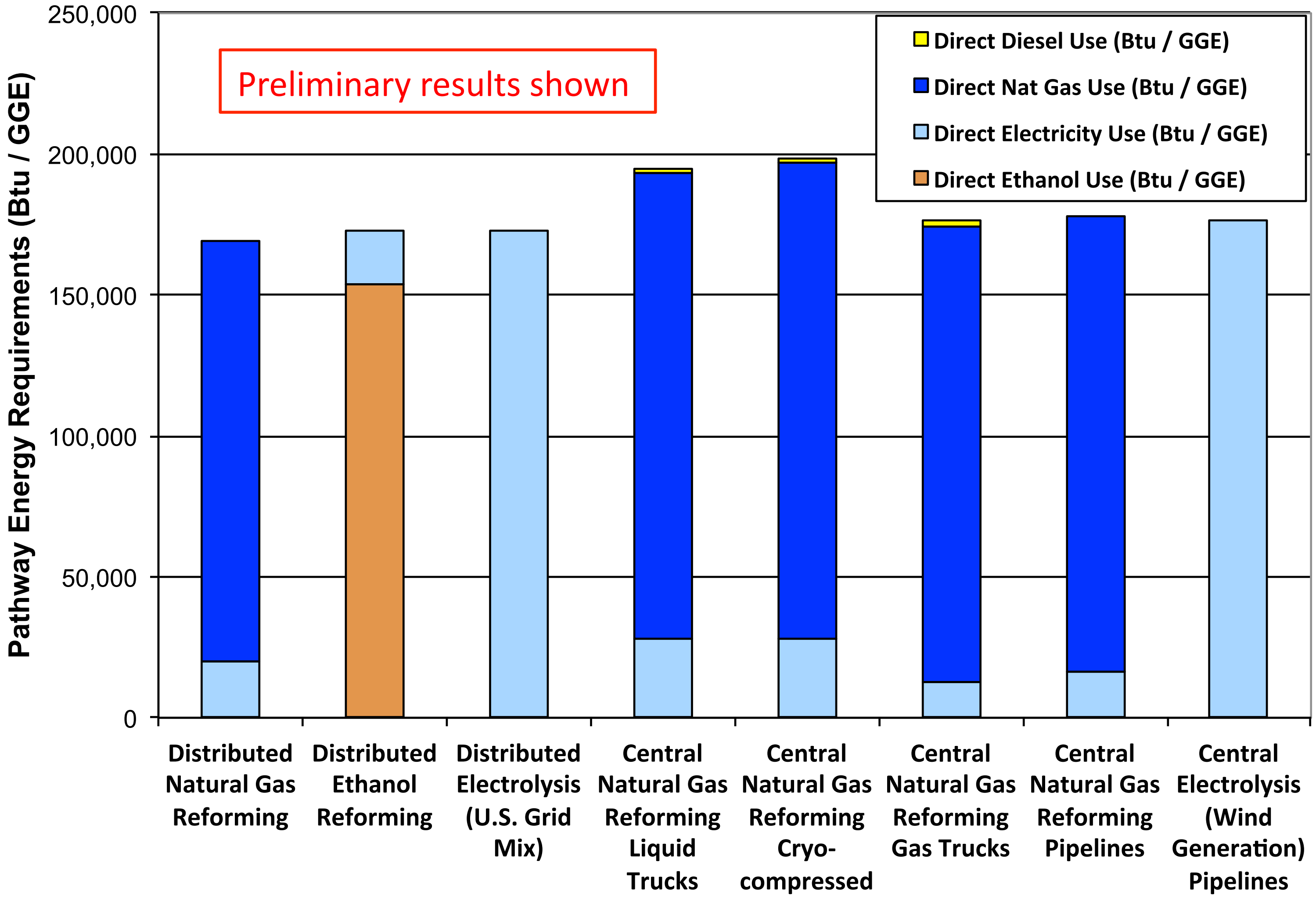
Central Natural Gas Reformation with Gas Truck Delivery Case	U.S. Average Grid Mix (58 mpgge)	U.S. Average Grid Mix (68 mpgge)	"Green" Grid Mix (58 mpgge)
WTW GHG Emissions (g/mile)	230	200	200
WTW Fossil Energy (Btu/mile)	3,400	2,900	3,000
WTW Petroleum Energy (Btu/mile)	70	60	60
WTW Total Energy (Btu/mile)	3,500	3,000	3,300

Detailed sensitivity analyses (conducted for all pathways) investigate the effect of such parameters as:

- Feedstock cost and usage
- Process efficiency
- Capital and O&M costs
- Electric grid mix (low carbon electric grid)
- FCEV fuel economy and market penetration
- Hydrogen delivery distance, station size, and city population

Pathway Energy Use Results

Distributed pathways use the least total energy (no delivery energy); liquid hydrogen delivery pathways use the most energy



8 Pathways Analyzed:

3 Forecourt

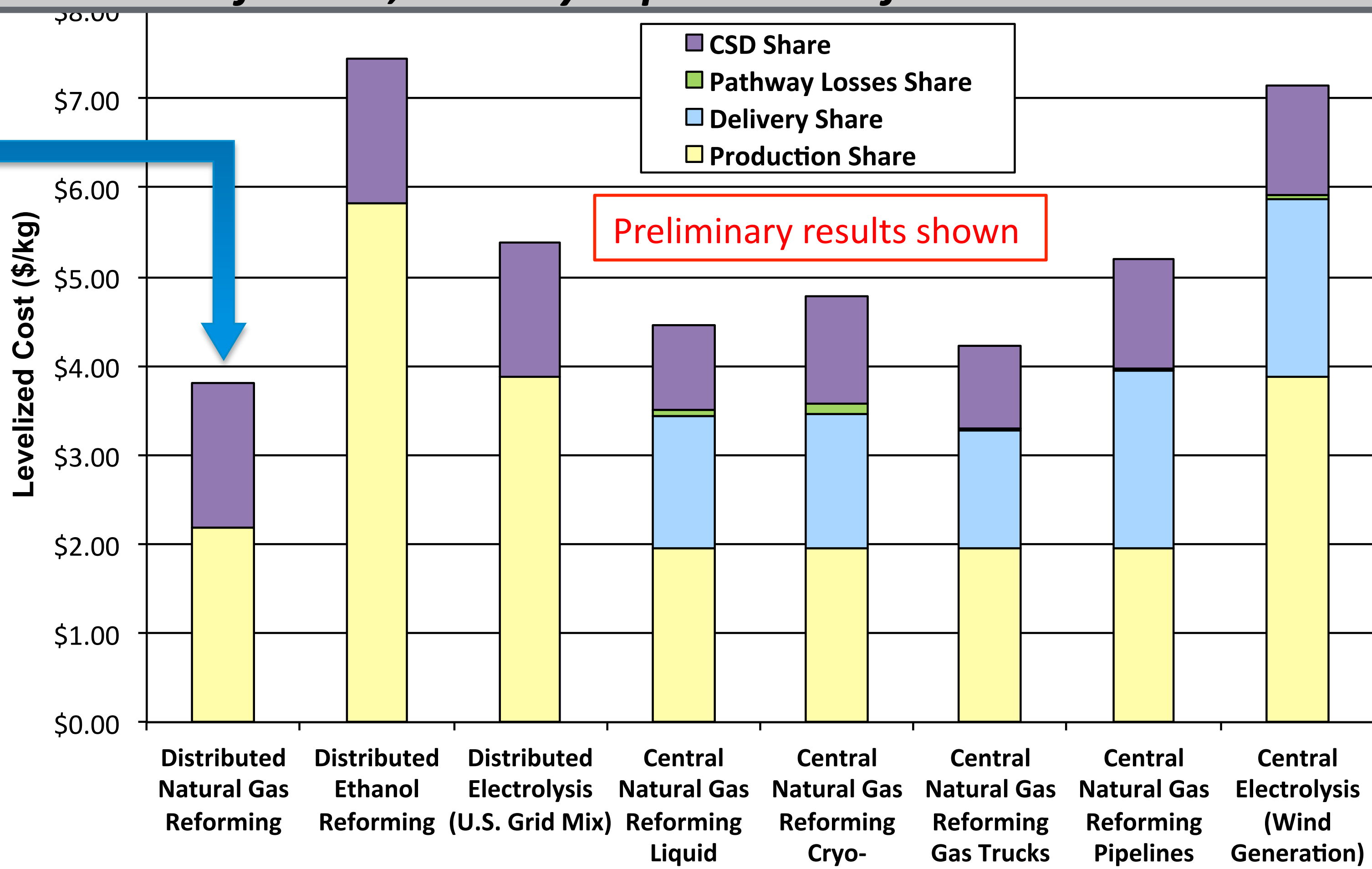
5 Central

4 Natural gas cases showing all delivery types

H2 Cost Breakdown Results

$2-4 cost target can be met with distributed natural gas pathway; need further R&D to reduce costs for CSD, delivery & production from renewables

Distributed natural gas is the lowest cost pathway ($3.80/kg)

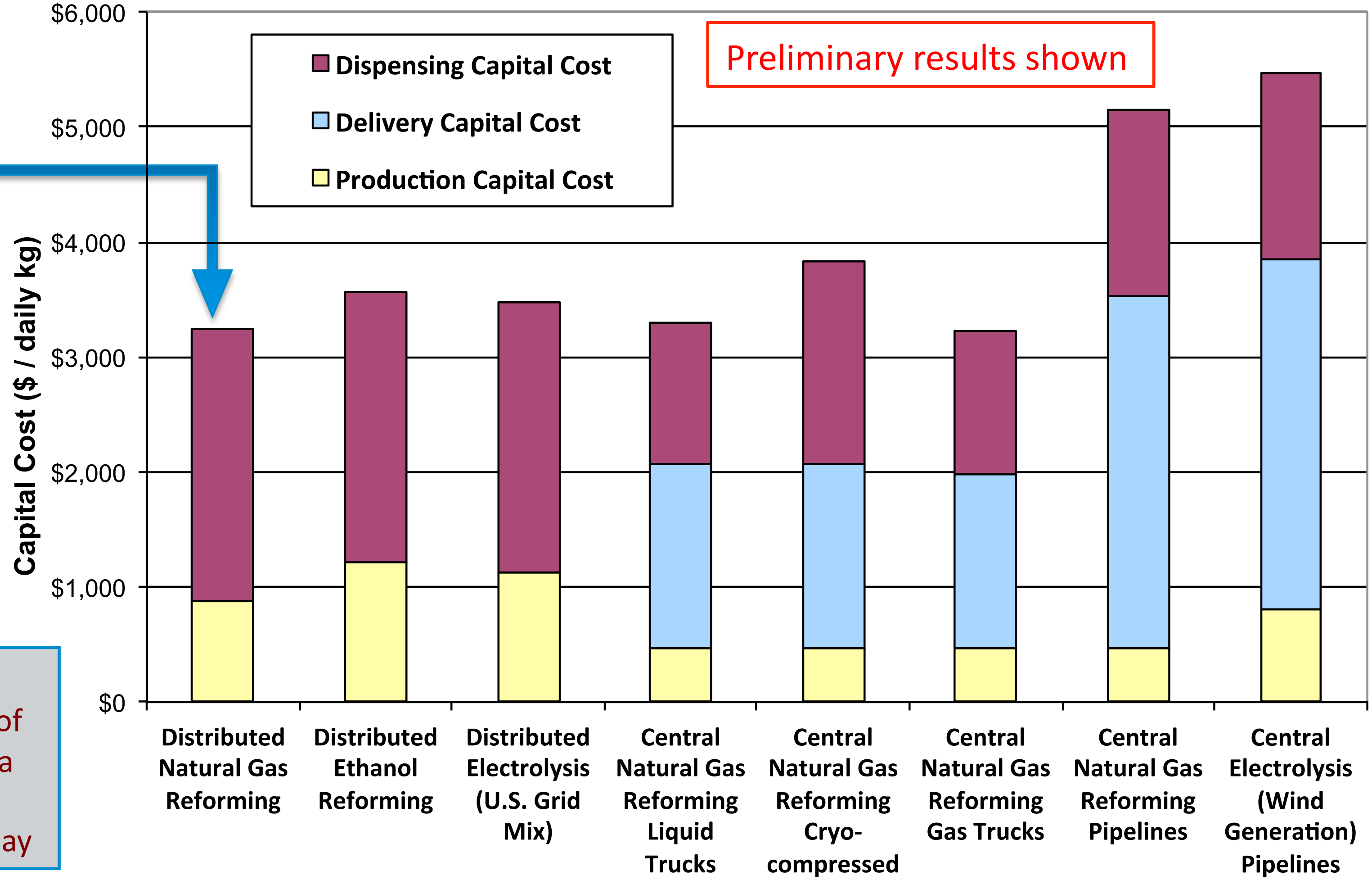


- Natural gas pathways can meet production target of $2/kg (deployed in a mature market)
- Combined CSD and delivery costs remain a challenge, further research is required

Pathway Capital Cost Results

Total capital costs are an important hurdle reflecting the investment needed for a FCEV market -- >$200M of capital investment per 100,000 FCEVs

$3,200 / daily kg capital cost means $3.2M for a 1000 kg/d station

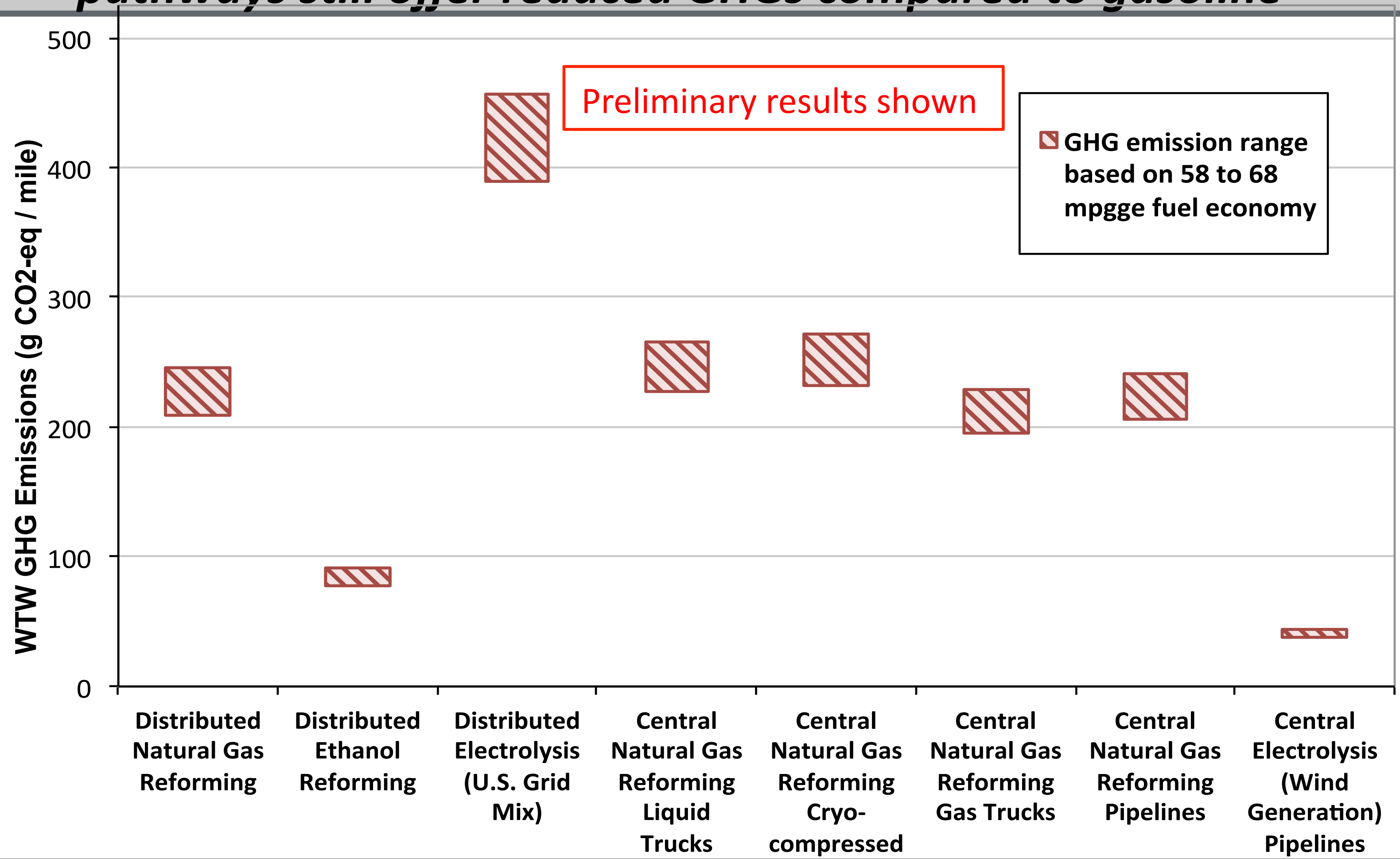


Note: At a 58 mpgge fuel economy, a fleet of 100,000 FCEVs needs a hydrogen supply of about 70,000 kg per day

All pathways have significant delivery & CSD capital requirements

Pathway WTW GHG Emissions Results

Renewable pathways offer the lowest GHG emissions, but natural gas pathways still offer reduced GHGs compared to gasoline

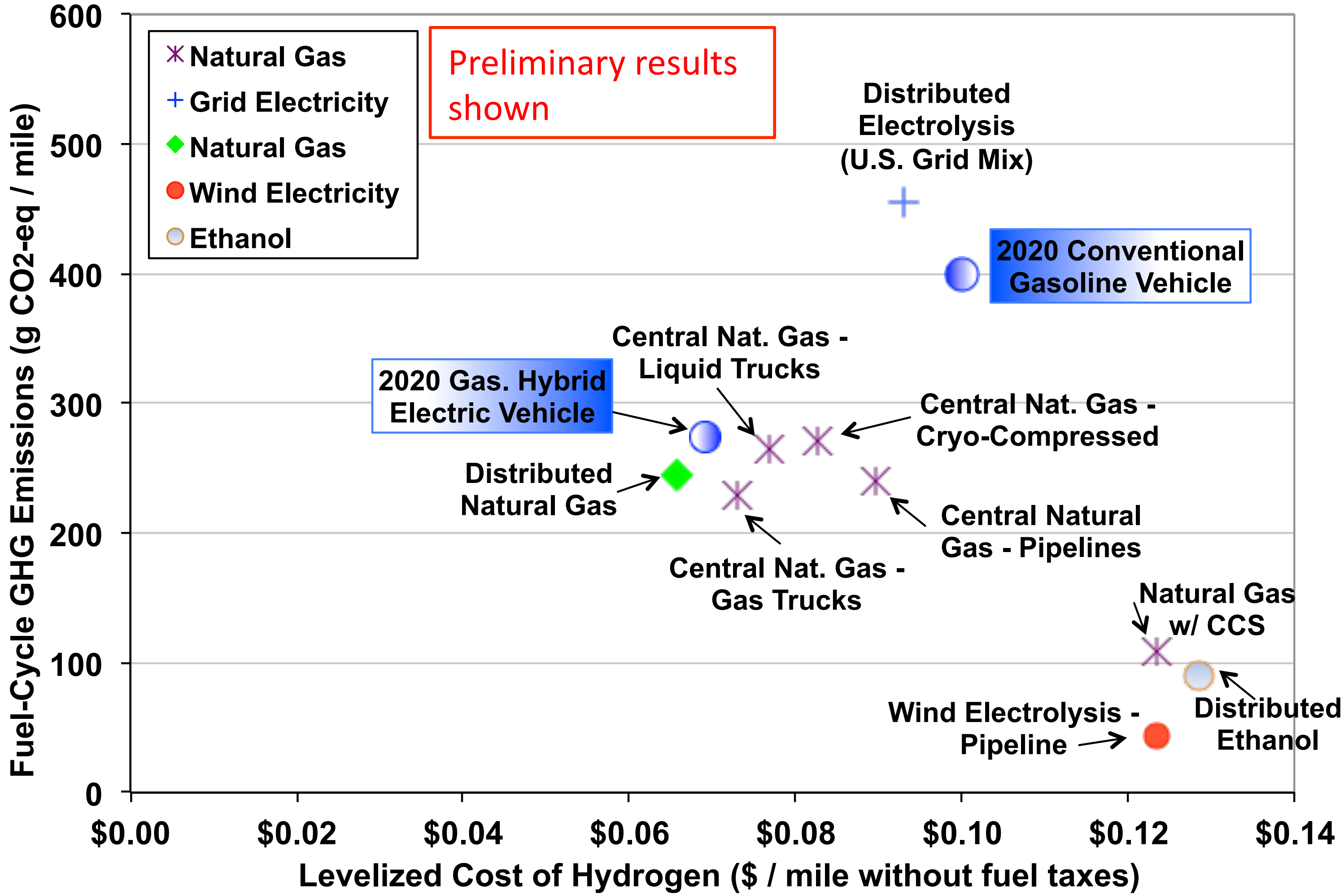


- **Electrolysis emissions depend on grid mix** (wind electricity vs U.S. mix)
- **Liquid hydrogen delivery has higher GHG emissions** due to liquefaction energy required

Pathway GHG vs Fuel Cost Results

FCEVs show promise over HEVs, but more R&D is needed to lower costs/GHG

58 mpgge fuel economy results

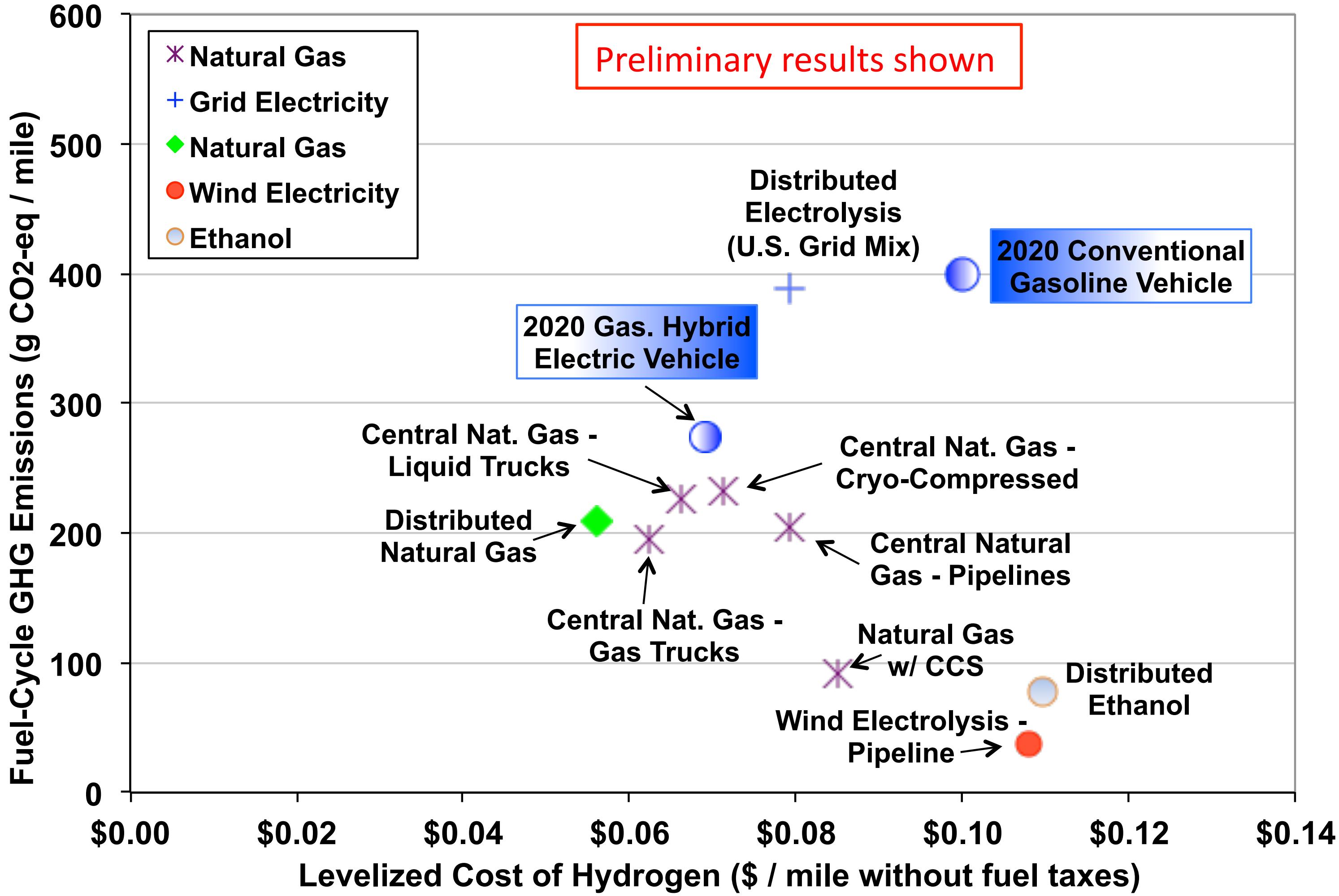


- H_2 from distributed natural gas reformation has better cost & GHG emissions vs. gasoline HEV
- All pathways except one have lower GHG emissions than HEVs, but cost remains an issue

Pathway GHG vs Fuel Cost Results

At 68 mpgge, several H_2 pathways have lower costs & GHGs than HEVs

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

Future Technology Hydrogen Pathways	• Conduct electrolysis pathway analyses using recently published H2A cases on PEM electrolysis • Revise and publish report on future technology hydrogen pathways (companion to published current technologies pathway report)
FY14 Pathways Work	• Complete initial analysis of emerging hydrogen production technology pathways (photo-electrochemical, photo-biological, solar thermo-chemical) • Complete initial analysis of central natural gas reformation with carbon capture and sequestration, including deeper investigation into CCS costs • Conduct initial analysis of central natural gas reformation with high-pressure gas truck delivery, based on latest HDSAM modeling from Argonne and data from recent independent panel report on station CSD costs
Potential Future Work *(funding dependent)*	• Develop and publish report on advanced and emerging hydrogen production, delivery and dispensing pathways • Conduct pathway analyses of additional emerging technology pathways (high-temperature electrolysis, natural gas reformation with combined heat and power considerations, etc.)

Project Summary

Hydrogen Pathways Analysis Project Summary	
Approach	Conduct lifecycle analyses of complete future-technology hydrogen production, delivery and dispensing 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 DOE H_2 component models through industry review • Understand lifecycle costs, energy & emissions of H_2 technologies to inform R&D
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 & H_2 component models • Detailed hydrogen cost and capital costs developed for future H_2 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 Pathway Integration Technical Team
Future Work	• Conduct companion pathway analyses of additional hydrogen pathways, including emerging and renewable feedstock technologies • Use evaluations to assist in component model improvements and R&D needs

Questions & Discussion

THANKS!

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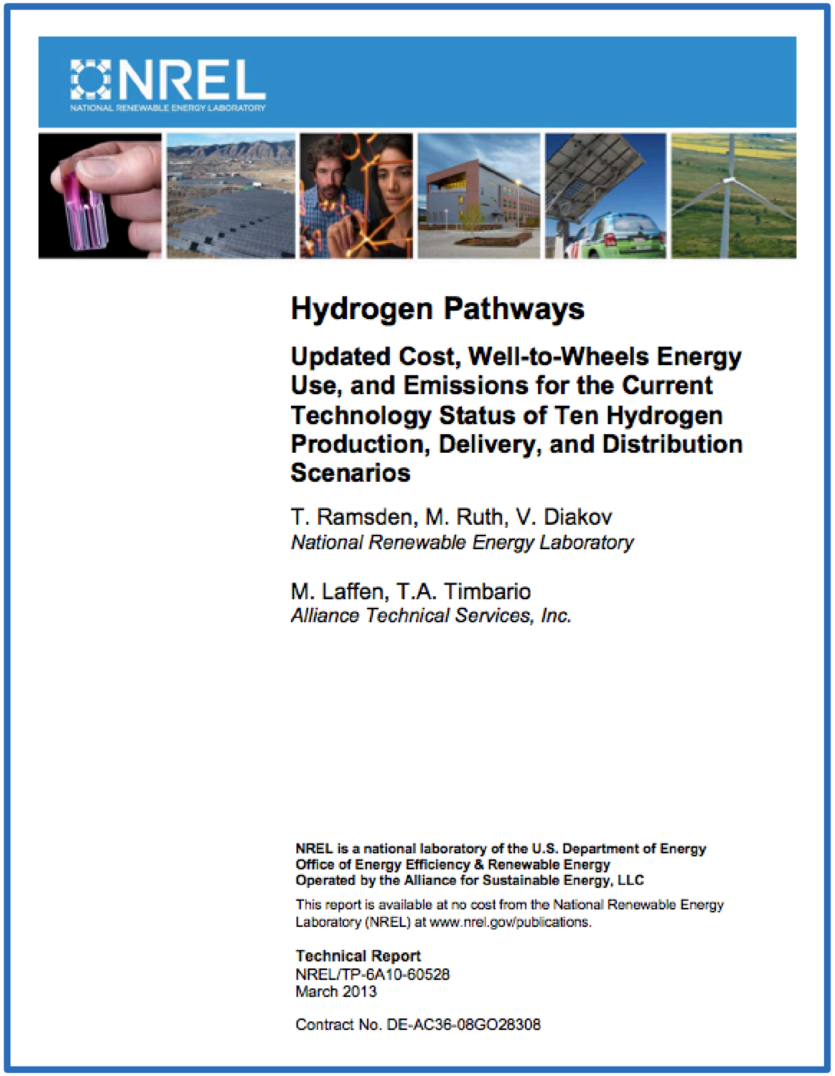

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NREL/TP-6A10-60528
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Contract No. DE-AC36-08GO28308

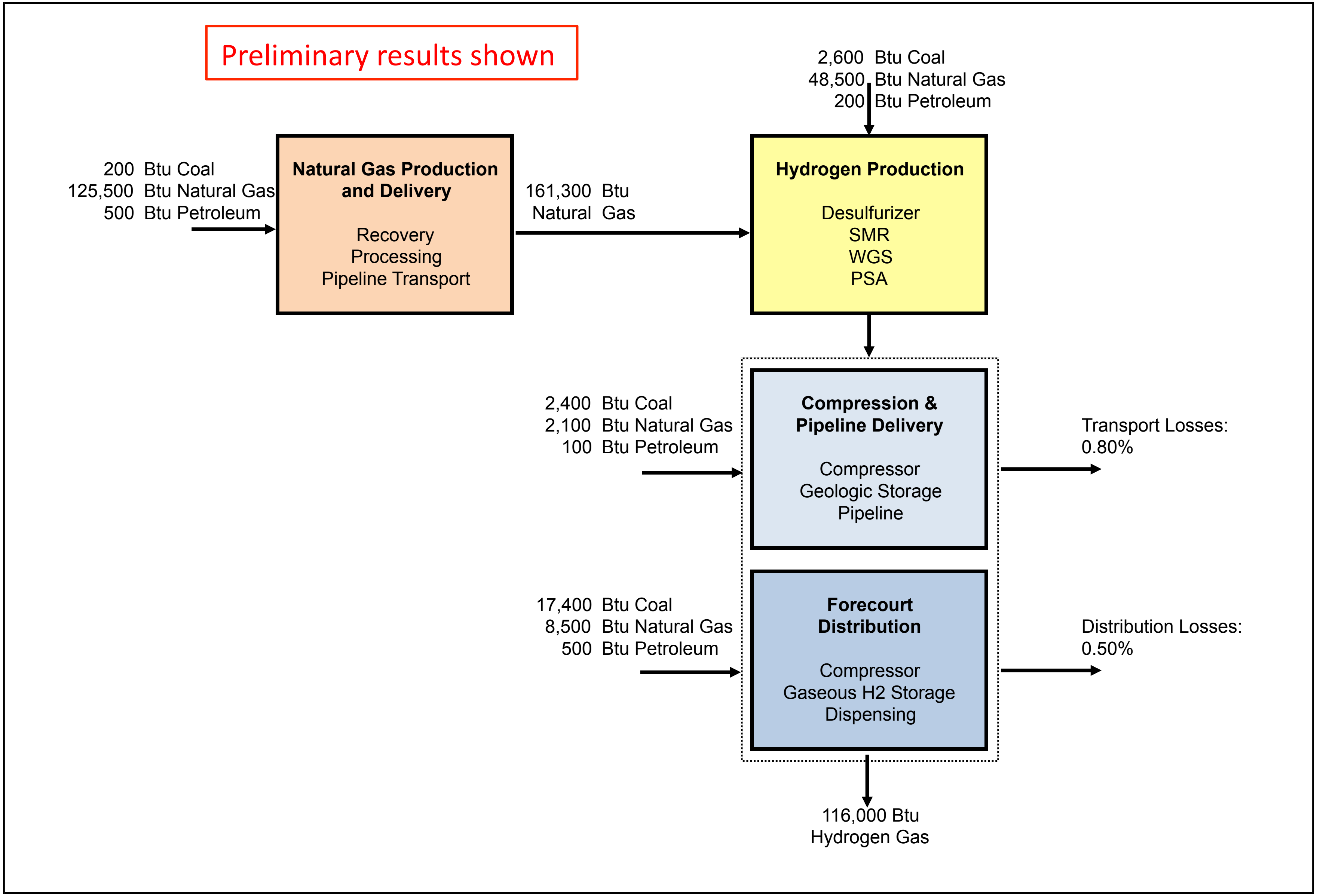
Current technologies report available at:
http://www.nrel.gov/docs/fy14osti/60528.pdf

BACK-UP SLIDES

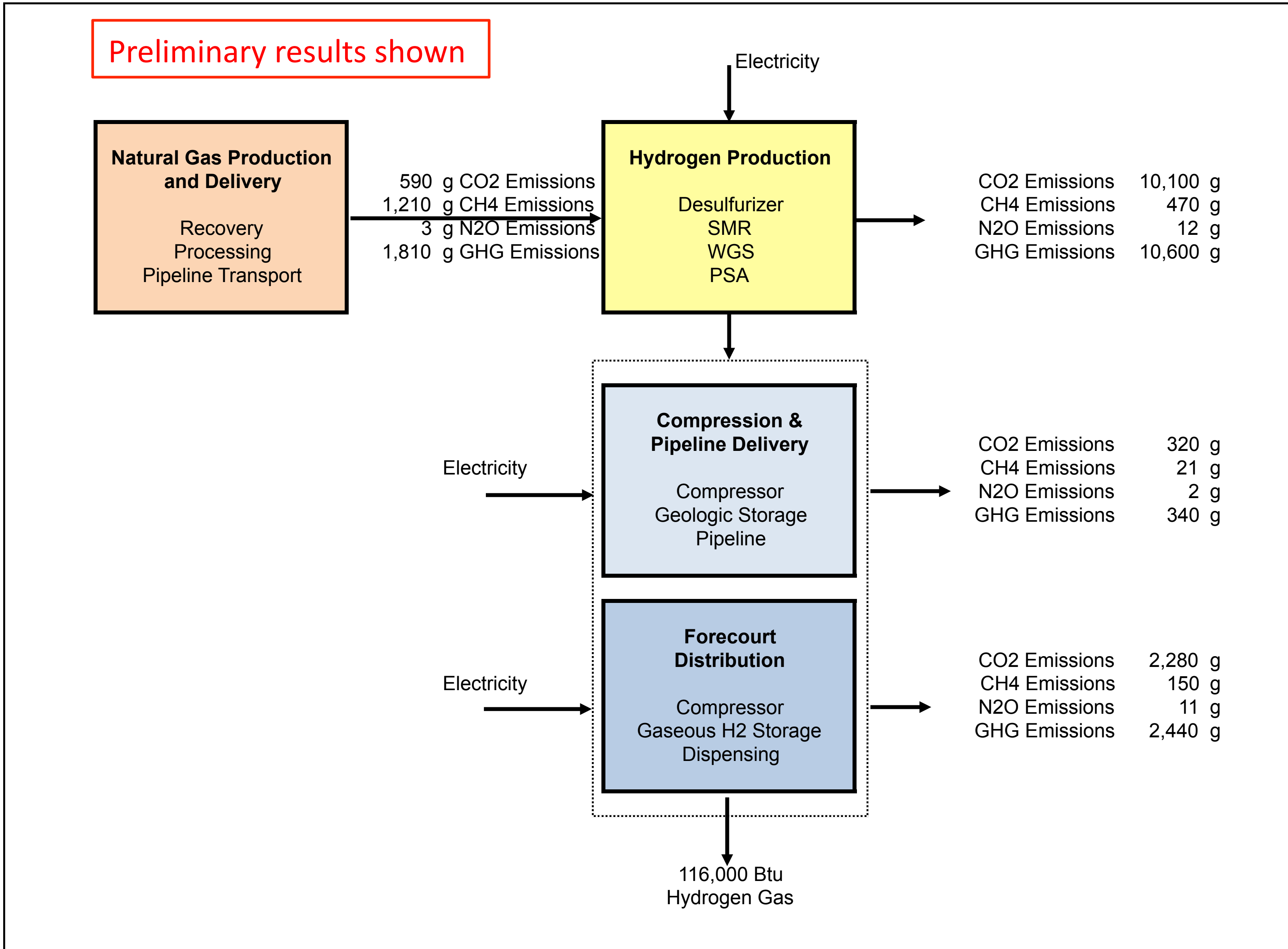
Acronyms

AEO	DOE Energy Information Agency's Annual Energy Outlook
CCS	Carbon Capture and Sequestration
CSD	Compression, Storage & Dispensing
DOE	U.S. Department of Energy
FCEV	Fuel Cell Electric Vehicle
FCTO	DOE's Fuel Cell Technologies Office
FPITT	U.S. DRIVE Fuel Pathway Integration Technical Team
GHG	Greenhouse Gas
GREET	Greenhouse gas, Regulated Emissions & Energy in Transportation model
H_2	Hydrogen
H2A	DOE's H2A ("hydrogen analysis") Production model
HEV	Hybrid Electric Vehicle
HDSAM	DOE's Hydrogen Delivery Scenario Analysis Model
HyARC	Hydrogen Analysis Resource Center
MPGGE	Miles per gallon gasoline equivalent
NREL	National Renewable Energy Laboratory
SNL	Sandia National Laboratory
U.S. DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency Partnership
VMT	Vehicle Miles Traveled
WTW	Well-to-Wheels (i.e., fuel-cycle)

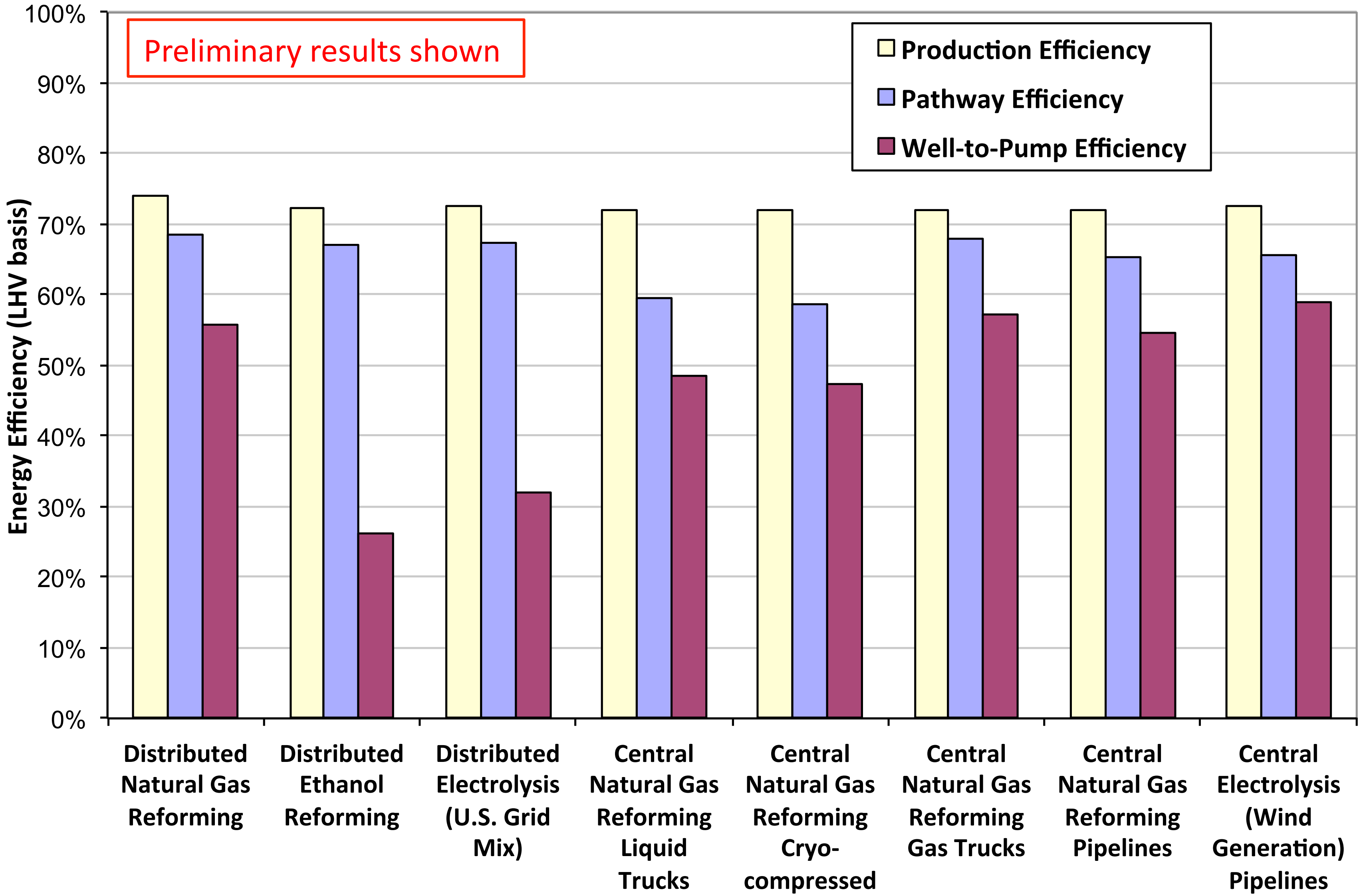
Fuel-Cycle Energy Summary – Block Diagram (Example)



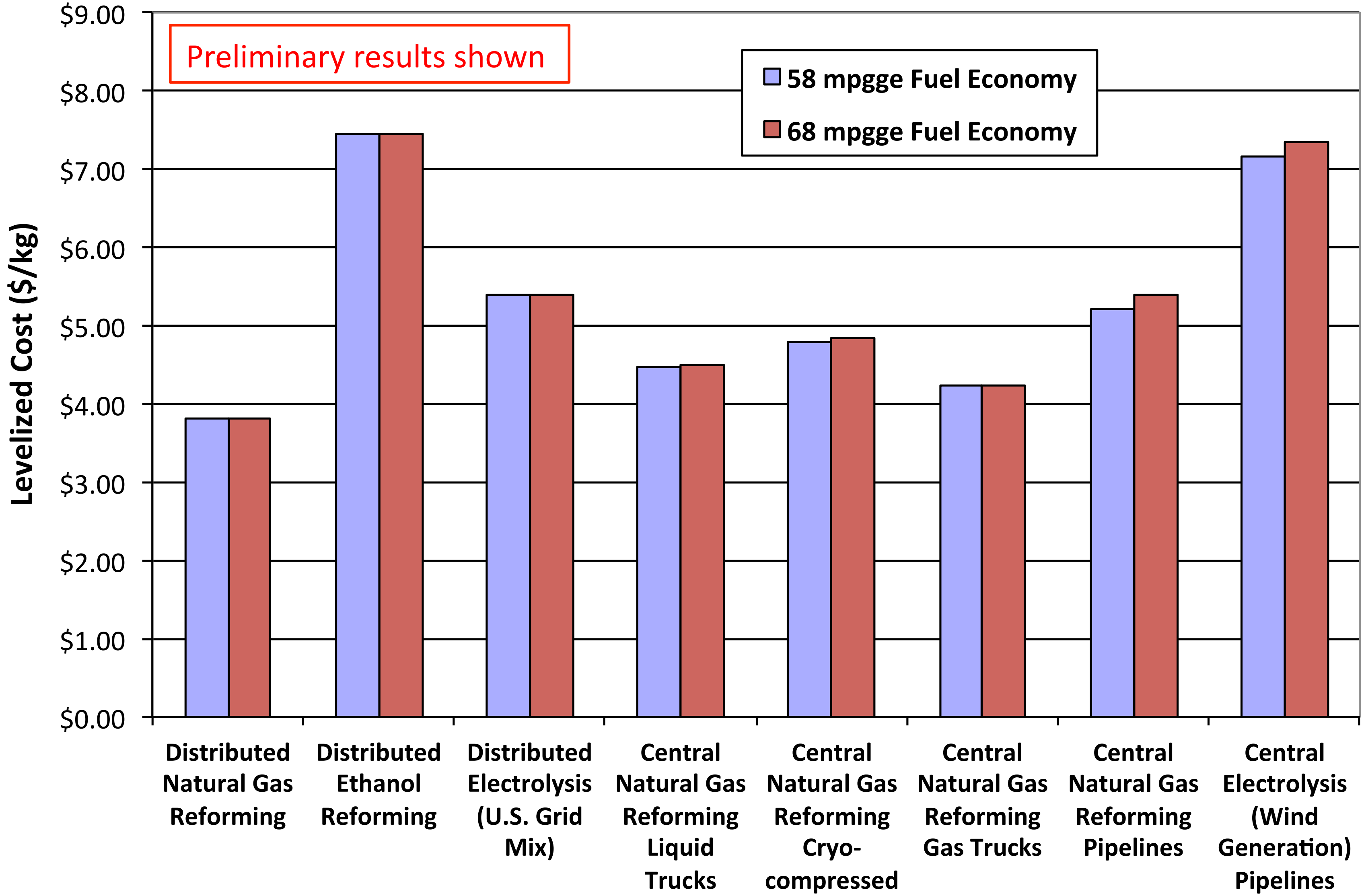
Fuel-Cycle GHG Summary – Block Diagram (Example)



Comparative Results – Efficiency



Comparative Results – H2 Cost at 58 vs 68 mpgge



Comparative Results – H2 Production Cost