Sustainability Analysis
Hydrogen Regional Sustainability (HyReS)

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National Renewable Energy Laboratory
DOE Hydrogen and Fuel Cells Program
2017 Annual Merit Review and Peer Evaluation Meeting
June 6, 2017

This presentation does not contain any proprietary, confidential, or otherwise restricted information.
### Overview

#### Timeline

<table>
<thead>
<tr>
<th>Start: September, 2015</th>
<th>End: September, 2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>45% complete</td>
<td></td>
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</tbody>
</table>

#### Barriers

<table>
<thead>
<tr>
<th>4.5 A. Future Market Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Consumer preferences for green hydrogen</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.5 B. Stove-piped/Siloed Analytical Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Integration of metrics from internal (DOE) and external models</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>4.5 D. Insufficient Suite of Models and Tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>• More complete analytics across all aspects of sustainability</td>
</tr>
</tbody>
</table>

#### Budget

<table>
<thead>
<tr>
<th>Total Project Funding: $600k</th>
</tr>
</thead>
<tbody>
<tr>
<td>• FY16: $200k</td>
</tr>
<tr>
<td>• FY17: $200k</td>
</tr>
<tr>
<td>• FY18: $200k</td>
</tr>
</tbody>
</table>

#### Partners

**Argonne National Laboratory (GREET)**

**Project Steering Team**

• Institute for Sustainable Infrastructure (ISI)
• Louis Berger
• Toyota Motor Corporation
• 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

Studies & Analysis
- Sustainability science and green business communities
- Other frameworks

Outputs & Deliverables
- Reports
- Workshops
- Public framework

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**

- [Goals 1 to 6: No Poverty, Zero Hunger, Healthy People, Quality Education, Gender Equality, Clean Water and Sanitation]

**BETO Sustainability Goals**

- [Goals 7 to 17: Affordable Clean Energy, Industry, Innovation and Infrastructure, Sustainable Cities and Communities, Responsible Consumption and Production, Climate Action, Life on Land, Life Below Water, Peace & Justice, Partnerships for the Goals]

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**Environmental Sustainability**
- Climate
- Water quality and quantity
- Air quality
- Biodiversity
- Land use

**Economic Sustainability**
- Commercial viability
- Return on investment
- Net present value
- Process efficiency
- Outputs on desired products

**Social Sustainability**
- Social acceptability
- Social well-being
- Energy security and external trade
- Resource conservation
- Rural development and workforce training
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.
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.

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

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

<table>
<thead>
<tr>
<th>Feedstocks</th>
<th>Delivery</th>
<th>Outputs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural Gas</td>
<td>Gaseous or Liquid</td>
<td>GHG Emissions</td>
</tr>
<tr>
<td>Coal</td>
<td>Tube Trailer</td>
<td>Criteria Emissions</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Pipeline</td>
<td>Energy Consumption</td>
</tr>
<tr>
<td>Solar</td>
<td>Barge</td>
<td>Water Consumption</td>
</tr>
<tr>
<td>Biomass</td>
<td>Rail</td>
<td></td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Dim. of sustainability</th>
<th>Indicator</th>
<th>Relevance to HyReS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Directly modeled</td>
</tr>
<tr>
<td>Economic</td>
<td>Fuel prices/cost([1],[2],[3])</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Total investment cost([1],[2])</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>External costs of transport activities (congestion, emission costs, safety costs) ([1])</td>
<td>✓</td>
</tr>
<tr>
<td>Environmental</td>
<td>NOx emissions([1],[2],[3],[4])</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Land-use change([1],[2])</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Polluting accidents([1])</td>
<td>✓</td>
</tr>
<tr>
<td>Social</td>
<td>Contribution to employment growth([1],[2])</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Fueling opportunities([3])</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Average passenger journey time</td>
<td>✓</td>
</tr>
</tbody>
</table>

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
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

Integrated Framework Leverages Existing Models

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

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

**Preliminary Results**

- GH2 from NG via Truck
- LH2 from NG via Truck
- GH2 from Poplar via Pipeline
- GH2 from Wind via Pipeline

**Vehicle Cycle**

LH2 from NG is most GHG intensive (higher than GH2 from NG due to additional electricity for liquefaction)

GH2 from poplar is most water intensive (>50% water use for poplar farming)

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

Regionalized results from GREET based on state electricity mixes

Electricity Mix by State

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

<table>
<thead>
<tr>
<th>Metric and units</th>
<th>Pipeline delivery at 100 miles (0.0049 MMBtu electricity)</th>
<th>GH2 truck delivery at 100 miles (0.12 MMBtu diesel)</th>
<th>LH2 truck delivery at 100 miles (0.012 MMBtu diesel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG-100 (g/MBtu H2)</td>
<td>795</td>
<td>11,553</td>
<td>1,155</td>
</tr>
<tr>
<td>Water Use (cm$^3$/MMBtu H2)</td>
<td>3,487</td>
<td>10,120</td>
<td>1,011</td>
</tr>
</tbody>
</table>
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)

Results for $10^6$ VMT displaced by FCEVs in 2020

![Graph showing GHG Benefits, Air-Pollution Benefits, Energy Security Benefits, and Water Use Benefits](image)

Based on water scarcity of 23% and average price of $1.50/m³, we assume the value of water to be $2.37/m³
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

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

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
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.
Collaboration

- Argonne National Laboratory
  - GREET Model

- Project Steering Team:
  - Argonne National Laboratory
  - Institute for Sustainable Infrastructure (ISI)
  - Louis Berger
  - Toyota Motor Corporation
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
Complete integration with SERA / ADOPT Market Simulation Capabilities

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
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
Elizabeth.Connelly@nrel.gov
Technical Back-Up Slides
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)

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

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.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADOPT</td>
<td>Automotive Deployment Options Projection Tool</td>
</tr>
<tr>
<td>BETO</td>
<td>Bioenergy Technologies Office</td>
</tr>
<tr>
<td>(B)EV</td>
<td>(Battery) Electric Vehicle</td>
</tr>
<tr>
<td>COBRA</td>
<td>Co-Benefits Risk Assessment Screening Model</td>
</tr>
<tr>
<td>FASTSim</td>
<td>Future Automotive Systems Technology Simulator</td>
</tr>
<tr>
<td>FCEV</td>
<td>Fuel Cell Electric Vehicle</td>
</tr>
<tr>
<td>FCTO</td>
<td>Fuel Cells Technologies Office</td>
</tr>
<tr>
<td>GH2</td>
<td>Gaseous Hydrogen</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model</td>
</tr>
<tr>
<td>H2A</td>
<td>Hydrogen Analysis</td>
</tr>
<tr>
<td>H2FAST</td>
<td>Hydrogen Financial Analysis Scenario Tool</td>
</tr>
<tr>
<td>ICEV</td>
<td>Internal Combustion Engine Vehicle</td>
</tr>
<tr>
<td>LH2</td>
<td>Liquid Hydrogen</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>SERA</td>
<td>Scenario Evaluation and Regionalization Analysis models</td>
</tr>
<tr>
<td>WTP</td>
<td>Well-to-Pump</td>
</tr>
<tr>
<td>WTW</td>
<td>Well-to-Wheels</td>
</tr>
</tbody>
</table>
References (for Indicators on Slide 9)


