

## **Emissions Modeling: GREET<sup>™</sup> Life Cycle Analysis**

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#### Acronyms

AEO: Annual Energy Outlook **HEV: Hybrid Electric Vehicles** AHSS: Advanced High-Strength Steel HSS: High Strength Steel ANGA: America's Natural Gas Alliance **ICEV:** Internal Combustion Engine Vehicle API: American Petroleum Institute LCA: Life Cycle Analysis **BEV: Battery Electric Vehicles**  $\Box$ LCFS: Low Carbon Fuel Standard BIW: Body In White LDV: Light Duty Vehicles C2G: Cradle-to-Grave LNG: Liquefied Natural Gas CARB: California Air Resources Board LP: Linear Programming CFRP: Carbon Fiber Reinforced Polymer LPG: Liquefied Petroleum Gas CMU: Carnegie Melon University Mi: Mile **CNG: Compressed Natural Gas** Mg: Magnesium Denver-Julesburg **MOVES: MOtor Vehicle Emission Simulator DLA: Defense Logistics Agency** MPGDE: Miles Per Gallon of Diesel Equivalent **DOD:** Department of Defense MPGGE: Miles Per Gallon of Gasoline Equivalent DOE: Department of Energy NREC: North American Electric Reliability Corporation eGRID: Emissions & Generation Resource Integrated NG: Natural Gas Database NOAA: National Oceanic and Atmospheric Administration EIA: Energy Information Administration NREL: National Renewable Energy Laboratory **EPA:** Environmental Protection Agency **ORNL: Oak Ridge National Laboratory EREV: Extended Range Electric Vehicle** PHEV: Plug-in Hybrid Electric Vehicle ERG: Eastern Research Group **RFO: Residual Fuel Oil** FAA: Federal Aviation Administration **RFS: Renewable Fuel Standard** FCEV: Fuel Cell Electric Vehicle SMR: Steam Methane Reforming FFV: Flexible Fuel Vehicles Stl: Steel FRA: Federal Rail Administration US DRIVE: U.S. Driving Research and Innovation for Vehicle GFRP: Glass Fiber Reinforced Polymer efficiency and Energy sustainability **GHG:** Greenhouse Gases VTO: Vehicle Technologies Office GREET: Greenhouse gases, Emissions, and Energy use in W. Al: Wrought Aluminum Transportation WTP: Well-To-Pump HDV: Heavy Duty Vehicles WTW: Well-To-Wheels

## **Project overview**

## Timeline

- Start: FY94
- End: Annual
- % complete: 70% (for FY15)

## Budget

- Funding for FY14: \$550K (100% from DOE)
- Funding for FY15: \$550K (100% from DOE)

### **Barriers to Address**

- Indicators and methodology for evaluating environmental sustainability
- Evaluate energy and emission benefits of vehicle/fuel systems
- Overcome inconsistent data, assumptions, and guidelines

## **Partners/Collaborators**

- In Kind:
  - NREL, ORNL, U. of Wisconsin Madison
  - Sasol Synfuels, Jacobs Consultancy
  - Other agencies (EPA, CARB, FRA, FAA, DOD-DLA-Energy)
  - Industry stakeholders (US DRIVE)

#### Supported:

Stanford University, UC Davis, ERG, Great Plain Institute

# The GREET<sup>™</sup> (<u>G</u>reenhouse gases, <u>R</u>egulated <u>E</u>missions, and <u>E</u>nergy use in <u>T</u>ransportation) model evaluates alternative vehicle/fuel systems

- With support from DOE since 1994, GREET has been developed to include over 100 fuel pathways and 85 vehicle/fuel systems (VTO sole early sponsor)
- Most recent GREET version (GREET1\_2014) was released in Oct. 2014
- GREET user base grew to over 23,000 registered users worldwide
- GREET is employed by regulatory agencies for WTW evaluation of various fuels (e.g., California for LCFS and EPA for RFS2)
- GREET and its reports are available on the GREET website <a href="https://greet.es.anl.gov/">https://greet.es.anl.gov/</a>



VEHICLE CYCLE (GREET 2 Series)

## **Relevance and project objectives -- to address VTO identified** barriers

#### Overcome inconsistent data, assumptions, and guidelines

- ✓ Develop the GREET model as a consistent platform for life cycle analysis (LCA) of vehicle/fuel systems
- $\checkmark~$  GREET LCA scope includes fuel cycle and vehicle cycle
- ✓ Interact with agencies, research institutes, and companies to develop reliable data for GREET LCA
- Develop indicators and methodology for evaluating environmental sustainability
  - ✓ Continue to examine emerging LCA methods and issues, and incorporate into GREET
  - Identify major contributors along the supply chain to life-cycle energy use and emissions
  - Addition of new sustainability metrics such as water consumption and detailed examination of methane leakage in NG supply chain

### Evaluate energy and emission benefits of vehicle/fuel systems

- ✓ Continue to update life-cycle energy use and emissions for baseline fuels
- $\checkmark$  Evaluate energy and emissions of natural gas and electric vehicle technologies

## Approach -- GREET methodology and data sources

#### GREET LCA methodology

- Use widely accepted LCA methods and protocols (e.g., ISO)
- Address transportation-related unique LCA issues: system boundary, co-product methods, technology advancements over time
- Maintain openness and transparency of a LCA platform with GREET

#### Extensive databases in GREET

- Data sources for fuel and vehicle technologies
  - Open literature
  - Fuel production: simulation results with models such as ASPEN Plus and refinery LP models for fuel productions
  - Vehicles: simulation results from models such as Autonomie for fuel economy and EPA MOVES for emissions
  - Technology developers and companies (energy and auto companies)

#### Data variation and uncertainty

- Temporal and spatial variations in data reflect technology and geographic differences
- Stochastic modeling is built in GREET; sensitivity analysis can be readily done inside of GREET

## **Technical accomplishments**

- Addressed baseline petroleum gasoline and diesel
  - Oil sands and petroleum refineries
- Examined natural gas pathway GHG effects with methane leakage uncertainty
  - Impacts on LDVs and HVDs
- Expanded GREET to include water consumption for vehicle/fuel systems
  - > As a new sustainability metric
- Updated manufacturing of vehicles and vehicle components
  - Impacts of vehicle lightweighting
- Extend GREET.net to add usability and functionality to GREET users
  - New modeling platform

#### **Accomplishment** -- baseline petroleum gasoline and diesel: petroleum products and individual refineries vary in GHGs



Updated refinery products CO2 intensity with LP modeling of 43 large U.S. refineries (~70% U.S. refining capacity)

✓ Reliable estimates for GHG emissions are needed for baseline petroleum fuels

#### **Accomplishment -- baseline petroleum gasoline and diesel:** *quantify oil sands GHG intensity*



Developed four oil sands pathways in GREET using actual field operation data.

✓ Oil sand share in US crude mix is projected to increase to 14% by 2030

### Accomplishment -- natural gas pathway GHGs: methane leakage varies between two approaches

Sector	CH <sub>4</sub> Emissions: Percent of Volumetric NG Produced (Gross)												
	EPA - Inventory 5 yr avg (2011)	CMU - Marcellu s Shale (2011)	NREL - Barnett Shale (2012)	API/ ANGA Survey (2012)	NOAA - DJ Basin	NOAA - Uintah Basin (2013)	Exxon Mobil (2013)	EPA - Inventory 2011 data (2013)	Texas	EPA - Inventory 2012 data (2014)	Stanford (2014)	IUP - Bakken (2014)	IUP - Eagle Ford (2014)
Gas Field	1.18		0.9	0.75	2.3-7.7	6.2-	0.6	0.44	0.42	0.33		2.8-	2.9-
						11.7						17.4	15.3
Completion/			0.7					0.17	0.03	0.04			
Workover													
Unloading			0					0.04	0.05	0.05			
Other			0.2					0.22	0.24	0.24			
Sources			0.2					0.23	0.34	0.24			
Processing	0.16		0				0.17	0.16		0.15			
Transmission	0.38		0.4				0.42	0.34		0.35			
Distribution	0.26							0.23		0.21			
Total	1.98	2.2						1.17		1.03	3.6-7.1		

- Studies in **GREEN** are with bottom-up approach: measuring emissions of individual sources -> aggregating emissions along supply chain
- Studies in RED are with top-down approach: measuring CH4 concentration above or near fields/cities -> deriving CH4 emissions -> attributing emissions to NG-related activities

Examined methane leakage along natural gas (NG) supply chain

Domestic, abundant, and low cost NG is being considered as a potential transportation fuel

CH4 leakage can deter NG pathway GHG benefits

### Accomplishment -- natural gas pathway GHGs: methane leakage and CNGV efficiency determine CNGV GHG impacts



With bottom-up leakage, CNGVs have ~10-20% GHG reductions
With top-down leakage, CNGVs may increase GHGs

#### Accomplishment -- natural gas pathway GHGs: LNG HDVs show GHG risk relative to diesel HDVs



✓ Efficient NG engines are key to manage NG HDV GHG risk

# Accomplishment-- water consumption as a new sustainability metric is developed in GREET



DOE energy-water nexus addresses energy and water issues together

✓ Water consumption for vehicle/fuel systems can occur at different WTP stages of fuel pathway

# **Accomplishment** -- vehicle and component manufacturing: material substitution for lightweighting can have GHG implications



Lightweighting is pursued by OEMs for MPG gains

 Replacement of steel parts by lighter materials offers weight reduction opportunities but with various GHG emissions impacts

# Accomplishment -- vehicle and component manufacturing: holistic LCA results show vehicle cycles are small contributors to LCA differences



Provides answer to the debate on whether new vehicle materials/technologies offset benefits of efficiency gains

✓ Holistic LCA is required to have complete and objective results

#### Accomplishment -- GREET.net continues to be upgraded: modular user interface & structured database in GREET.net



## Collaboration and interaction are key to GREET success

- Argonne reaches out other organizations for their expertise in enhance LCA research and GREET development
  - Stanford University and UC Davis: examined Canadian oil sands and Bakken and Eagle Ford light crude
  - Jacobs Consultancy: conducted detailed LP modeling of US refineries
  - Eastern Research Group (ERG): updated stationary combustion emissions
  - Univ. of Wisconsin and Great Plain Institute: supported GREET.net development
- Interactions with agencies have benefited Argonne GREET development and applications
  - Other national labs: NREL, ORNL
  - CARB in their CA-GREET development
  - US DRIVE cradle-to-grave (C2G) working group: provided valuable input to C2G analysis and critical GREET review

### Future work

Continue to update and upgrade GREET to serve DOE and stakeholders

- Expand GREET2 to include additional lightweighting materials and their GHGs
- Examine GHGs of US crude supplies (light shale oil, heavy crudes)
- Expand water consumption in GREET for alternative fuel pathways and vehicle technologies
- Continue expanding and updating GREET with new data for emerging fuel pathways and vehicle technologies
- GREET LCA applications for VTO and stakeholders
  - Continue C2G analysis and support for US DRIVE partnership
  - Examine efficiency and emission reduction potentials of HDV fuels and technologies
  - Updated GHG results of PEV technologies (e.g., PEV electric use rate, battery manufacturing/recycling; PEV usage patterns)

#### Community engagements

- Interact with OEMs and US DRIVE Tech Teams
- Communicate with other agencies such as EPA and DOT
- Publish LCA results and GREET development in peer-reviewed reports and journal articles

### Summary

- GREET has been a relevant tool to serve VTO and other stakeholders to address GHGs and sustainability of vehicle/fuel systems
  - > A consistent LCA platform to compare environmental performance of technologies and fuels
  - Assist R&D decisions for GHG reductions of VTO portfolios
- Argonne has improved GREET approach
  - Gathered reliable data to develop and expand GREET databases
  - > Examined additional environmental attributes such as water consumption
  - Evaluated trade-offs between GHG intensity of lightweighting materials and their contribution to efficiency
- Key technical accomplishments in 2014 include
  - Updated baseline gasoline and diesel pathways
  - Continued to monitor NG methane leakage results and LCA impacts
  - > Evaluated impact of lightweighting materials in overall GHG benefits
  - Identified key stages impacting water consumption at different WTP stages for fuel pathways
- External collaborations with other labs, agencies, OEMs, energy companies, and universities have been key to Argonne LCA success

## Selected recent publications

- Elgowainy, A., Han, J., Cai, H., Wang, M., Forman, G.S., and DiVita, V.B. (2014) "Energy Efficiency and Greenhouse Gas Emissions Intensity of Petroleum Products at US Refineries," Environmental Science and Technology, doi: 10.1021/es5010347.
- Forman, G.S., Divita, V.B., Hao Cai, J.-H., Elgowainy, A., and Wang, M. (2014) "US Refinery Efficiency: Impacts Analysis and Implications for Fuel Carbon Policy Implementation," Environmental Science and Technology, doi: 10.1021/es501035a.
- Han, J., Forman, G., Elgowainy, A., Cai, H., Wang, M., and DiVita, V. (2015) "A Comparative Assessment of Resource Efficiency in Petroleum Refining," accepted for publication in Fuel.
- Cai, H., Brandt, A., Yeh, S., Englander, J., Han, J., Elgowainy, A., and Wang, M. Well-to-Wheels Greenhouse Gas Emissions of Canadian Oil Sands Products: Implications for U.S. Petroleum Fuels. Submitted to Environmental Science & Technology. 2015.
- Kelly, J.C.; Sullivan, J.L.; Burnham, A; and Elgowainy, A. Impacts of Vehicle Weight Reduction via Material Substitution on Life-Cycle Greenhouse Gas Emissions. Submitted to Environmental Science and Technology.
- Han, J., Chen, H., Elgowainy, A., Vyas, A., and Wang, M. (2014) "Rail Module Expansion in GREET," Argonne National Laboratory. Available at https://greet.es.anl.gov/publication-rail-module
- Cai, H, A Burnham, W Hang, A Vyas, M Wang, 2015, "The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles, "Argonne National Laboratory report under review.
- Lampert, D., Cai, H., Wang, Z., Keisman, J., Wu, M., Han, J., Dunn, J., Frank, E., Sullivan, J., Elgowain, A., and Wang, M. (2015) "Development of a Life Cycle Inventory of Water Consumption Associated with the Production of Transportation Fuels," Argonne National Laboratory report under review.
- "Cradle to Grave Lifecycle Analysis of Vehicle and Fuel Pathways," 2014, DOE Record 14006, March 25. Available at http://www.hydrogen .energy.gov/pdfs /14006\_cradle\_to\_grave\_analysis.pdf .

# **Technical backup slides**

Accomplishment: Fuel economy gains from lightweighting are based on fuel reduction values (FRV) assuming powertrain resizing to match lightweighted vehicle



## Accomplishment: fuel economy gain quickly offsets GHG emissions increase with material substitution



Production Phase

**Operation Phase** 

Kelly et al., 2015, submitted to ES&T

**Operation phase GHG reductions are many times greater than production phase GHG increases** 

## Accomplishment: updated hydropower electricity

Mean water consumption estimate much lower than previous studies and closer to other electricity generation technologies

