SA-036

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

2015 U.S. DOE Hydrogen and Fuel Cells Program and Vehicle Technologies Office Annual Merit Review and Peer Evaluation Meeting

Washington, DC

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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: March 2014
- Finish: September 2015
- 70% Complete

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

Budget

- Total Funding: $130K
  - 100% DOE funded
- FY14 Funding: $40K
- FY15 Funding: $90K

Note: Budget addresses only the emerging-technologies pathway analysis; completed future- and current-technologies analyses funded at $310K during FY12-14

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 Objectives and Relevance

Hydrogen Pathways Analysis Project Objectives	
Lifecycle evaluation of complete H_2 production, delivery & dispensing pathways	• Determine cost, energy use, and greenhouse gas (GHG) emissions of H_2 fuel pathways, deployed in a mature market • Provide detailed reporting of hydrogen cost and capital costs of complete H_2 fuel pathways to support fuel cell electric vehicles (FCEVs) • Lifecycle reporting of energy & feedstock usage and GHG emissions

Relevance	
Evaluate the potential of various hydrogen fuel pathways	• Evaluate the potential of various hydrogen production, delivery, and dispensing configurations to meet DOE's $4/kg cost target • Evaluate pathways to understand associated energy use and GHG emissions
Consistent and transparent analysis of hydrogen technologies	• Common modeling platform and assumptions with detailed reporting of input parameters and results allows for cross-pathway comparisons • Helps DOE overcome stove-piped analysis and inconsistent data by providing a modeling framework using published DOE component models
Assist in R&D decisions	• Helps assist DOE's Fuel Cell Technology Office (FCTO) in goal setting and R&D decisions by providing detailed understanding of technologies • In-depth analysis of pathways provides insight into cost drivers
Industry review and model improvement	• Industry review of input parameters and results helps validate and improve the MSM and the associated component models • In-depth reviews help determine modeling gaps, inconsistencies & concerns

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 (MSM)
- H2A Production
- HDSAM
- GREET 1 fuel cycle
- GREET 2 vehicle cycle
- Vehicle Cost Per Mile tool

Studies & Analysis

Cost, Energy Use & Emissions of H_2 Production & Delivery Pathways

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

Outputs & Deliverables

- Pathway Reports
- Pathway input & output spreadsheets

Detailed understanding of H_2 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
US DRIVE FPITT

NREL, DOE Fuel Cell Technologies Office & US DRIVE 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 (nominally 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

Pathways Analyzed in 2014/2015

8 future-technology production, delivery & dispensing pathways completed in FY2014; analysis of 4 emerging technology pathways in FY2015

Future technology pathways (analysis completed as of 2014 AMR): i–viii

Emerging technology pathways (results reported below): 1–4

	Production Feedstock / Technology	Delivery Mode	Dispensing Mode
i	*Natural Gas Reforming*	*Distributed Prod.*	*700 bar*
ii	*Ethanol Reforming*	*Distributed Prod.*	*700 bar*
iii	*Grid Electrolysis*	*Distributed Prod.*	*700 bar*
iv	*Central Natural Gas Reforming*	*Pipeline*	*700 bar*
v	*Central Natural Gas Reforming*	*Gaseous Truck*	*700 bar*
vi	*Central Natural Gas Reforming*	*Liquid Truck*	*700 bar*
vii	*Central Natural Gas Reforming*	*Liquid Truck*	*Cryo-compressed*
viii	*Central Wind Electrolysis*	*Pipeline*	*700 bar*
1	**Central Natural Gas Reforming w/CCS**	**Pipeline**	**700 bar**
2	**Central Photo-Biological H2**	**Pipeline**	**700 bar**
3	**Central Photo-Electrochemical H2**	**Pipeline**	**700 bar**
4	**Central Solar Thermo-Chemical H2**	**Pipeline**	**700 bar**

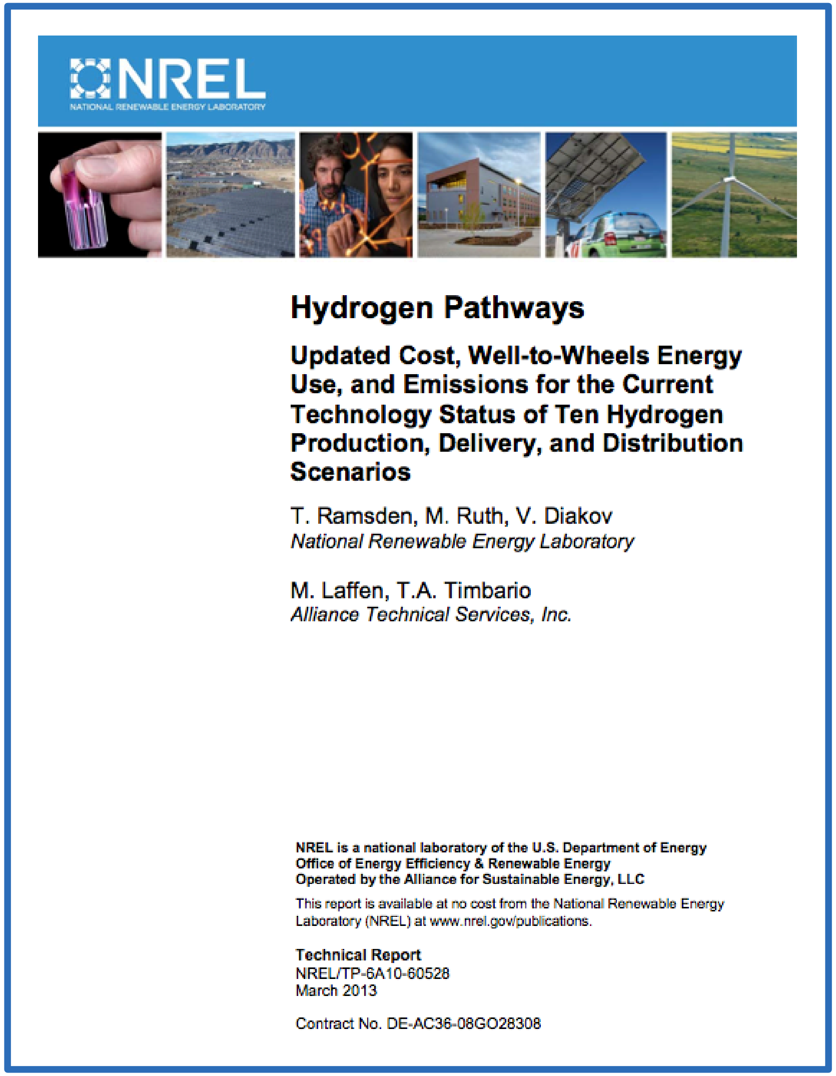
[CCS = Carbon capture and sequestration]

Future Technologies Pathway Evaluation Completed

Report on pathways evaluation of future technologies completed (under DOE review); Current technologies report published in 2014 (available on-line)

- Lifecycle cost, energy use and GHG emissions evaluation of 8 future-technology hydrogen production, delivery and dispensing pathways completed in FY 2014 (results presented at 2014 AMR)
- Future-technologies report completed (under review)
- Lifecycle cost energy use and GHG emissions evaluation of 10 current-technologies hydrogen pathways completed in FY 2013
- Current pathways 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
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Technical Report
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March 2013

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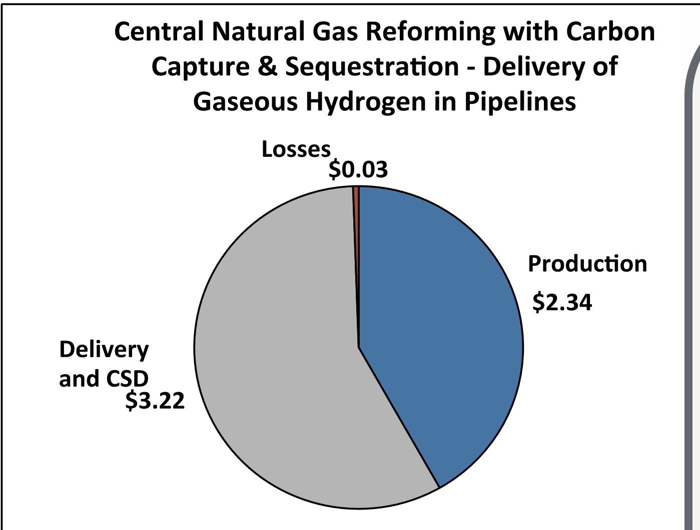
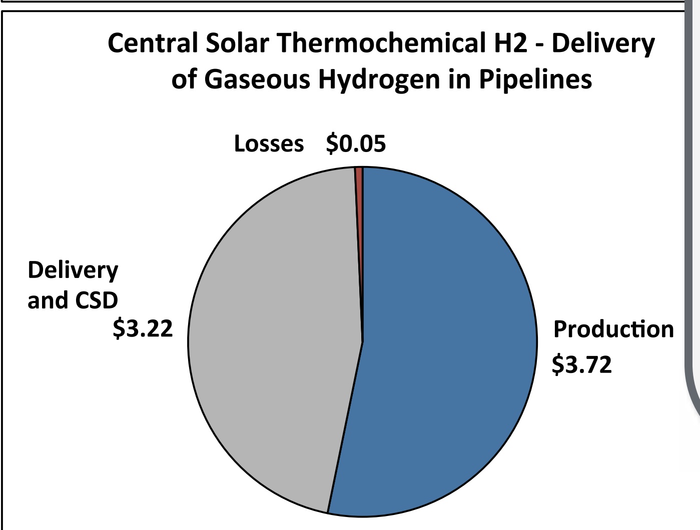
Dispensed H_2 Cost Results – Production & Delivery

Current modeling of emerging-technology pathways finds H_2 costs exceeding the $4/kg target; further R&D is needed, especially for renewable paths





Central H_2 Production Costs

Natural Gas SMR w/CCS:
$2.34/kg

Photo-electro-chemical:
$4.56/kg

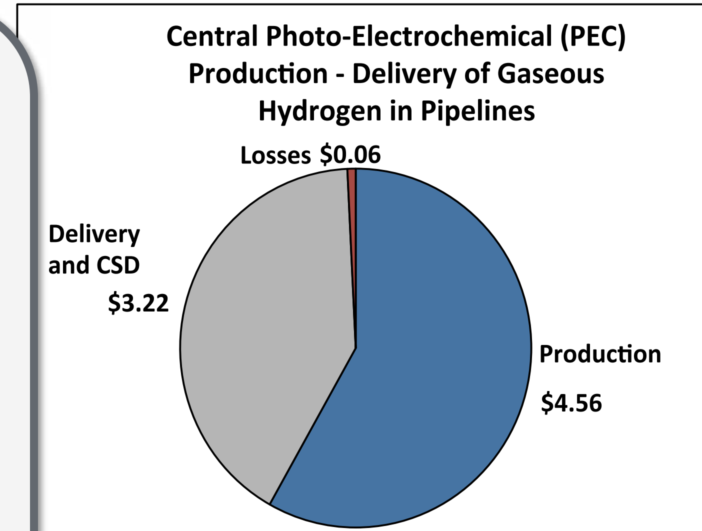
Solar Thermo-chemical:
$3.72/kg

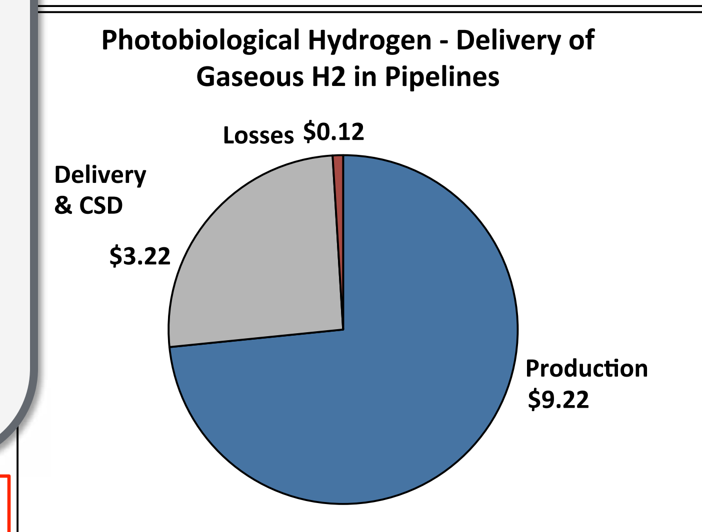
Photo-biological:
$9.22/kg

Pipeline Delivery and CSD Costs

$3.22/kg

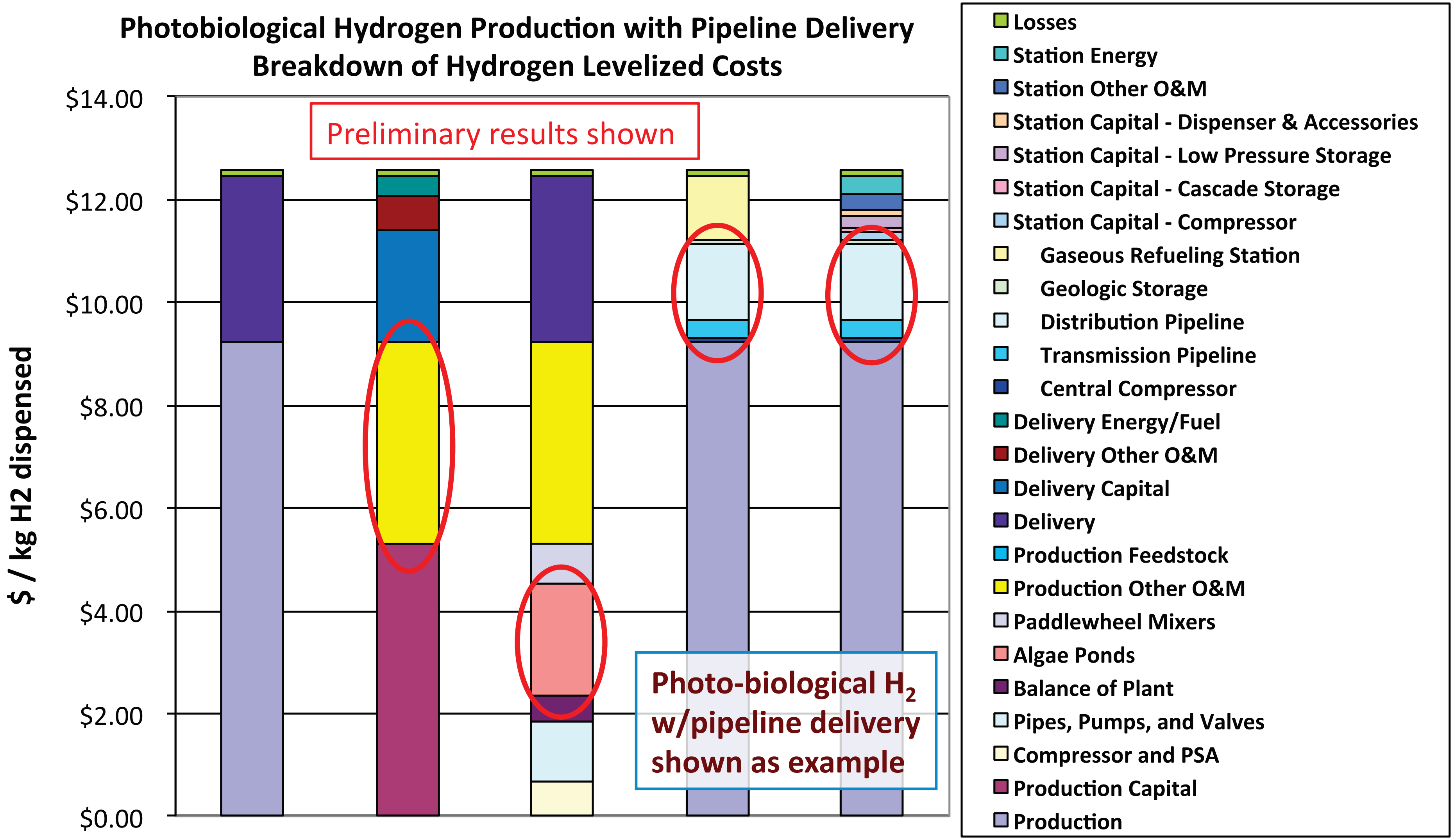
Preliminary results shown





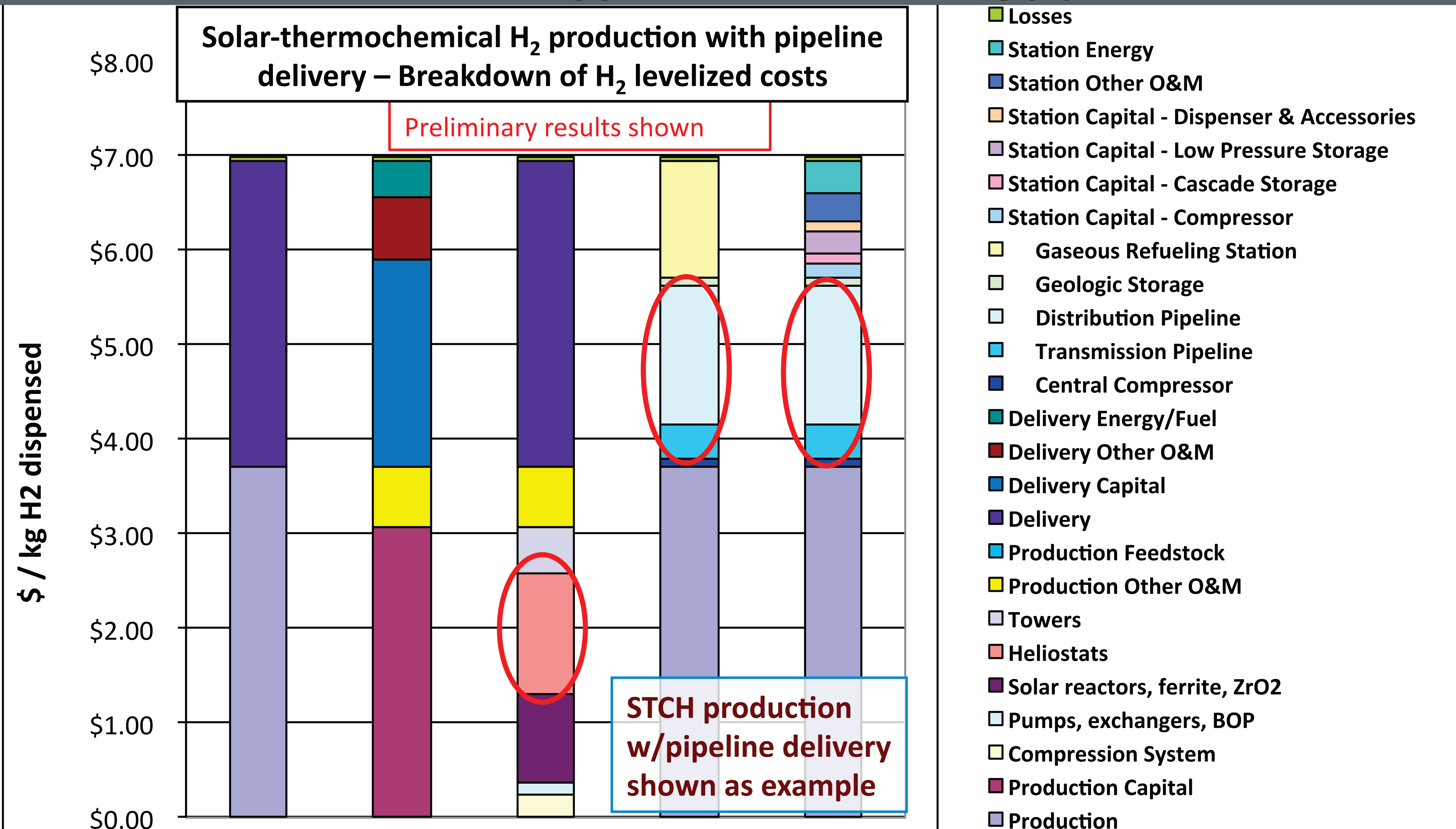
Dispensed H_2 Cost Results – Breakdown

Detailed H_2 cost breakdown provides insight to major costs. Photo-biological cost drivers include: $2/kg for algal ponds, ~$4/kg O&M, $1.80kg pipelines



Dispensed H_2 Cost Results – Breakdown

Detailed H_2 cost breakdown of solar-thermochemical path. Cost drivers include: \$1.30/kg for heliostats, \$1.80kg pipelines

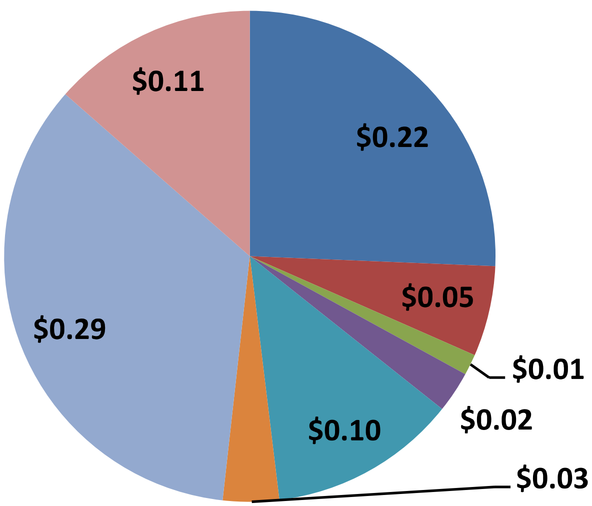


Total Cost Per Mile Results – Vehicle & Fuel

H_2 fuel costs represent 15-25% of ownership costs for emerging technologies; FCEV depreciation & financing represent ~50% or more of costs

Photo-biological H_2 production, with pipeline delivery

Total FCEV Ownership Costs for a 5-year ownership period
($/mile, not discounted)

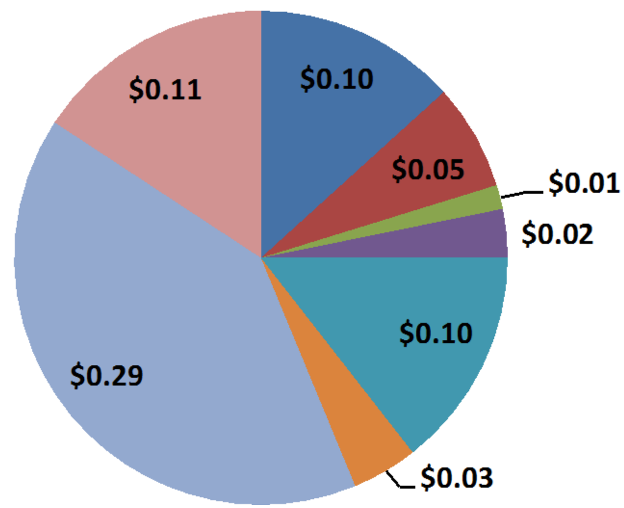


Total Ownership Cost: $0.84/mile
Hydrogen Fuel Cost: $0.22/mile

Preliminary results shown

Natural Gas SMR w/CCS, with pipeline delivery

Total FCEV Ownership Costs for a 5-year ownership period
($/mile, not discounted)

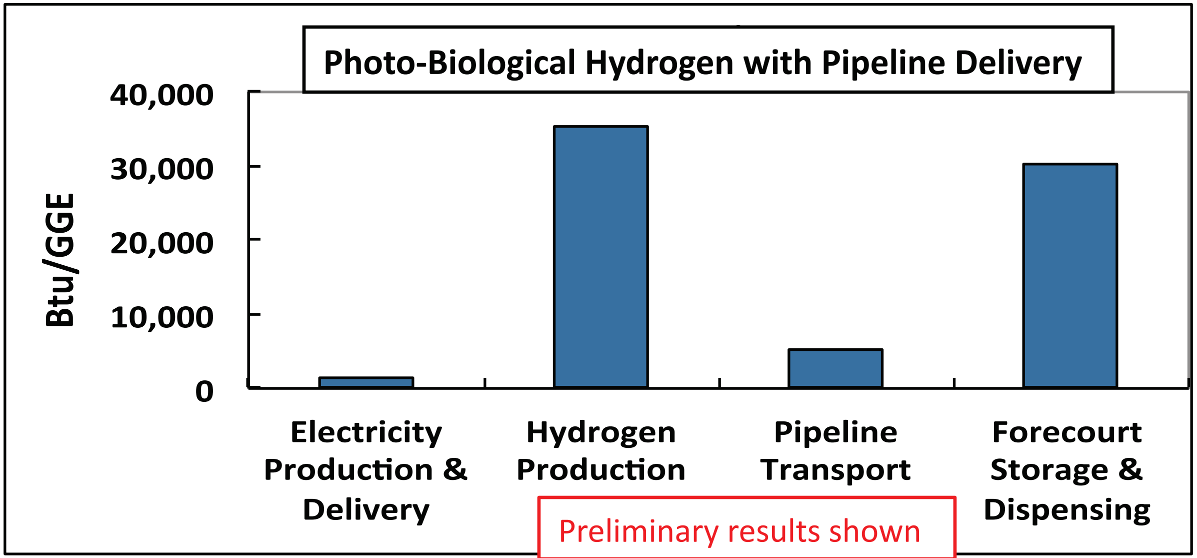


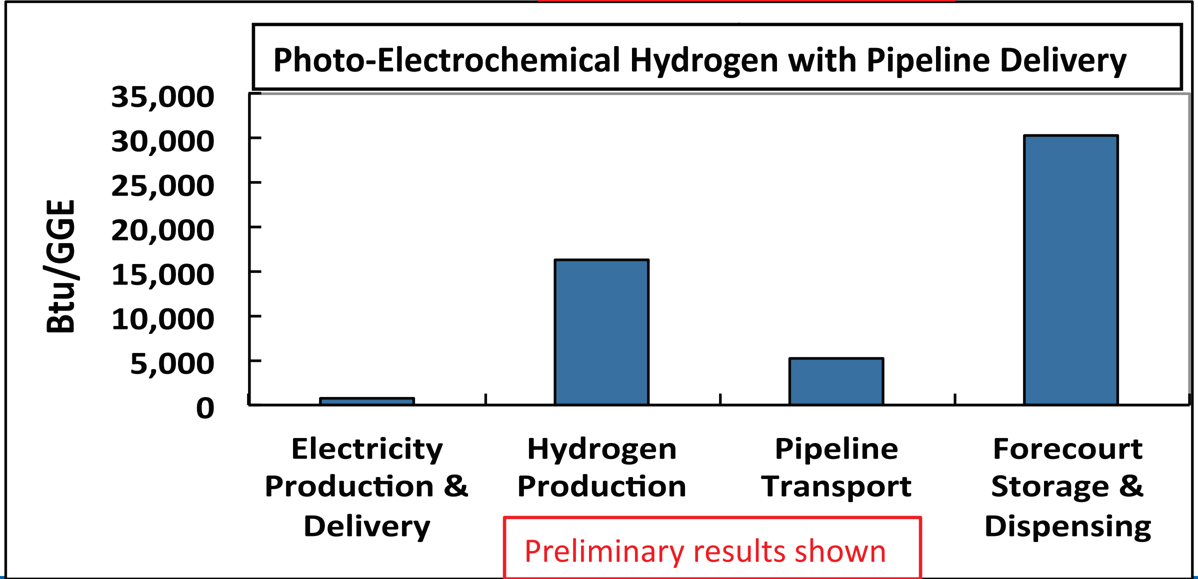
Total Ownership Cost: $0.72/mile
Hydrogen Fuel Cost: $0.10/mile

Similar results available for Photo-Electrochemical & Solar Thermo-Chemical H_2 pathways

Well-to-Wheels Energy Results

Low production energy for renewable pathways (some grid electricity used)





Well-to-Wheels Total Energy

(not including renewable production feedstocks)

Natural Gas SMR w/CCS:

225,000 BTU/gge

Photo-electro-chemical:
52,000 BTU/gge

Solar Thermo-chemical:

35,000 BTU/gge

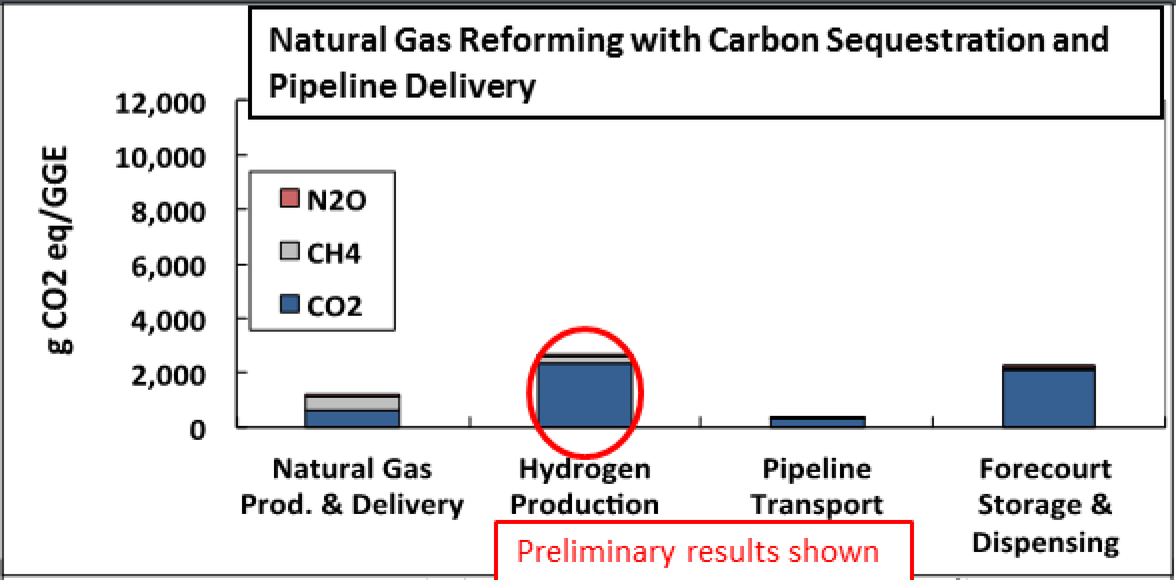
Photo-biological:
72,000 BTU/gge

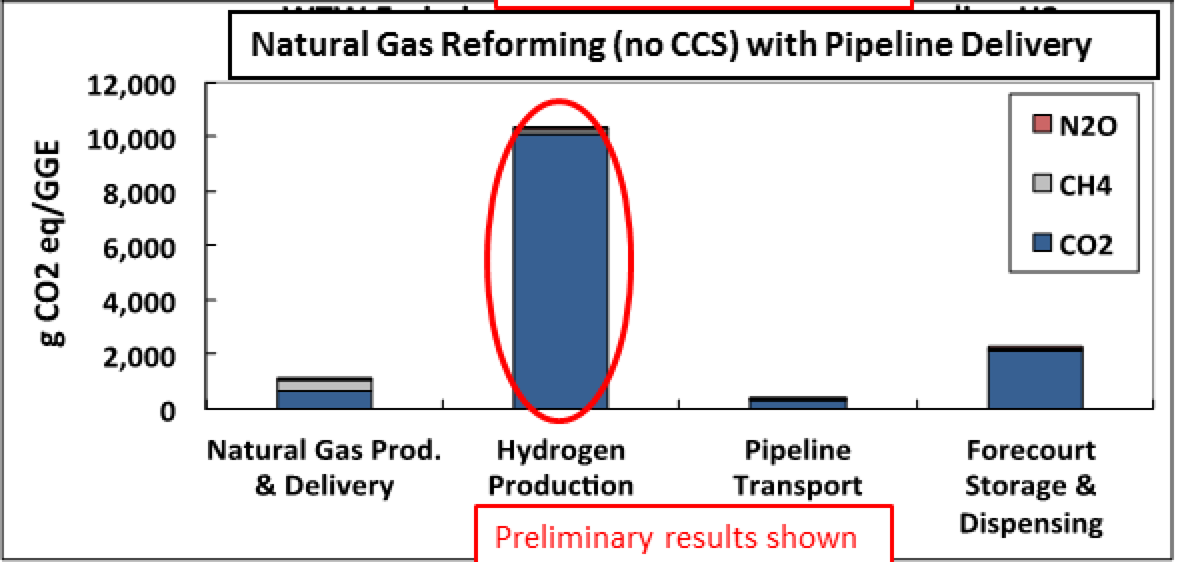
Initial results based on pathway electricity, natural gas, and petroleum energy use – No specific GREET cases

Similar results available for SMR w/CCS & Solar Thermo-chemical H_2 pathways

Well-to-Wheels GHG Emission Results

Carbon sequestration path has significantly lower GHGs from production





Production-Related GHG Emissions

Natural Gas Reforming with Carbon Sequestration:

2,600 g CO_2-eq/gge

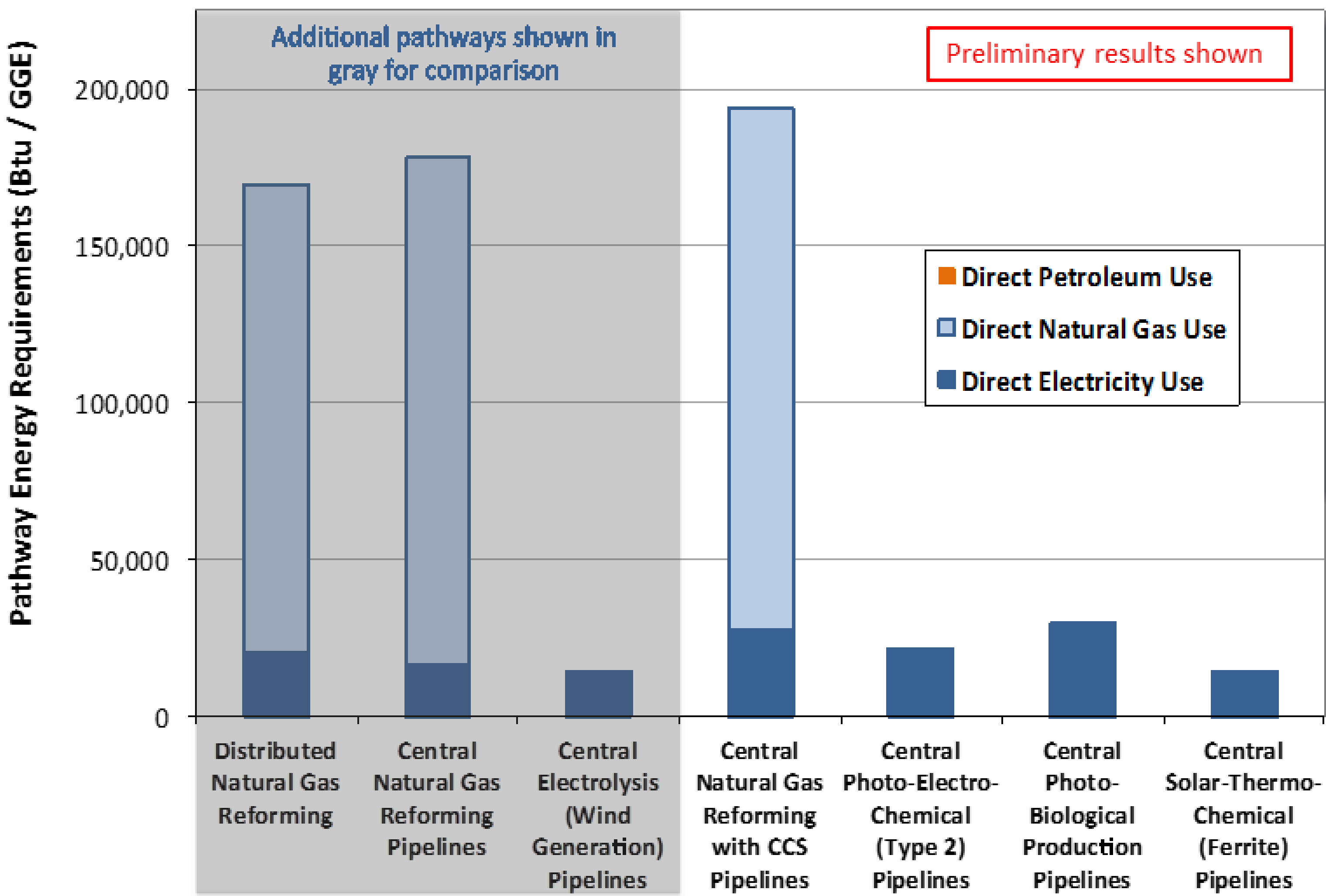
Natural Gas Reforming without sequestration :

10,000 g CO_2-eq/gge

Comparative Results – Direct Energy Use

Renewable pathways: small amount of direct energy use from ancillary production processes, compression & on-site cooling

H2 Pathway Direct Energy Use (not including renewables)



Pathway Direct Energy Use (btu/gge) [not including renewables]

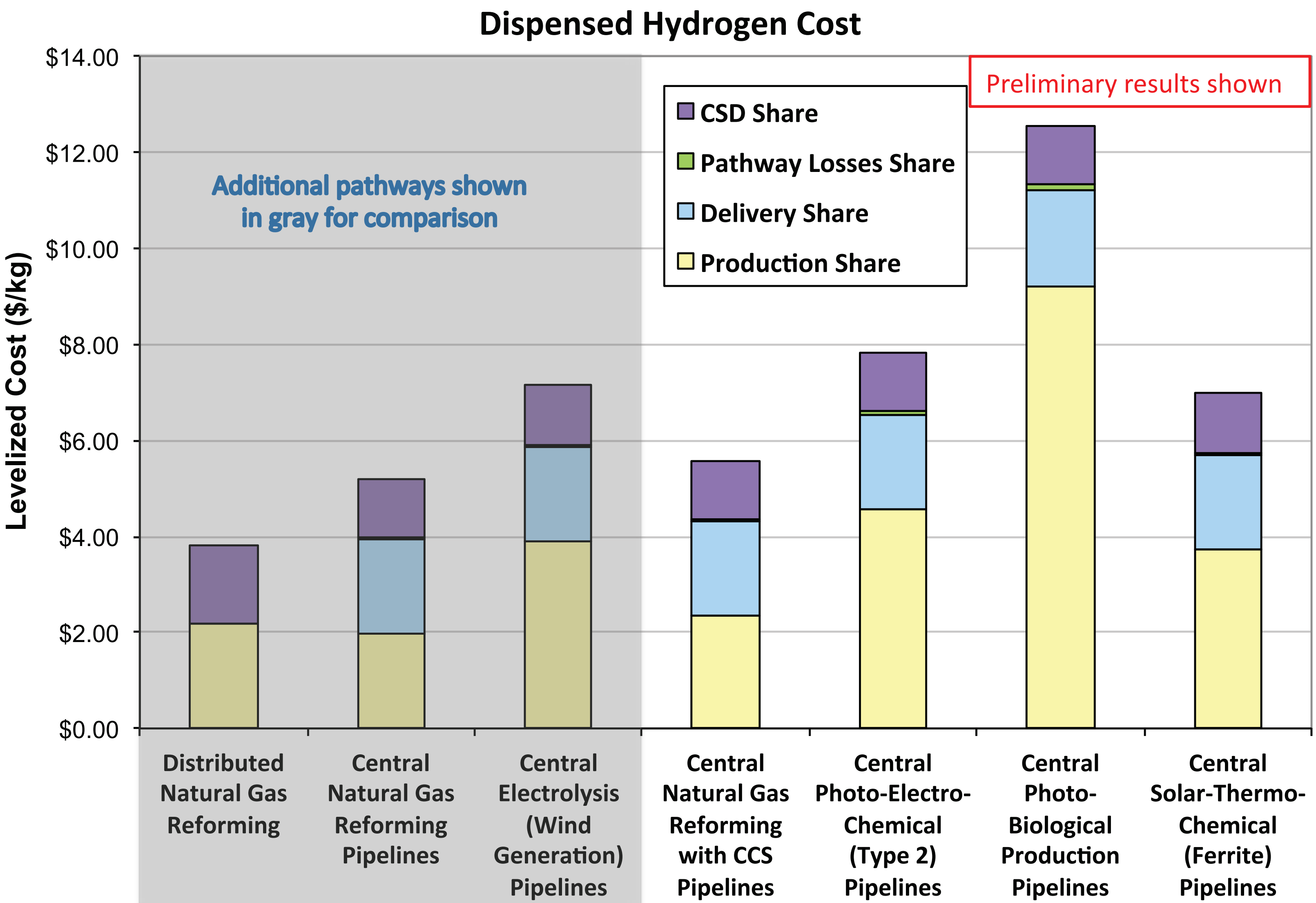
Natural Gas : 170,000-200,000

Renewable: ~15,000-30,000

Initial results based on pathway electricity, natural gas, and petroleum energy use – No specific GREET cases

Comparative Results – H_2 Cost Breakdown

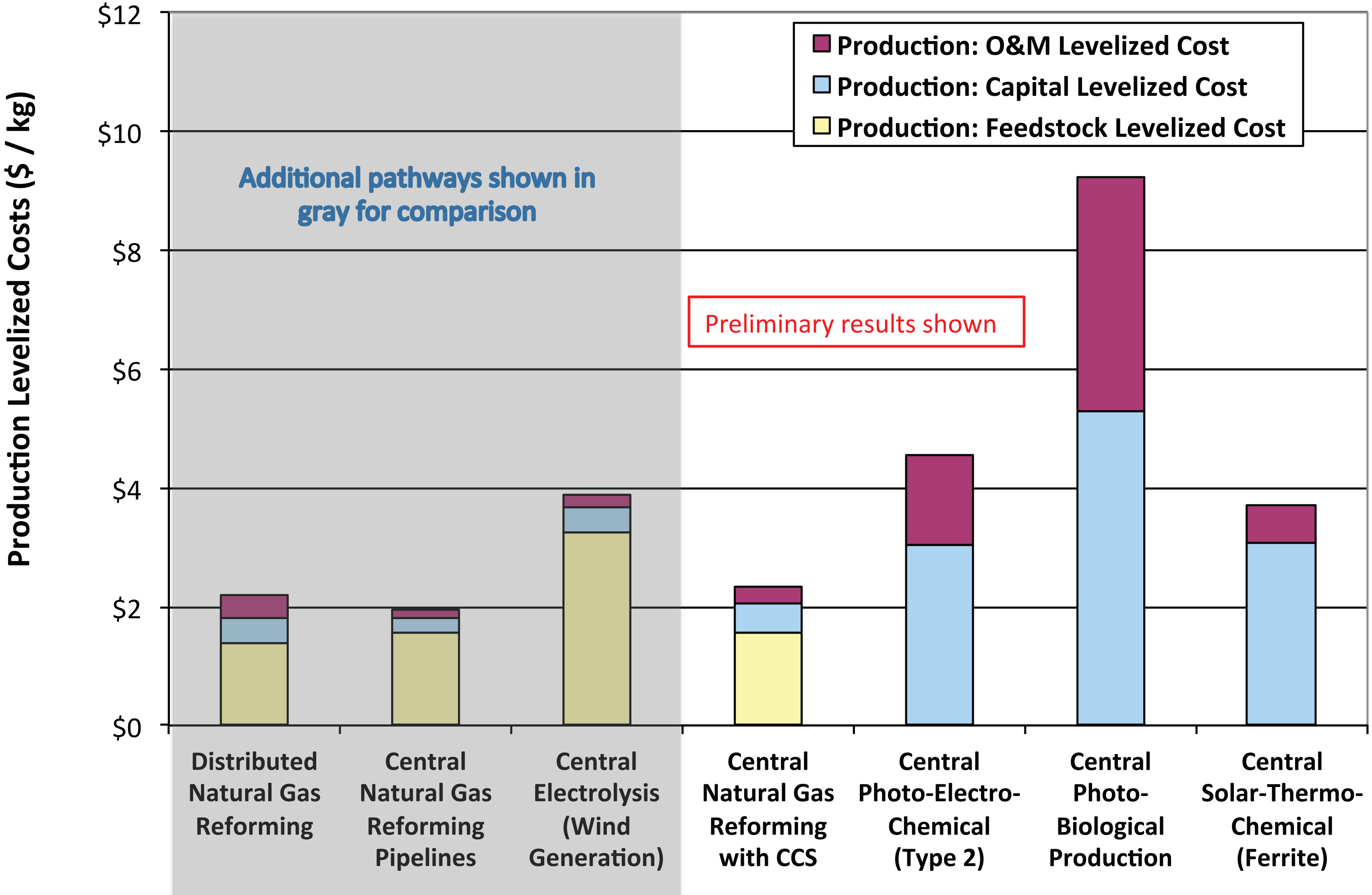
Emerging, lower carbon H_2 pathways have costs higher than \$4/kg target



Combined CSD and delivery costs remain a challenge

Comparative Results – H_2 Production Cost

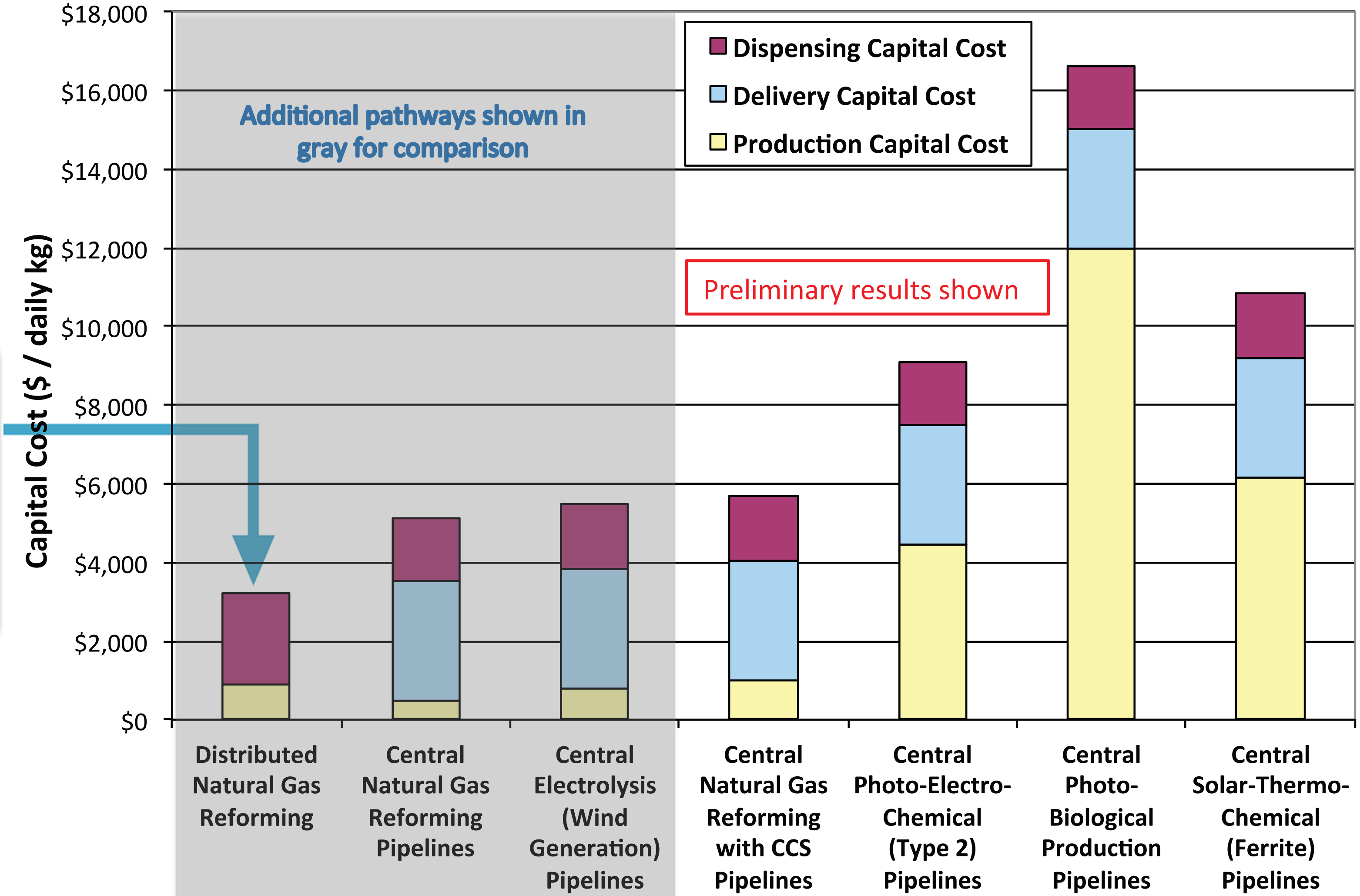
Renewable emerging H_2 production costs driven by capital and fixed O&M costs



Comparative Results – Capital Cost

Emerging, renewable pathways require substantial capital investment based on current level of technology development; more R&D is needed

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



Challenges and Barriers

Energy use and GHG emission results are preliminary: No GREET cases. Preliminary GHG results discussed with DOE and U.S. DRIVE

- Cost and lifecycle analysis based on publicly available H2A and HDSAM models, but specific cases for the emerging renewable production pathways are not available in GREET
  - Preliminary modeling of upstream energy and GHG emissions conducted, with results based on production electricity usage and GREET factors for these energy types
  - Preliminary GHG results for emerging renewable paths shared with DOE and U.S. DRIVE/FPITT
- Recommendation made that Argonne National Lab be funded to develop specific cases for the emerging renewable pathways
  - Lifecycle assessment of GHG emissions will be revised based on new GREET cases, once developed

Model Gaps and Concerns Raised

Industry reviewers would like a better understanding of the processes involved for emerging renewable hydrogen production

Industry comments on modeling of emerging production technologies:

- Contingency costs may be under-estimated considering the low technology-readiness levels (TRL) of renewable processes analyzed
- Need better understanding of the processes modeled and comparison to similar fuel production processes
  - e.g., algal processes for non-H2 fuel production
- Total electricity usage and/or necessary grid electricity may be under-estimated (solar-only electricity may be inadequate)
- Land usage may be an important consideration for renewable paths
  - Overall solar-to-hydrogen efficiency of the process will impact both capital cost and total land usage requirements
- CCS costs may be underestimated *(DOE expected to fund CCS cost review)*
- Specific cases for the emerging renewable production pathways are not currently available in GREET

Collaborations & Technology Transfer

Collaborations and Acknowledgements:

Pathway Analysis Collaborators	• U.S. DRIVE Fuel Pathway Integration Technical Team (FPITT) • Review of key assumptions, modeling parameters, analysis inputs and results • Alliance Technical Services
Core Model Developers (funded separately by DOE)	• GREET: Argonne National Laboratory • H2A Production model: NREL • H2A Production case studies: NREL • HDSAM Delivery model: Argonne National Laboratory • MSM: NREL and Sandia National Laboratory • Cost Per Mile tool: Alliance Technical Services

Technology Transfer Activities:

Tech Transfer	• *Not applicable (analysis activity based on publicly available models, with results made public when finalized)*

Next Steps and Future Work

FY 2015 Activities:

- Joint FPITT and Hydrogen Production Tech Team meeting to discuss emerging H_2 production technologies and processes, modeling gaps and concerns, and potential updates to the emerging-technologies analysis
- Conduct initial analyses of emerging hydrogen delivery and on-board storage technologies, potentially including:
  - High-pressure gas truck delivery, 500 bar dispensing, cold- and cryo-compressed on-board storage, sorbent-based storage systems

Potential Future Work (*funding dependent*):

- Complete emerging production pathway analysis based on new GREET cases for photo-biological, photo-electrochemical and solar thermo-chemical H_2
- Complete evaluation of emerging delivery and storage technologies
- Conduct assessments of additional currently available technologies such as bio-methane SMR and tri-generation (H_2, heat, power) *[AMR suggestion]*
- Revise FY13 current-technologies pathway evaluation based on new data from recent hydrogen fuel infrastructure/installations *[AMR suggestion]*

Project Summary

Project Overview:

- Lifecycle assessment of complete hydrogen production, delivery, and dispensing pathways evaluating cost, energy use & GHG emissions
- Assessment conducted with MSM (linking H2A, HDSAM, and GREET)
- Evaluation of future-technology pathways completed in FY 2014
- FY 2015 analysis focused on emerging-technology pathways: natural gas reforming with CCS, photo-biological, photo-electrochemical and STCH
    - Preliminary GHG assessment of renewable paths shared only with DOE & FPITT

Emerging-Technology Pathways:

- Current modeling of emerging-technology pathways finds hydrogen costs exceeding the $4/kg target; further R&D is needed, especially for renewable paths
- H_2 fuel costs represent 15-25% of ownership costs for emerging technologies; FCEV purchase costs represent ~50% or more of costs
- Renewable H_2 production costs driven by capital and fixed O&M costs

Questions & Discussion

THANKS!

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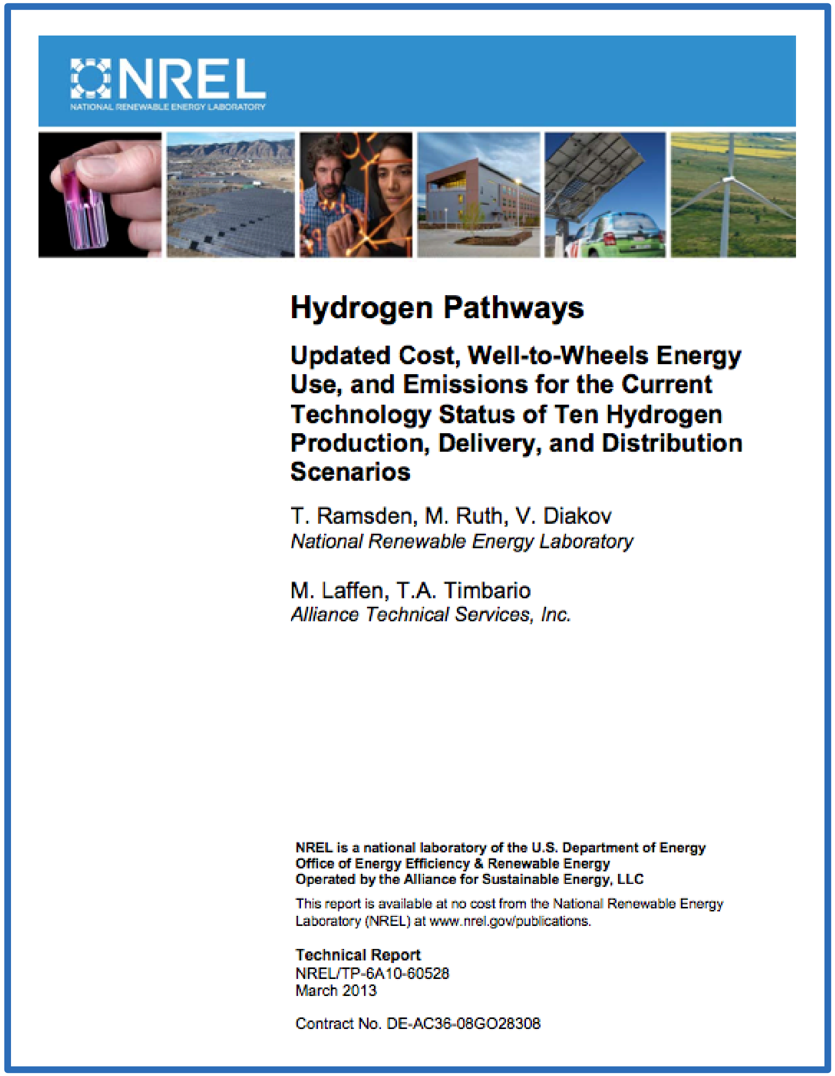

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NREL/TP-6A10-60528
March 2013

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)