NRELNATIONAL RENEWABLE ENERGY LABORATORY

Sustainability Analysis

Hydrogen Regional Sustainability (HyReS)

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National Renewable Energy Laboratory

Project ID SA059

DOE Hydrogen and Fuel Cells Program

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Overview

Timeline	Barriers
Start: September, 2015 End: September, 2018 45% complete	**4.5 A. Future Market Behavior** • Consumer preferences for green hydrogen **4.5 B. Stove-piped/Siloed Analytical Capability** • Integration of metrics from internal (DOE) and external models **4.5 D. Insufficient Suite of Models and Tools** • More complete analytics across all aspects of sustainability
Budget	**Partners**
Total Project Funding: $600k • FY16: $200k • FY17: $200k • FY18: $200k	**Argonne National Laboratory (GREET)** **Project Steering Team** • Institute for Sustainable Infrastructure (ISI) • Louis Berger • Toyota Motor Corporation

FCTO Systems Analysis Framework

- Expansion of existing systems analysis models that address costs and environmental impacts
- Additional sustainability metrics and a general regionalization of all inputs and results, given available data.

Analysis Framework
- Cost estimation
- Supply chain efficiencies
- Energy resource and water utilization
- GHG and criteria emissions

Models & Tools
- H2A production and delivery models
- GREET
- H2FAST
- SERA

- FCTO Program Targets
- BETO Sustainability Framework

Studies & Analysis
- Sustainability metrics
- Framework implementation

- Sustainability science and green business communities
- Other frameworks

Outputs & Deliverables
- Reports
- Workshops
- Public framework

- Fuel Cell Technologies Office
- Sustainable energy analysis community

Acronyms

BETO: Bioenergy Technologies Office

GHG: Greenhouse gas

GREET: Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model

H2FAST: Hydrogen Financial Analysis Scenario Tool

SERA: Scenario Evaluation and Regionalization Analysis model

Analysis of environmental, economic, and social sustainability of hydrogen supply chains

The Hydrogen Regional Sustainability (HyReS) framework will integrate existing sustainability metrics and indicators to examine environmental, economic and social impacts of hydrogen supply chains and FCEVs.

HyReS Objectives:

- To develop an applied *sustainability assessment* framework that facilitates the integration of hydrogen and FCEVs into sustainability assessments conducted by private businesses, investment firms, government agencies, and non-government *stakeholders*
- To examine *environmental* burdens in an integrated regional assessment approach that also takes into account the *economic* and *social* aspects of hydrogen supply chains and the FCEV life cycle

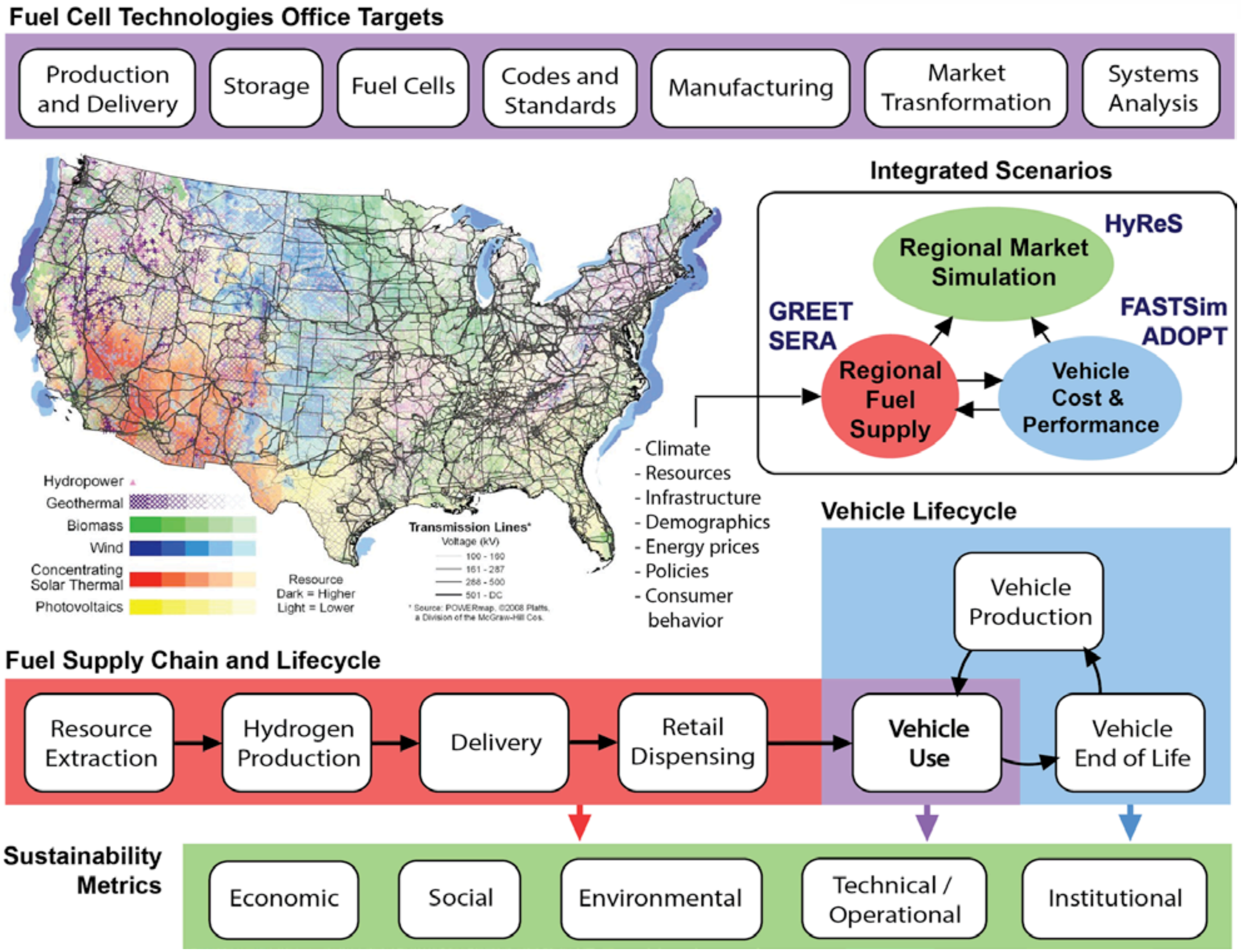
UN Sustainable Development Goals

BETO Sustainability Goals

Modeling Approach Builds on SERA Framework

Approach 1

- The ***Scenario Evaluation and Regionalization Analysis (SERA)*** modeling framework develops optimized hydrogen supply networks in response to FCEV hydrogen demands
- Spatially explicit supply chain components, accounting for resource geography and component cost and performance

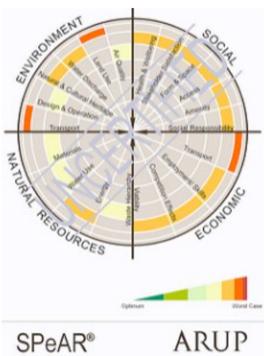


The HyReS framework will identify optimal hydrogen supply chains considering spatially- and temporally-based constraints and aspects of sustainability

Develop Indicators and Metrics that are Compatible with Existing Sustainability Frameworks

Approach 2

- Many sustainability frameworks have been developed to inform different stakeholders at different scales within different sectors.
- The HyReS framework will serve as an information warehouse and sustainability resource, facilitating the integration of metrics specific to hydrogen into ongoing and future assessment activities



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The HyReS framework will develop indicators that are compatible with existing sustainability frameworks to reach a wide range of decision makers

Guidelines for Determining Key Performance Indicators

Policy relevance and utility for users:

- Be representative of environmental conditions, pressures on the environment, or society's responses.
- Be simple, easy to interpret, and able to show trends over time.
- Be responsive to changes in the environment and related human activities.
- Provide a basis for regional and international comparisons.
- Have a threshold or reference value against which to compare the indicator

Analytical soundness:

- Be theoretically well founded in technical and scientific terms.
- Be based on international standards and international consensus about its validity.
- Lend itself to being linked to economic models, forecasting, and information systems.

Measurability:

- Readily available or made available at a reasonable cost/benefit ratio.
- Adequately documented and of known quality.
- Updated at regular intervals in accordance with reliable procedure.

(adapted from OECD 2003, Table 2)

Modeling Approach Leverages the GREET Model

Approach 3

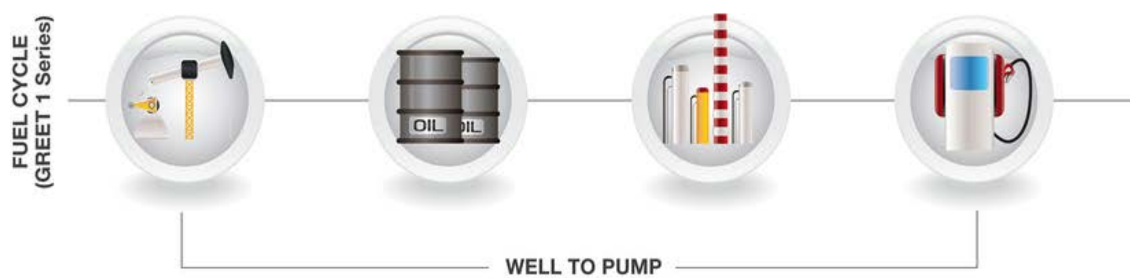
The GREET model will be integrated into the SERA framework such that regional environmental impacts are assessed

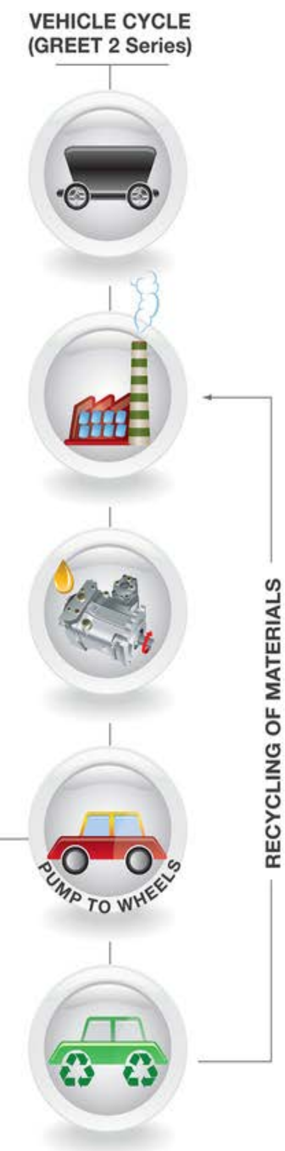
The GREET model provides data for environmental sustainability metrics related to both fuel (hydrogen supply) and vehicle cycles.

Combinations of feedstocks and delivery methods will be compared, accounting for changes in:

- Process efficiencies
- Transportation distances
- Electricity mixes by region/state

Feedstocks	Delivery	Outputs
Natural Gas	Gaseous or Liquid	GHG Emissions
Coal	Tube Trailer	Criteria Emissions
Nuclear	Pipeline	Energy Consumption
Solar	Barge	Water Consumption
Biomass	Rail	⋮
⋮	⋮	

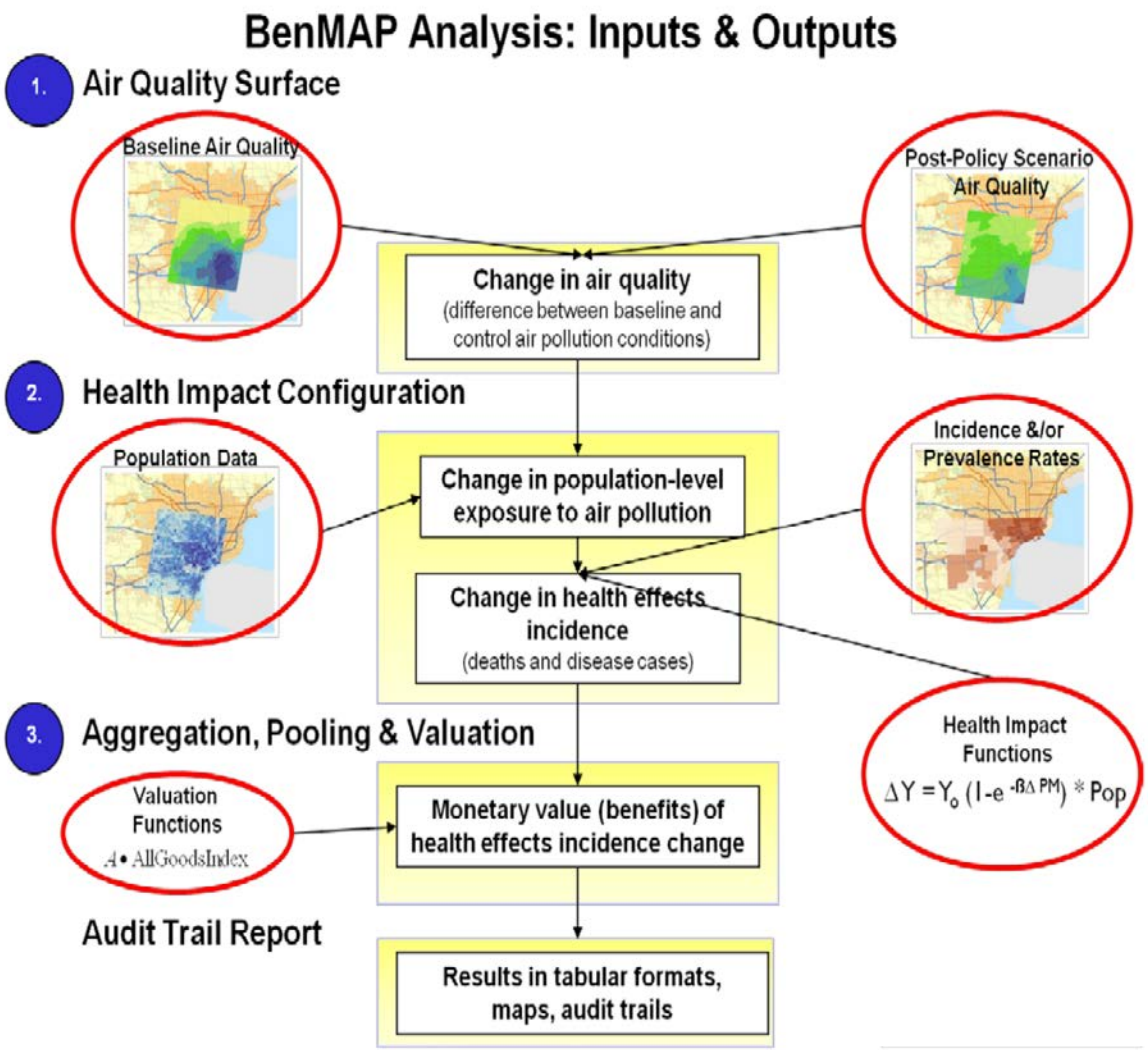




Argonne's GREET Model Analyzes Impacts of Fuel and Vehicle Cycles

Health Impacts Assessed Based on Changes in Criteria Emissions

Approach 4



The EPA has released models, the Environmental Benefits Mapping and Analysis Program (BenMAP) tool and the Co-Benefits Risk Assessment Screening Model, that estimate and map changes in air quality, human health, and related economic benefits due to changes in criteria emissions.

- Spatially and temporally explicit – baseline air quality and population projections
- Provides monetization of benefits

The HyReS framework will assess social sustainability, such as health benefits from changes in air pollutants using existing EPA tools (BenMAP, COBRA)

Identified Sustainability Indicators to be included within the HyReS Framework

Evaluated relevance of existing sustainability indicators and frameworks for expanded Hydrogen Regional Sustainability (HyReS) framework

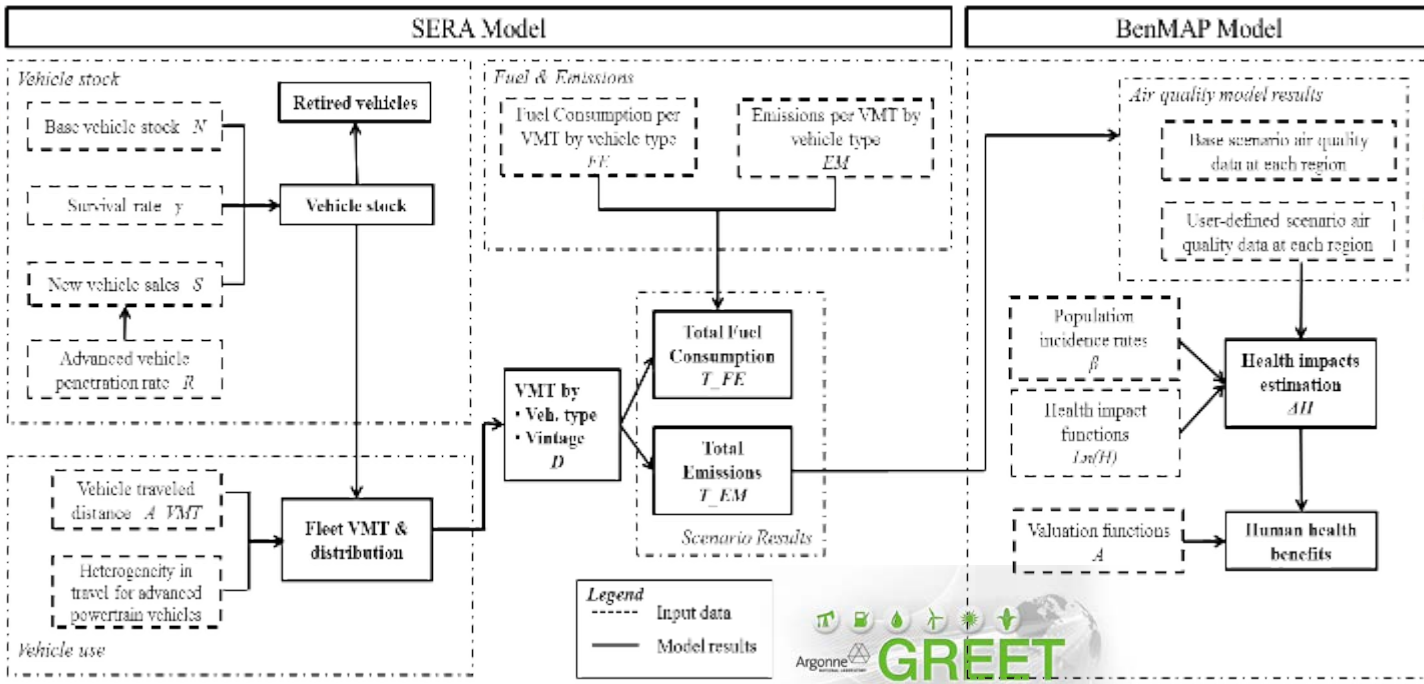
Dim. of sustainability	Indicator	Relevance to HyReS		
		Directly modeled	Estimated	Out of scope
Economic	Fuel prices/cost[1],[2],[3]	☑		
	Total investment cost[1],[2]	☑		
	External costs of transport activities (congestion, emission costs, safety costs) [1]			
Environmental	NOx emissions[1],[2],[3],[4]	☑		
	Land-use change[1],[2]			
	Polluting accidents[1]			☑
Social	Contribution to employment growth[1],[2]		☑	
	Fueling opportunities[3]	☑		
	Average passenger journey time			☑
	⋮			

Of 63 indicators identified in the literature review, the HyReS framework will:
- **Directly model 22**
- **Estimate 26**
- **Not address 15**

Inclusion of social and economic sustainability indicators addresses 2016 AMR reviewer comments

Integrated Framework Leverages Existing Models

Developed framework for integrating and tailoring existing models for hydrogen regional sustainability analysis

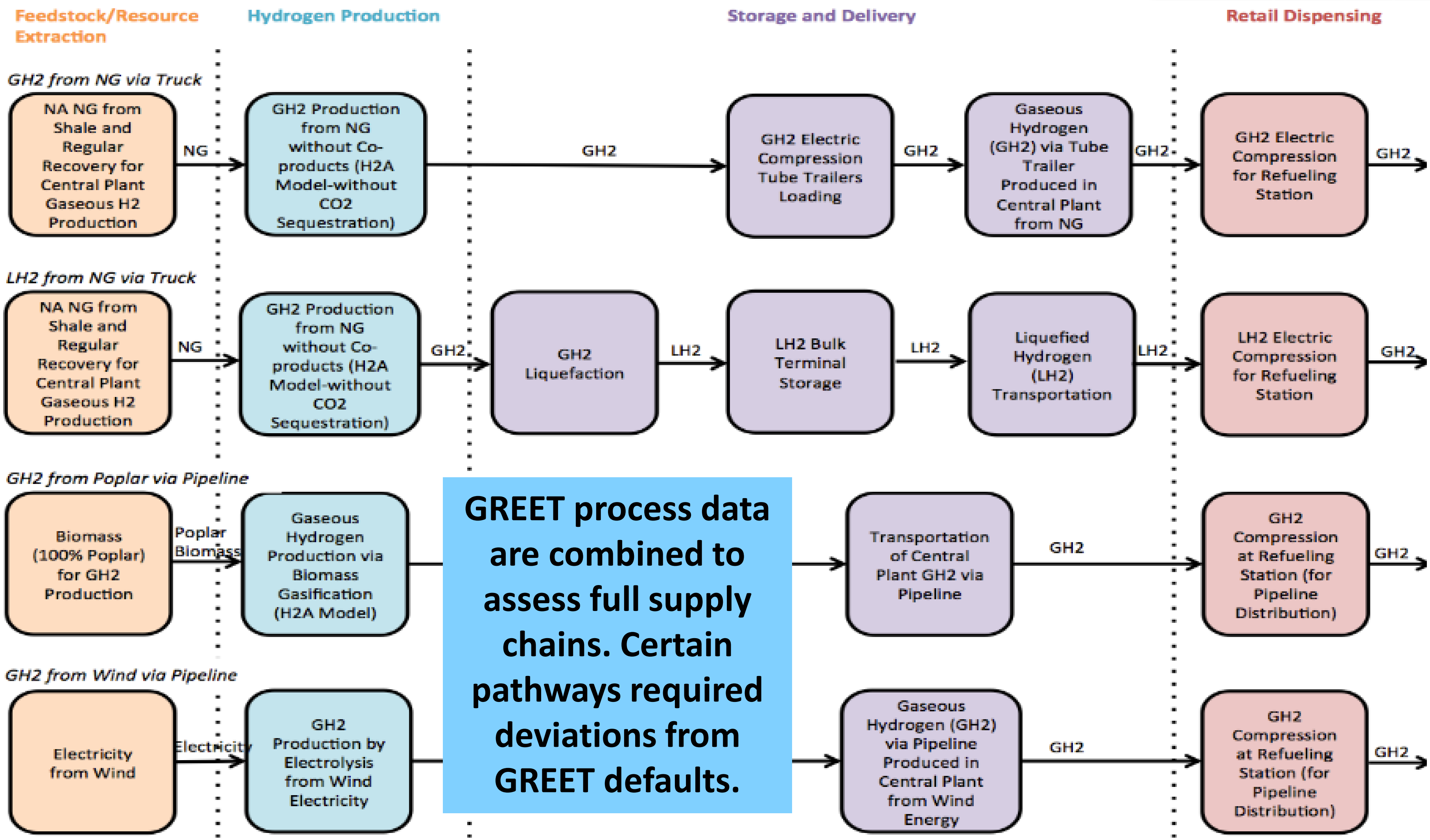


- **SERA** model performs spatiotemporal optimization
- **ADOPT** provides projections of consumer purchase decisions
- **FASTSim** evaluates the impact of technology improvements on efficiency, performance, cost, and battery life

Increased integration with existing databases and models addresses 2016 AMR reviewer comments

Demonstrated Analytic Methods for Example Pathways

Accomplishments 3



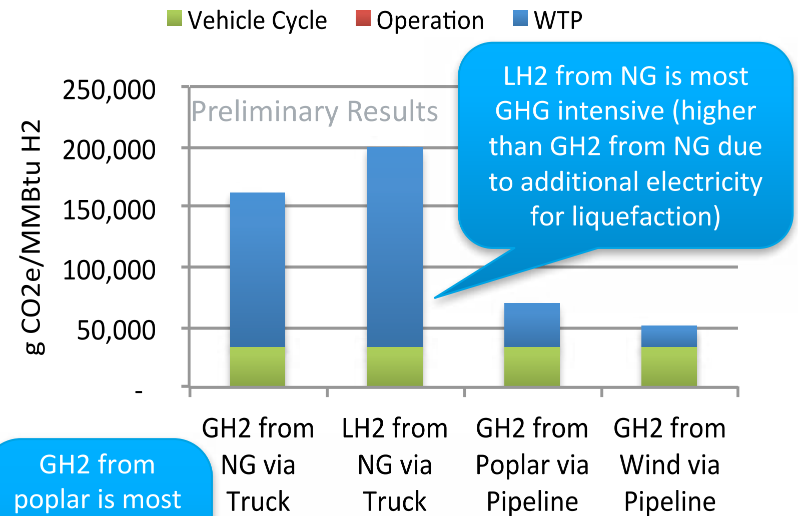
GREET process data are combined to assess full supply chains. Certain pathways required deviations from GREET defaults.

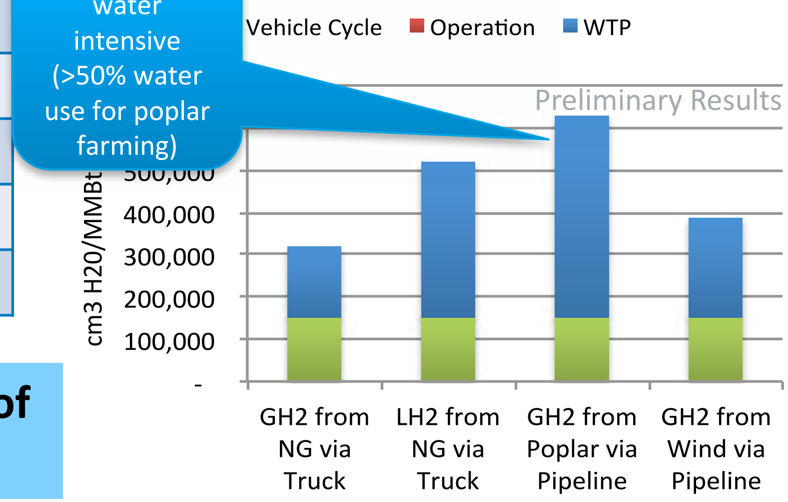
Four case studies evaluate environmental impacts, including two fossil-based and two renewable-based supply chains

Case Study Results for Four Pathways

Evaluated life cycle impacts of FCEVs corresponding to the four production pathways, focusing on emissions, water usage and energy usage

LC Impacts (g/mi, water: cm3/mi)	GH2 from NG via Truck	LH2 from NG via Truck	GH2 from Poplar via Pipeline	GH2 from Wind via Pipeline
GHG-100	336	414	145	106
CO	0.28	0.29	0.24	0.19
NOx	0.26	0.27	0.21	0.09
PM10	0.07	0.09	0.05	0.05
PM2.5	0.04	0.05	0.02	0.02
SO2	0.00	0.00	0.00	0.00
CH4	0.91	1.07	0.35	0.27
SOx	0.38	0.55	0.41	0.34
N2O	0.003	0.004	0.016	0.002
VOC	0.25	0.25	0.23	0.22
Water Use	663	1,078	1,304	804





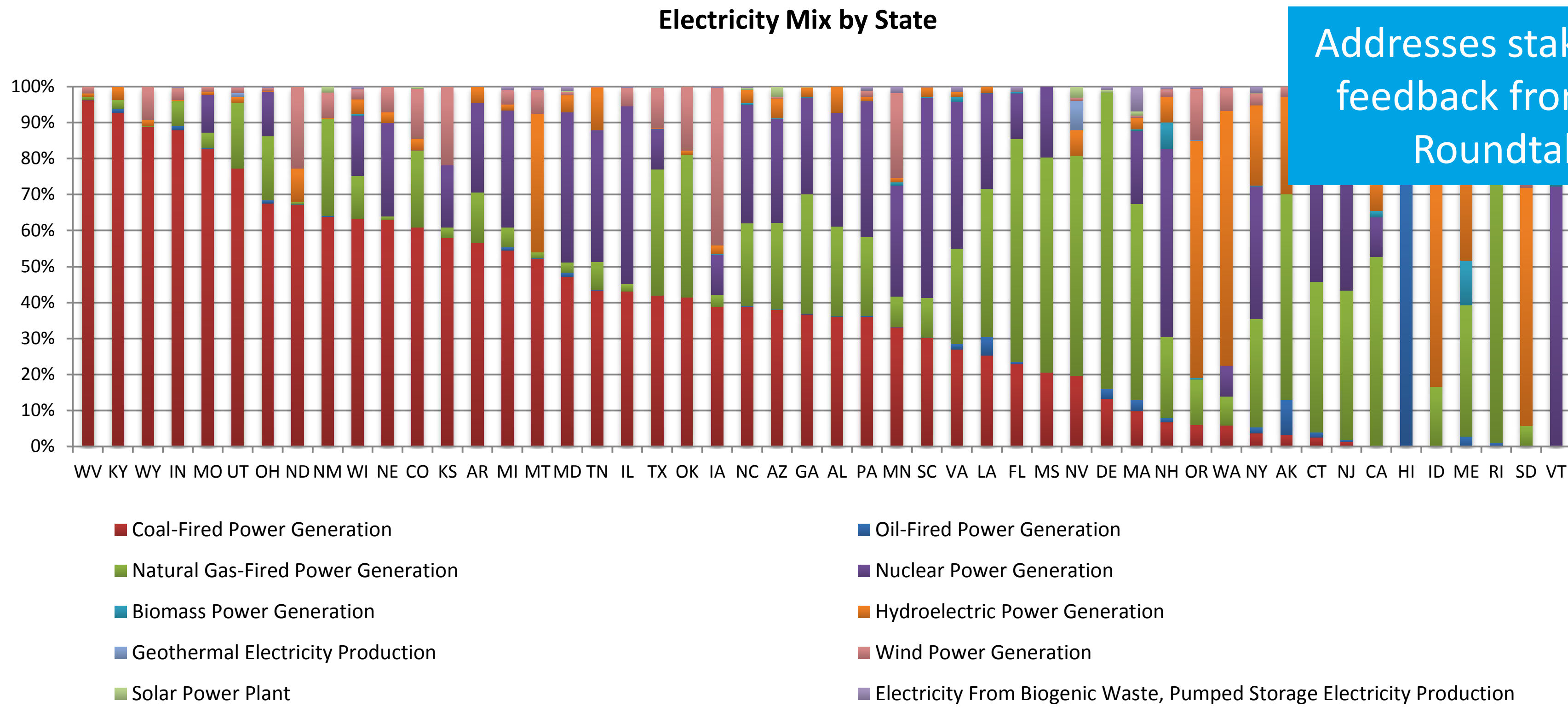
GREET defaults were varied so that transportation of hydrogen is consistent across modes (100 miles)

Regionalization of Electricity Mix

Accomplishments 5

Regionalized results from GREET based on state electricity mixes

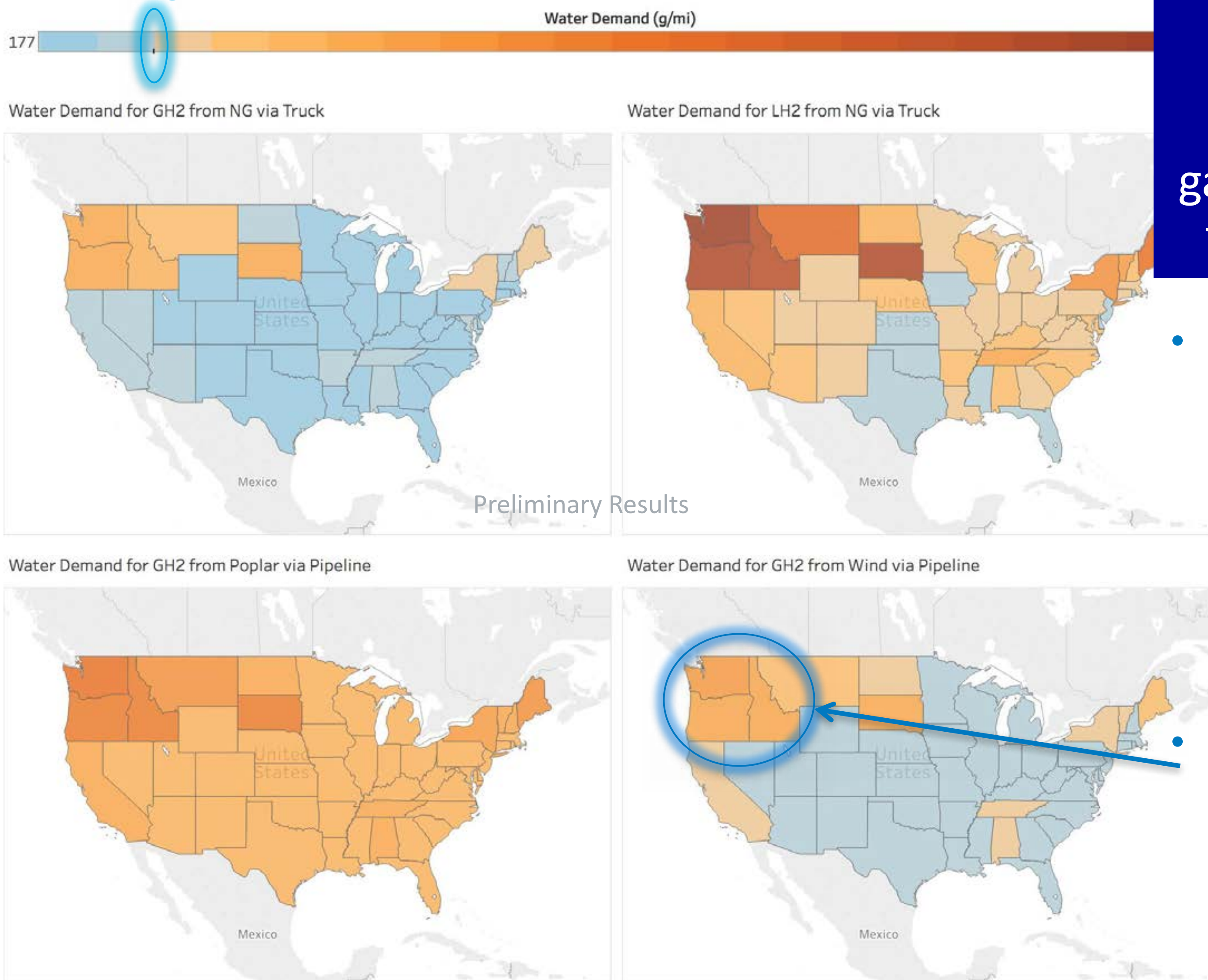
Addresses stakeholder feedback from 2016 Roundtable



- Calculated electricity impacts based on percentage generation by technology given in GREET documentation
- Greater levels of coal-fired power generation is associated with higher GHG emissions
- Greater levels of hydroelectric power generation is associated with higher water use

Case Study Results by State

Orange coloring represents states where pathway WTW water use is higher than conventional gasoline water use



WTW performance of H2 pathways relative to conventional gasoline depends on the electricity mix

- Identified states where pathways result in higher WTW GHG emissions (see backup slides) or water usage compared to conventional gasoline vehicles
- States resulting in high water use tend to be those with relatively high hydroelectric power generation

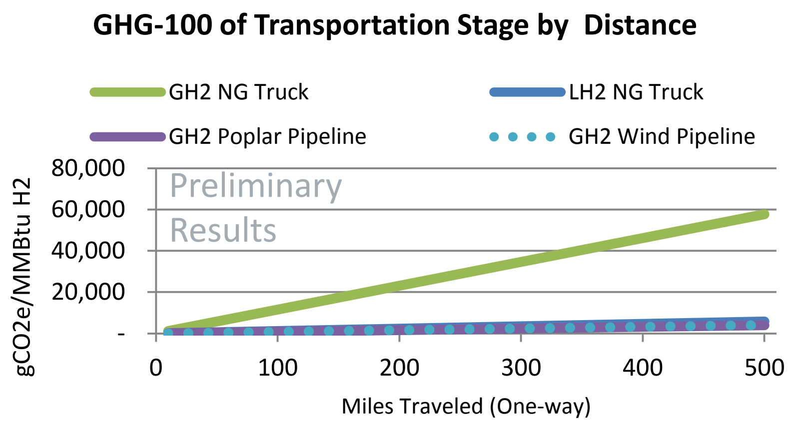
Explored Influence of Delivery Transportation Distance

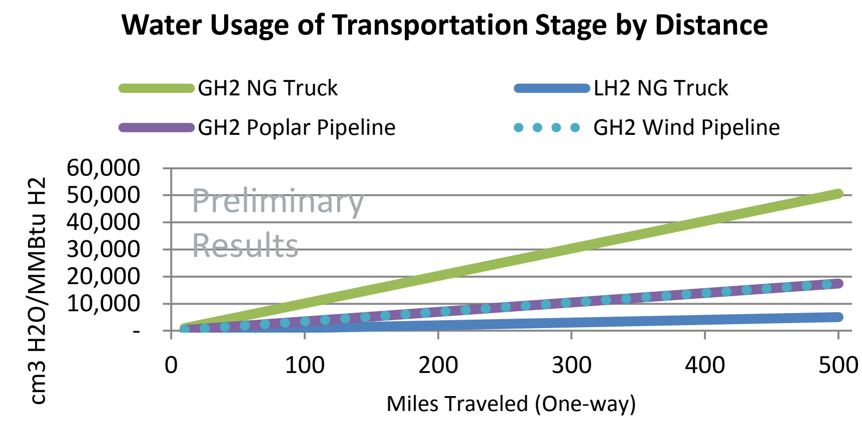
GH2 from NG with Truck Delivery results in lower WTW GHG emissions than LH2 from NG by Truck when <400 miles

Results for Transportation Stage Only: 100 mile Delivery

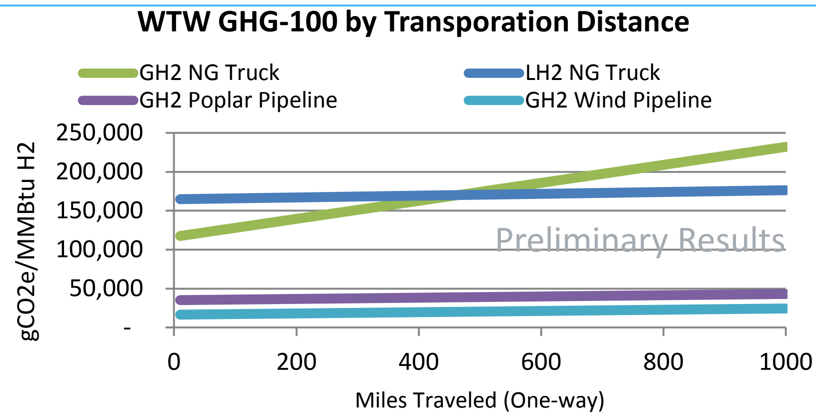
Metric and units	Pipeline delivery at 100 miles (0.0049 MMBtu electricity)	GH2 truck delivery at 100 miles (0.12 MMBtu diesel)	LH2 truck delivery at 100 miles (0.012 MMBtu diesel)
GHG-100 (g/MMBtu H2)	795	11,553	1,155
Water Use (cm^3/MMBtu H2)	3,487	10,120	1,011

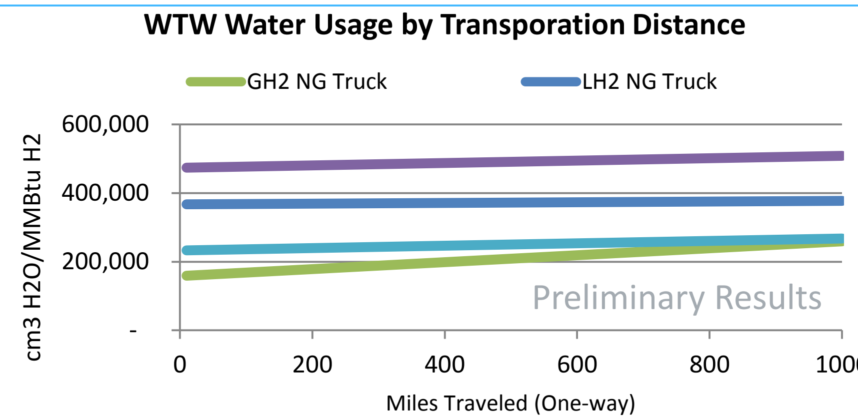
Delivery Stage Only





Full WTW Results

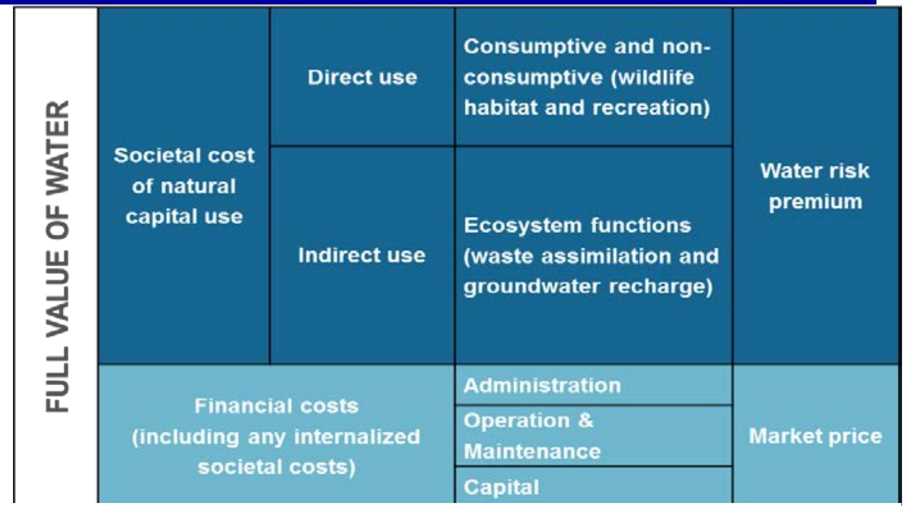




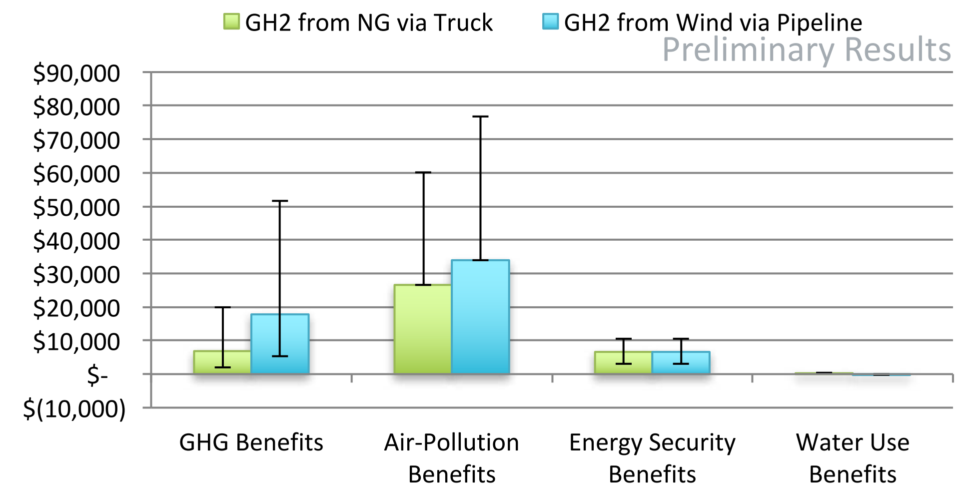
Demonstrated Monetization of Benefits

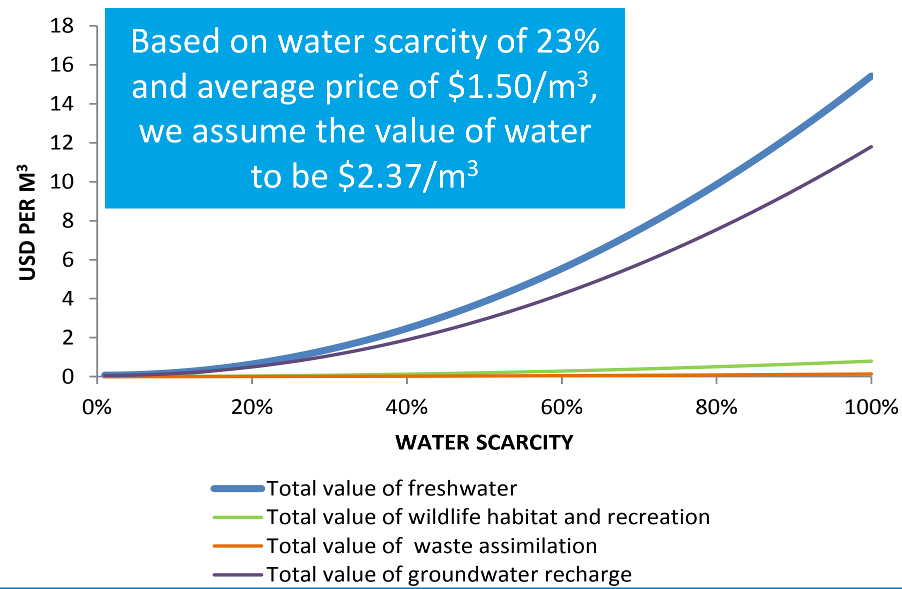
Monetized benefits of two pathways with respect to four impact categories: reduction in air pollution provides greatest benefits

- **GHG Benefits** (EPA's Social Cost of Carbon)
- **Air Pollution Benefits** (EPA's COBRA model)
- **Energy Security Benefits** (following monetization method from EPA and NHTSA (2010) regulatory impact analysis)
- **Water Use Reductions** (Ecolab and Trucost (2015) Water Risk Monetizer)



Results for 10^6 VMT displaced by FCEVs in 2020





Estimated Life Cycle Impacts of EV400 to Approximate an Apples-to-Apples Comparison with FCEVs

Used FASTSim and GREET to estimate impacts of an electric vehicle with comparable range to an FCEV

Preliminary Results	FASTSim base BEV400	FASTSim base BEV300	GREET BEV300	FASTSim base BEV100	GREET BEV100
Motor Power (kW)	152	129	-	92	-
Battery Energy (kWh)	150	102	84	29	27
Glider (lbs)	2206	2206	2206	2206	2206
Transmission (lbs)	165	165	165	165	165
Battery weight (lbs)	2877	1956	1750	556	583
Motor and Electronic (lbs)	490	427	450	324	377
Total weight	5738	4754	4571	3251	3331
MPGGE	85.9	94.7	83.6	112.2	110.8
0-60mph acceleration time (seconds)	9.1	9.0	9.0	9.0	9.0
Mileage Range (mile)	400	300	300	101	100

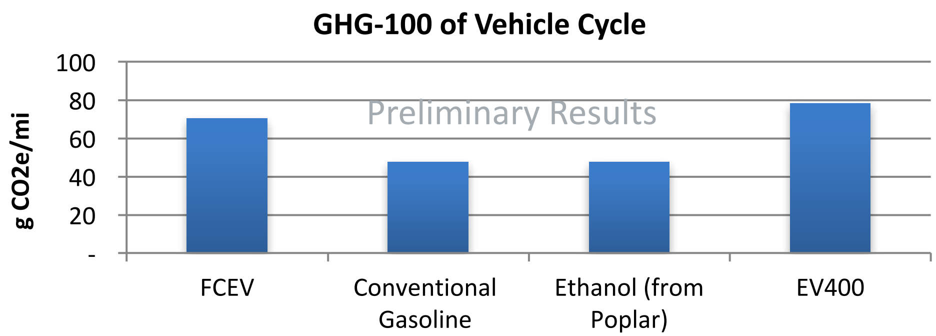
1) Calibrated FASTSim to match the GREET specifications for EV100 and EV300
2) Simulated EV400 in FASTSim
3) Changed GREET parameters to match simulated EV400
   - Total weight
   - Battery weight
   - Component weight (%)
   - Fuel economy

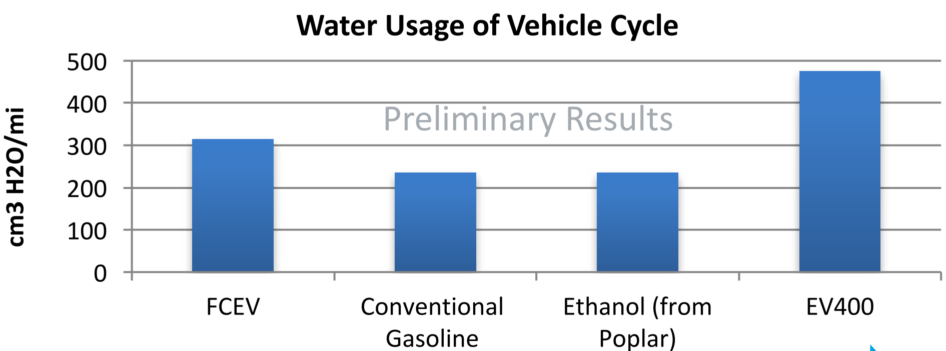
- Future analysis will include charging phase

Benchmarked Case Study Results

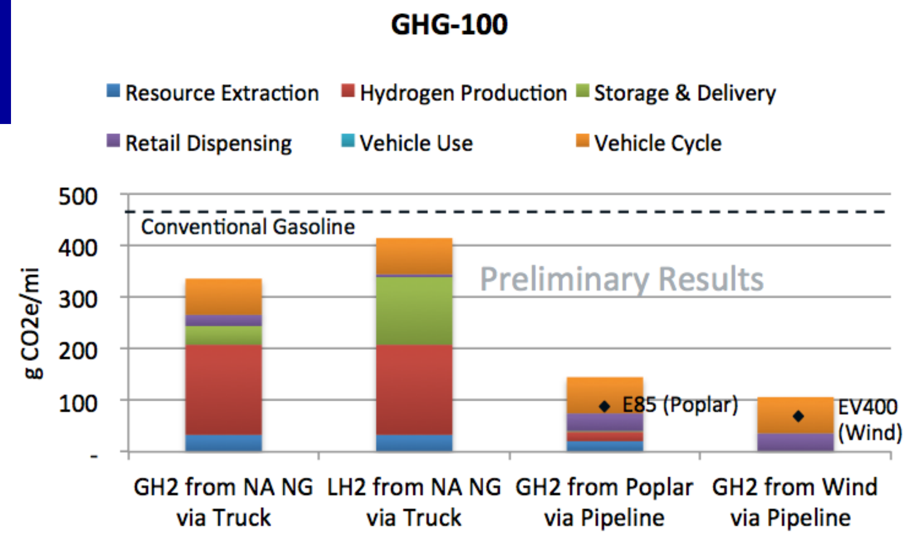
Benchmarking compares FCEVs to conventional gasoline, E85, and BEVs

Vehicle Cycle (Manufacturing) of EV400 is more GHG and water intensive than FCEVs or CVs.

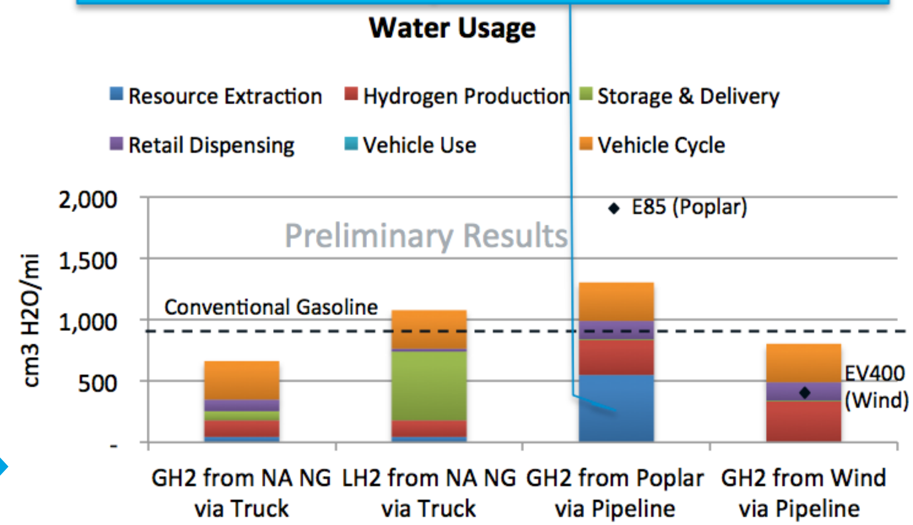




EV400 based on wind energy performs better than FCEV with H2 from wind



Poplar farming accounts for ~55% of GH2 from Poplar water use



Collaboration

- Argonne National Laboratory
    - GREET Model
- Project Steering Team:
    - Argonne National Laboratory
    - Institute for Sustainable Infrastructure (ISI)
    - Louis Berger
    - Toyota Motor Corporation

Future Work: Remaining Tasks in FY17

Future Work 1

Finalizing model structure

- Integration of BenMAP/COBRA with the SERA model
- Automating integration of GREET data into SERA
  - Continuous updates to GREET will be incorporated into HyReS
- Calculation of water reductions/benefits
  - *Consumptive* water use vs. withdrawals
  - Identifying water prices by region
- Incorporate updated GREET results on air quality, water, and medium/heavy-duty vehicle emissions and fuel economy

Increase Relevance to stakeholders

- Addition steering team members may be added
- Engage sustainability science, policy, and investment communities for feedback

Project Plan

Year One

- Subject Review ☑
- Steering Team ☑
- Expanded Framework ☑

Year Two

- Additional Expansion ☑
- Framework Application ☑
- Corporate-Level Alignment ☐
- Beta Version ☐

Year Three

- Reviewer Feedback ☐
- Refine Framework ☐
- Implement Framework ☐

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SASB

California Environmental Protection Agency Air Resources Board

CALIFORNIA ENERGY COMMISSION

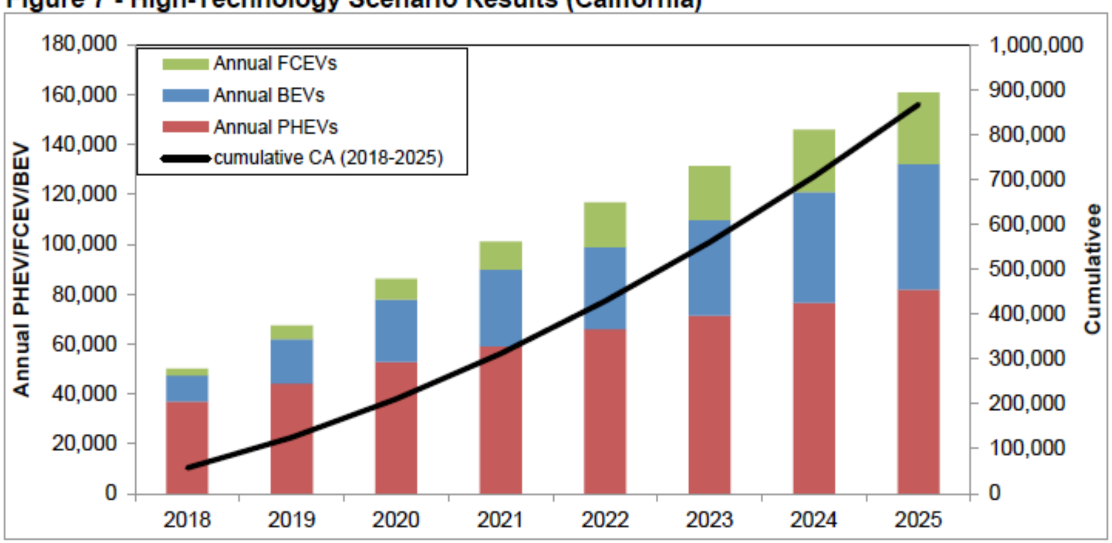
Complete integration with SERA / ADOPT Market Simulation Capabilities

Future Work 2

Relevance of sustainability in market growth

- California state policies will accelerate adoption of FCEVs, BEVs, and PHEVs
- HyReS will be fully integrated with the vehicle adoption capabilities of ADOPT and hydrogen supply and financing capabilities of SERA/H2FAST
- HyReS will then be able to inform broader discussions about sustainability impacts of specific state and federal policy mechanisms

Figure 7 - High-Technology Scenario Results (California)



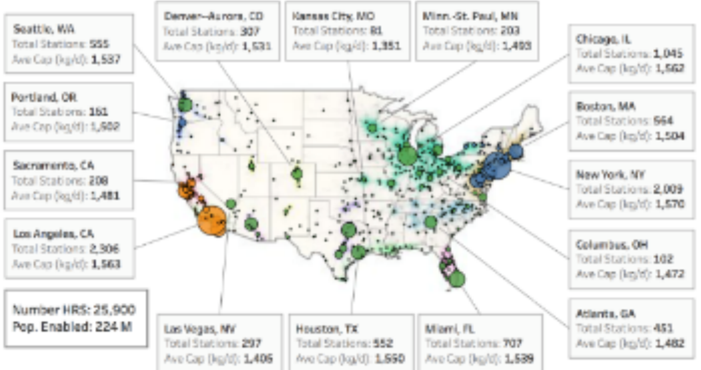
https://www.arb.ca.gov/msprog/zevprog/zevprog.htm

H2USA

Market simulation capabilities will enable HyReS to contribute to broader discussions around ZEV adoption

ADOPT

SERA



HyReS Project Summary

Relevance

- The Hydrogen Regional Sustainability (HyReS) framework integrates existing systems analysis models to address costs, environmental impacts, and market dynamics
- Updates and revisions are responsive to industry and other stakeholder feedback

Approach

- Literature review of sustainability indicators and metrics
- Leveraging multiple models: GREET, SERA, ADOPT, BenMAP/COBRA

Technical Accomplishments and Progress

- Selection of sustainability indicators
- Example case studies for 4 hydrogen supply pathways
- Tunable parameters to test sensitivity of results (transportation distance, state grid mix) – can be applied to FCTO targets (e.g., electrolyzer efficiency)
- Monetization of social benefits
- Benchmarking of results against comparable vehicles (e.g., EV400)

Collaboration

- GREET model developers at Argonne National Laboratory
- HyReS Project Steering Team (Argonne, Institute for Sustainable Infrastructure, Louis Berger, Toyota)

Planned Future Research

- Application of HyReS framework to comprehensive set of pathways
- Increase relevance to stakeholders by aligning with corporate practices
- Full integration with ZEV market simulation capabilities (e.g., ADOPT, SERA)

Questions?

Contact Information

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Technical Back-Up Slides

Modeling Assumptions

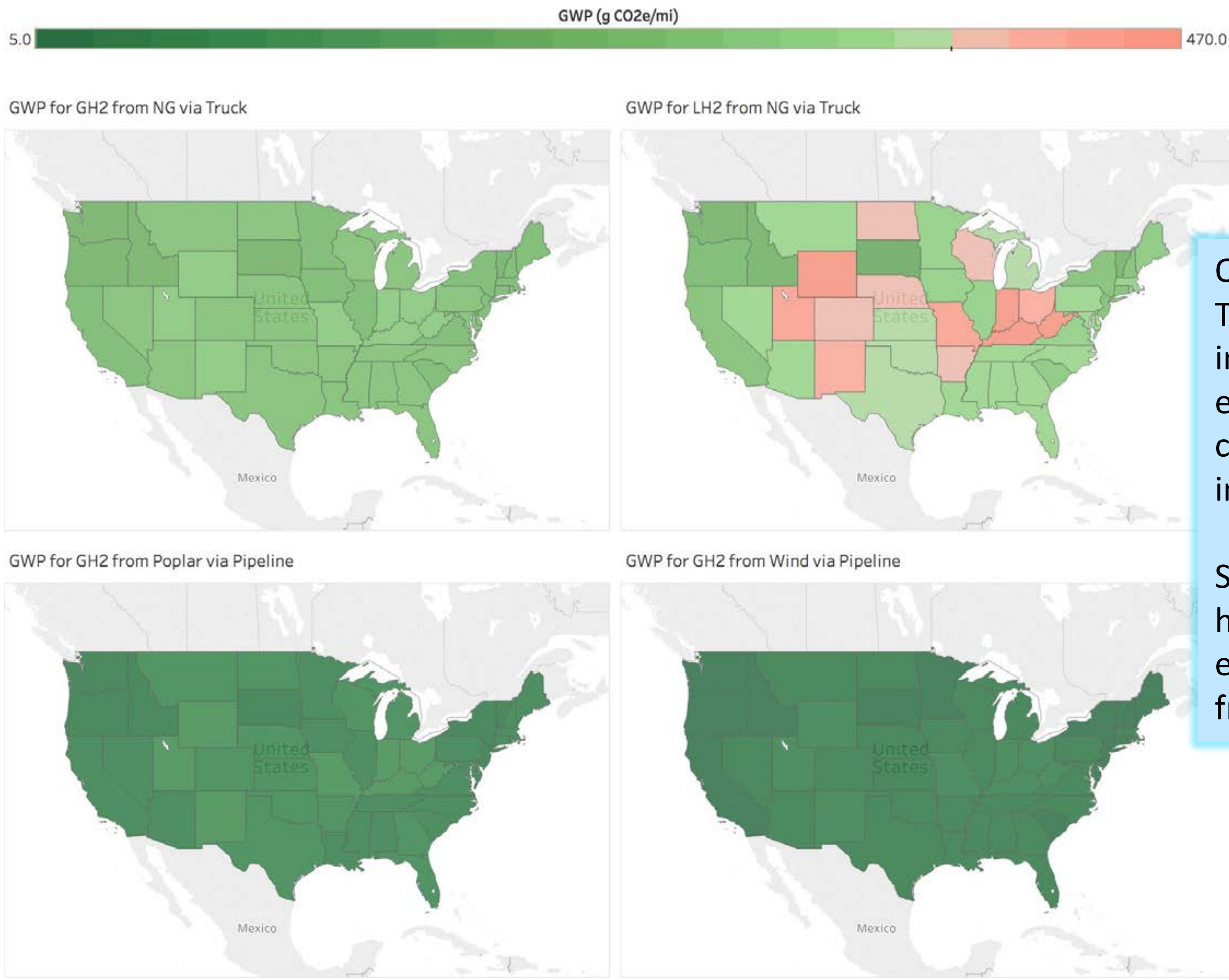
- Year for analysis is 2015 – consistent with the GREET target year for vehicle technology
- Vehicle Fuel Economies:
  - FCEV: 54.1 mpgge (GREET default)
  - ICEV: 26.2 mpgge (GREET default)
  - EV400: 85.9 mpgge (from FASTSim)
- GHG emissions reported in grams per mile or per MMBtu of H2
- Water use reported in cm3 (or equivalently, grams) either per mile or MMBtu of H2.

Components Composition from FASTSim and GREET Models (% by wt)

	FASTSim base BEV-400	FASTSim base BEV-300	GREET BEV300	FASTSim base BEV-100	GREET BEV100
Total Weight w/o Battery (lbs)	2996	2947	2954	2880	2886
Components Composition, % by wt					
Powertrain System (including BOP)	4.5%	5.0%	4.5%	4.7%	4.8%
Transmission System	5.5%	5.6%	5.6%	5.8%	5.7%
Chassis (w/o battery)	27.8%	28.3%	28.2%	29.5%	28.9%
Traction Motor	10.1%	8.9%	9.3%	6.3%	7.2%
Electronic Controller	6.3%	5.7%	5.9%	5.1%	5.9%
Body	45.8%	46.5%	46.5%	48.6%	47.5%

Percentage weights of components required by GREET model to calculate vehicle cycle impacts of EV400

WTW GHG Emissions by State



Only LH2 from NG via Truck pathway results in more WTW GHG emissions than conventional gasoline in any states.

States in red tend to have higher % of electricity generation from coal.

Acronymns

- **ADOPT:** Automotive Deployment Options Projection Tool
- **BETO:** Bioenergy Technologies Office
- **(B)EV:** (Battery) Electric Vehicle
- **COBRA:** Co-Benefits Risk Assessment Screening Model
- **FASTSim:** Future Automotive Systems Technology Simulator
- **FCEV:** Fuel Cell Electric Vehicle
- **FCTO:** Fuel Cells Technologies Office
- **GH2:** Gaseous Hydrogen
- **GHG:** Greenhouse gas
- **GREET:** Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model
- **H2A:** Hydrogen Analysis
- **H2FAST:** Hydrogen Financial Analysis Scenario Tool
- **ICEV:** Internal Combustion Engine Vehicle
- **LH2:** Liquid Hydrogen
- **NG:** Natural Gas
- **SERA**: Scenario Evaluation and Regionalization Analysis models
- **WTP:** Well-to-Pump
- **WTW:** Well-to-Wheels

References (for Indicators on Slide 9)

[1] Dobranskyte-Niskota, A., A. Perujo, and M. Pregl (2007). Indicators to Assess Sustainability of Transport Activities, EUR 23041 EN, European Commission, Joint Research Centre, Institute for Environment and Sustainability, available online: http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/10416/1/indicators%20report_green%20template.pdf

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[4] Vaidyanathan, S. and Langer, T. (2011). "Rating the Environmental Impacts of Motor Vehicles: ACEES'd Green Book Methodology, 2011 Edition." American Council for an Energy-Efficient Economy. Available from http://aceee.org/research-report/t111