January 27, 2025

Introducing R&D GREET® 1: Fuel Cycle Analysis

2:00-3:00 p.m. CT

Instructors

Gabrielle Olson, Great Plains Institute

Uisung Lee, Argonne National Laboratory

Argonne National Laboratory Subject Matter Experts

Longwen Ou, Uisung Lee

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

R&D GREET disclaimer

The R&D GREET effort at Argonne National Laboratory is supported by the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy and Carbon Management, the Office of Clean Energy Demonstration, the Office of Technology Transitions, the Office of Nuclear Energy, and ARPA-E of the US Department of Energy (DOE) under contract DE-AC02-06CH11357.

Argonne's R&D GREET is to inform the life cycle analysis of technical community. Not all pathways and data in R&D GREET are appropriate for use in circumstances where a high level of quantitative certainty or precision is required. GREET is referenced in numerous independent state and federal compliance and incentive programs (including solicitations, rulemakings, and tax incentives), but it is important to note that R&D GREET is not the version used by any of these specific programs. Argonne does not warrant that use of R&D GREET is consistent with the requirements of any particular regulatory or incentive program.

GREAT PLAINS INSTITUTE Argonne NATIONAL LABORATORY U.S. Department of ENERGY

GREET end-user licensing terms and conditions

Commercial use:

For commercial use, please contact www.anl.gov/partners.

Non-commercial use:

This license is based on the Creative Commons Attribution-Non Commercial 4.0 International Public License, with the following modified definition. Non-Commercial means internal use (including use for internal business or operational purposes by for-profit entities), use by non-profit entities, or use for United States federal, state, or local government purposes. Government purposes include work performed pursuant to a United States federal, state, or local government funding agreement, and work performed by or on behalf of the United States federal, state, or local government. For purposes of this Public License, the exchange of the Licensed Material for other material subject to Copyright and Similar Rights by digital file-sharing or similar means is Non-Commercial provided there is no payment of monetary compensation in connection with the exchange.

Redistribution and use of the GREET software are permitted for non-commercial uses and provided that the following conditions are met:

1. Redistributions of the GREET software must retain the above copyright notice, this list of conditions, and the following disclaimer. Modification or reverse compilation of the source code is not permitted.
2. Neither the names of UChicago Argonne, LLC or the Department of Energy nor the names of its contributors may be used to endorse or promote products derived from this software without prior written permission.
3. The software redistribution, if any, must include the following acknowledgment: "This product includes software produced by UChicago Argonne, LLC under Contract No. DE-AC02-06CH11357 with the Department of Energy."
4. Any published results should indicate that the GREET software was developed by Argonne National Laboratory. If you publish results generated using GREET you should identify the GREET software version number. If you publish results generated using input data other than the input data supplied with the GREET software you must indicate that these results relied upon changed input data.

Table of contents

How to Download R&D GREET

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Downloading R&D GREET 2023 Rev. 1

1. Go to Argonne's GREET Website: https://greet.anl.gov/greet_1_series
2. Enter your information and select **Submit**
3. **Scroll down** to the most recent download under Prior Revisions
4. Click on GREET 1 2023r1
5. Once the model is downloaded, extract the contents to any folder that is not the Downloads folder
6. Right-click on each of the Excel files in your newly extracted folder, select properties, check **"Unblock,"** then select "Apply"

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

GREET Model Tutorial Videos

For video tutorials on downloading R&D GREET and more, see the GREET Tutorials YouTube Channel

GREAT PLAINS INSTITUTE
Argonne NATIONAL LABORATORY
U.S. Department of ENERGY

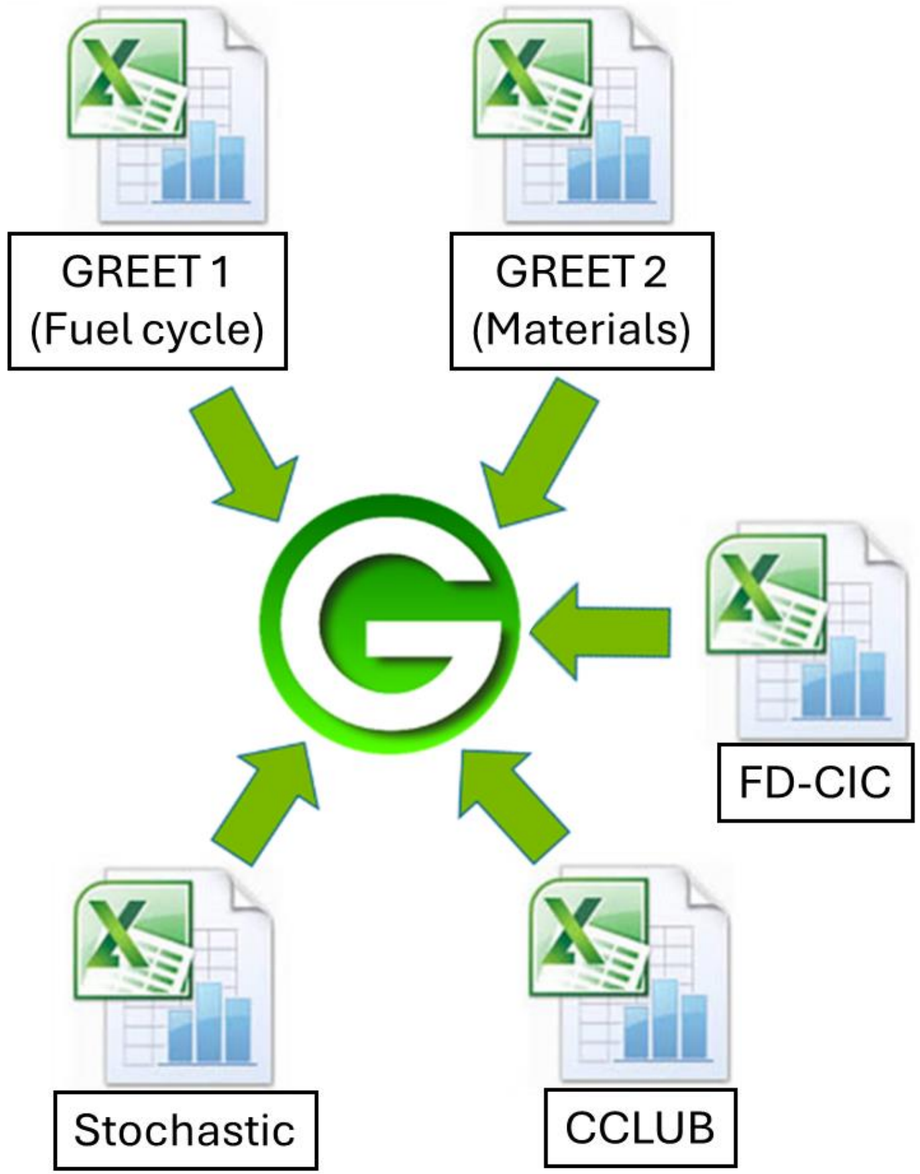
What Makes Up R&D GREET?

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

What makes up R&D GREET?



R&D GREET 1: Fuels Cycle - energy/products/fuels

R&D GREET 2: Vehicle/material Cycle - vehicles/materials

CCLUB - land-use and land-management changes

FD-CIC (Feedstock Carbon Intensity Calculator) - producing domestic and international agricultural feedstocks

Stochastic Toolkit - running stochastic analyses and determining error bars on LCA estimates

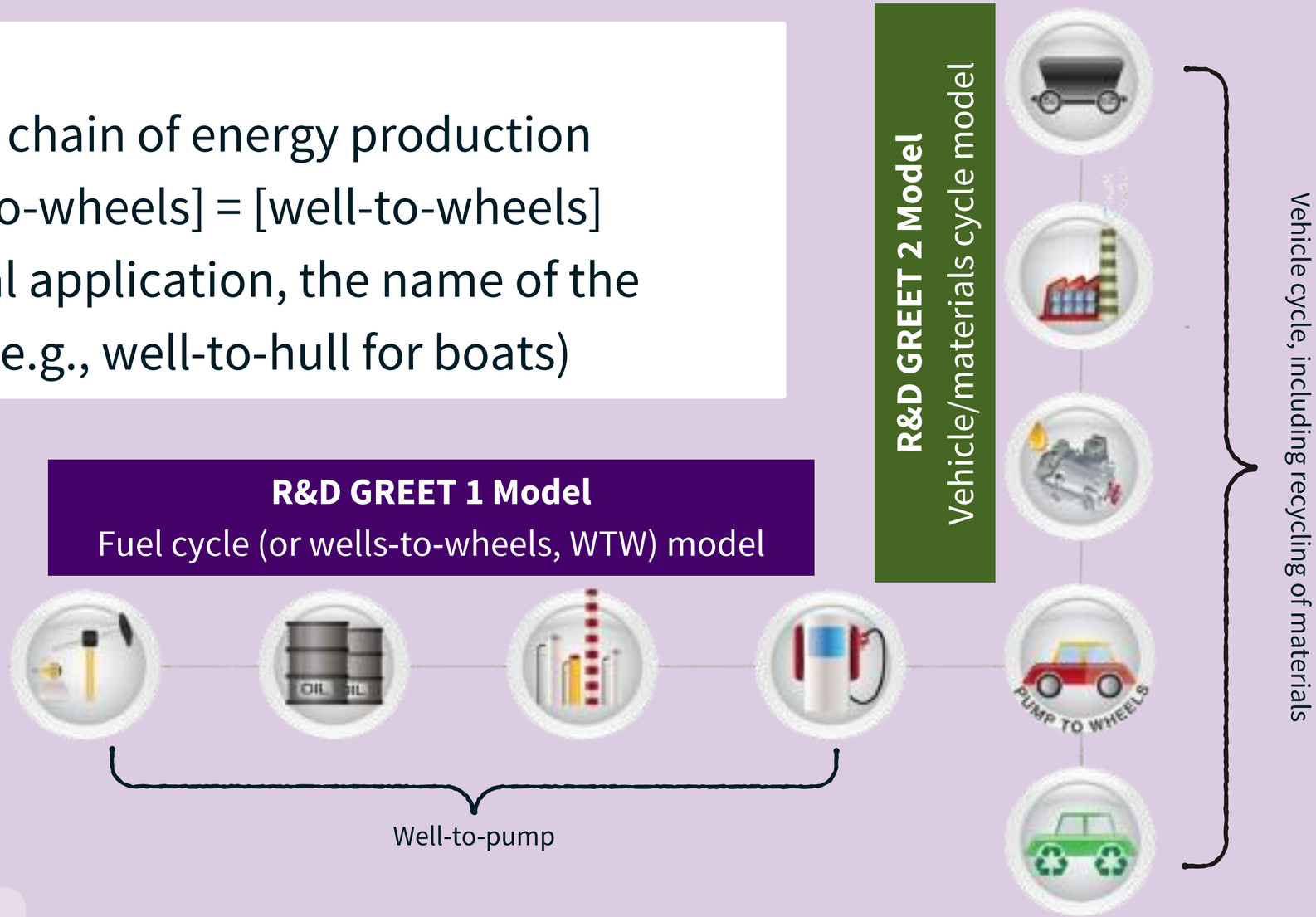
GREAT PLAINS INSTITUTE Argonne NATIONAL LABORATORY U.S. Department of ENERGY

The R&D GREET model framework

R&D GREET 1: Fuel Cycle

- Includes the entire supply chain of energy production
- [Well-to-pump] + [pump-to-wheels] = [well-to-wheels]
  - Depending on the final application, the name of the results could change (e.g., well-to-hull for boats)

Interacts with R&D GREET 2 for material cycle results



R&D GREET 1: Fuel Cycle

Raw Material Extraction

Feedstock Transportation

Fuel Production

Fuel Delivery and Dispensing

Fuel Use

Life Cycle Assessment (LCA) Methodology in R&D GREET

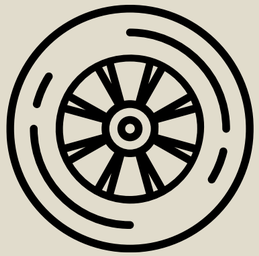
GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Simplified WTW pathway example

Process Progression



Emissions

Emissions

Emissions

Feedstock Stages
Production, Transportation, and Storage

Fuel Stages
Production, Transportation, Distribution, and Storage

Vehicle Operation
Vehicle Refueling, Fuel Combustion/conversion, and Fuel Evaporation

Energy Materials

Energy Materials

Well-to-Wheels (WTW) System Boundary

WTP Stages

PTW Stage

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

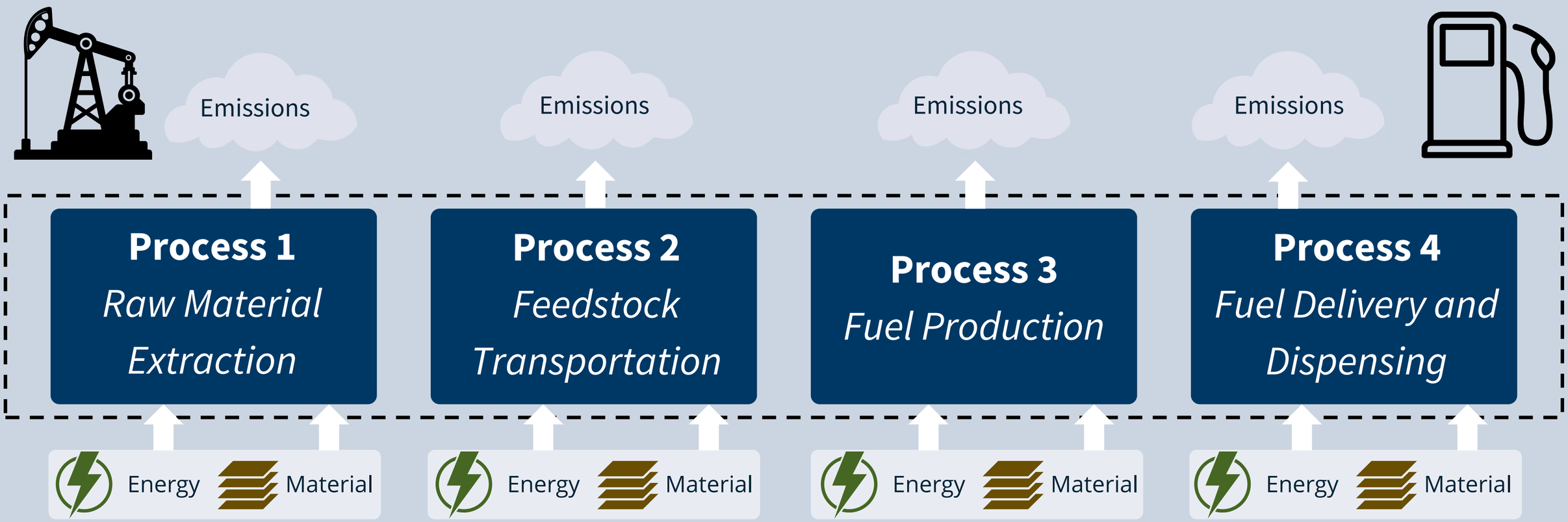
U.S. Department of ENERGY

Well-to-Pump (WTP) Methodology

Fuel Production

GREAT PLAINS INSTITUTE
Argonne NATIONAL LABORATORY
U.S. Department of ENERGY

Simplified WTP pathway example: *fuel production*



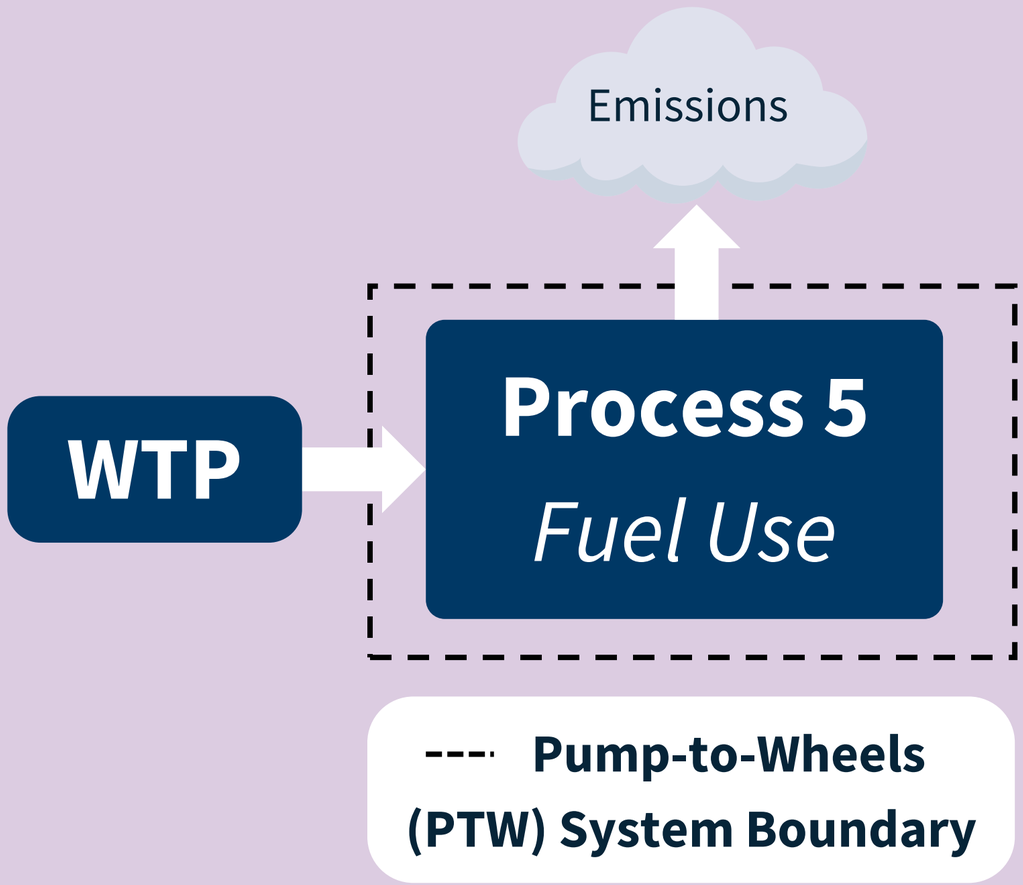
GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Pump-to-Wheels (PTW) Methodology

Vehicle Operation

GREAT PLAINS INSTITUTE
Argonne NATIONAL LABORATORY
U.S. Department of ENERGY

PTW block flow diagram examples: *fuel use*



Pump-to-Wheels (PTW) System Boundary

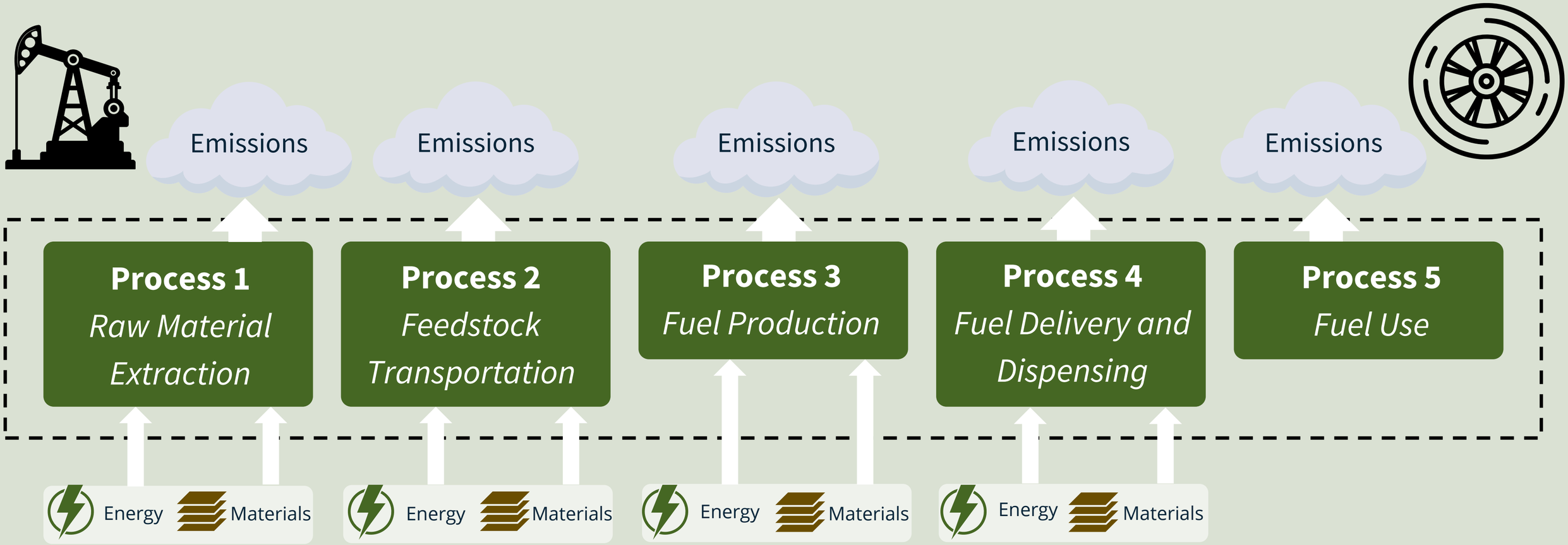
Pump-to-Wake (PTWa) System Boundary

Pump-to-Hull (PTH) System Boundary

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

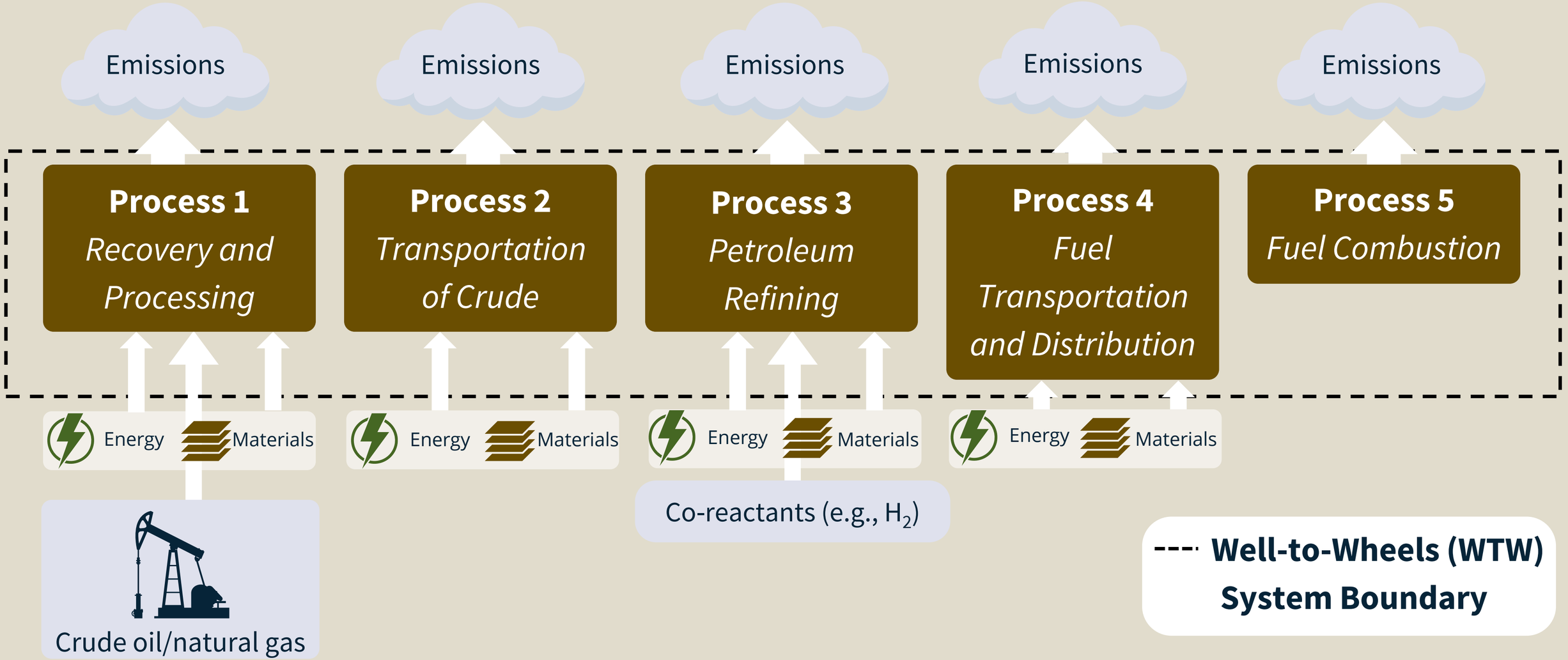
Well-to-Wheels (WTW) Methodology

Simplified WTW life cycle in R&D GREET



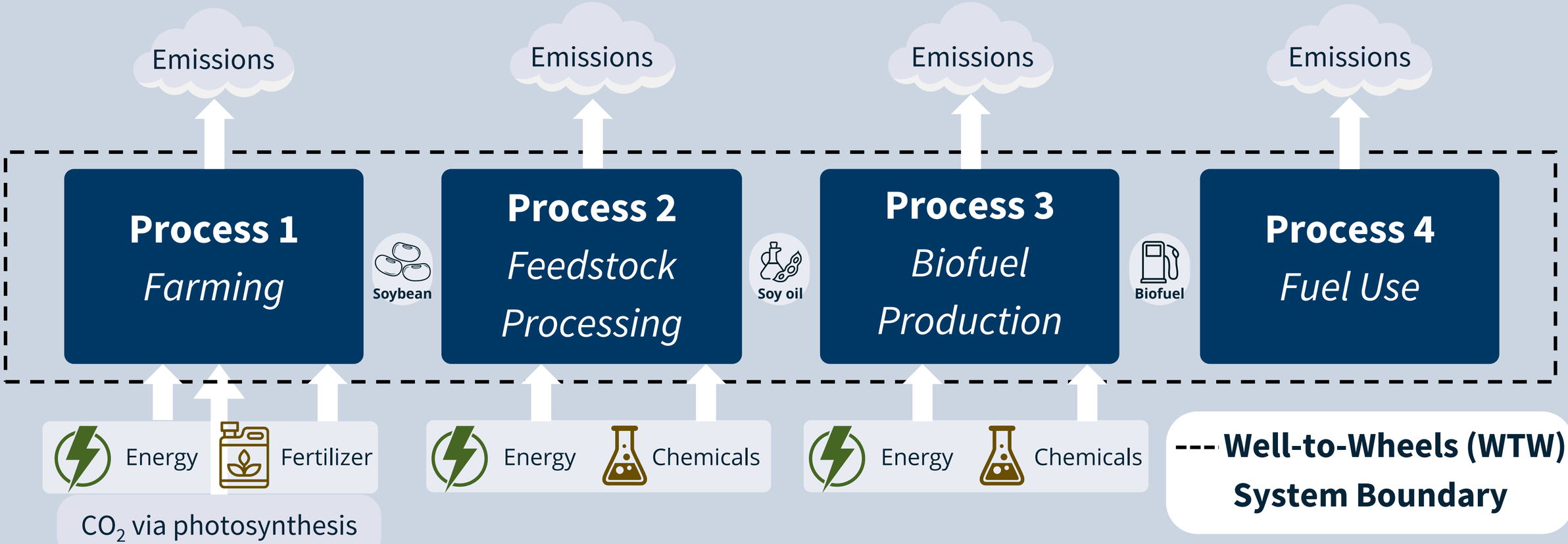
GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Simplified WTW life cycle of petroleum fuels in R&D GREET



GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Simplified WTW life cycle of biofuels in R&D GREET



GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Transportation processes in R&D GREET 1

Transportation processes occur at many stages of the life cycle of products

Transportation Modes

Ocean tanker | barge | truck | rail | pipeline

Parameters

Payload (ton), energy consumption (Btu/ton-mi), distance (mi), mode share (%), fuel type (diesel, residual oil, natural gas, and electricity)

Transportation modes require fuels and the production of fuels requires transport

R&D GREET uses an iterative calculation procedure to ensure results are self-consistent

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

R&D GREET energy/transportation datasets

R&D GREET Leverages Data

Feedstock specifications, fuel specifications, major parameters of various fuel production technologies (e.g., fuel yield, energy inputs, and material inputs), major parameters of various material production technologies, vehicle fuel economy and emission factors

All parameters, conditions, and assumptions are clearly documented in journal articles, technical reports, and memos

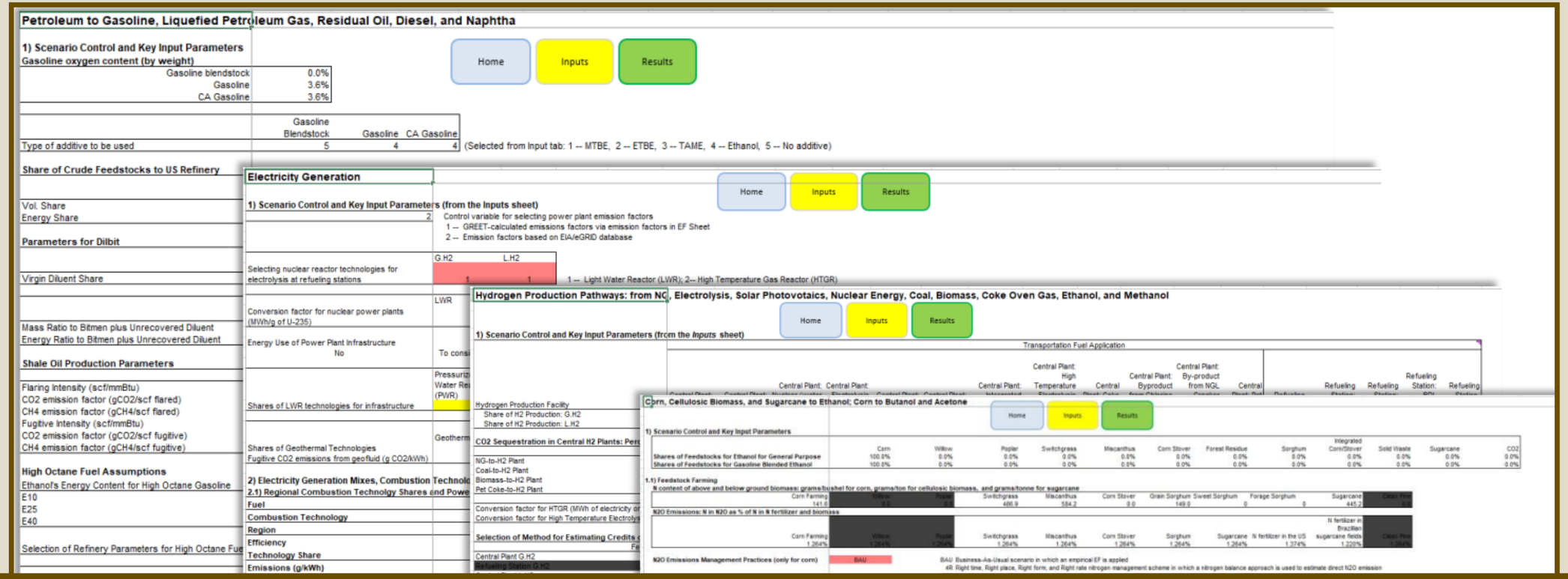
https://greet.anl.publications

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

All Tabs in R&D GREET 1

GREAT PLAINS INSTITUTE
Argonne NATIONAL LABORATORY
U.S. Department of ENERGY

Tabs in R&D GREET 1



R&D GREET Excel is run on Microsoft Excel, which allows calculations to be run on several interconnected "tabs"

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Categories of tabs in R&D GREET 1

Inputs Tab

Users can customize their LCA calculation

Fuel-specific Tabs

Users can further customize their specific fuel and provide detailed information and results for a specific fuel

Examples: *“Hydrogen” and “NG”*

“X”_TS Tabs

Indicates data that varies in time to allow for “historical” or “projected” LCA (typically from 1990s -> 2050)

Users can model the effects of specific emissions reduction strategies

Examples: *“Fuel_Prod_TS” and “Car_TS”*

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Categories of tabs in R&D GREET 1

Fuel_Specs Tab

Fuel properties and unit conversion

EF Tab

Emission factors of fuels when used in various technologies

Results Tabs

Results of the LCA calculation

Results: *WTP and light-duty vehicle WTW results*

HDV_WTW: *WTW results of heavy-duty vehicles*

JetFuel_WTWa: *Well-to-wake results for aviation LCA*

Rail_WTW: *WTW results for rail*

Tractor_WTW: *WTW results for a tractor*

Marine_WTH: *Well-to-hull results for marine vehicles*

Vehicles in R&D GREET

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

On-Road Vehicles in R&D GREET

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Light-duty vehicles (LDVs) in R&D GREET

Types of LDVs in R&D GREET

Passenger cars, sports utility vehicles (LDT1) and pickup trucks (LDT2)

Types of Fuels for LDVs in R&D GREET

Gasoline (E10), diesel, biofuels, different forms of natural gas (NG), electricity, and hydrogen

Time-series Data for Each LDV

LDV fuel economies can be modified in the Car_TS, LDT1_TS, and LDT2_TS tabs

WTP and WTW Results for LDVs in R&D GREET

Summary results can be found in the “Results” tab in R&D GREET 1

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Light-duty vehicles (LDVs) in R&D GREET 1

Types of LDV Technologies in R&D GREET

Internal combustion engine vehicle (ICEV)

Conventional spark ignition (SI)

Spark ignition direct injection (SIDI)

Compression ignition direct injection (CIDI)

Hybrid electric vehicle (HEV)

Plug-in hybrid electric vehicle (PHEV)

Battery electric vehicle (BEV)

Fuel-cell electric vehicle (FCV)

LDVs' fuel economy and emission factors in R&D GREET

Argonne's Autonomie Model

A detailed vehicle simulation model used to estimate energy-consumption using key parametric assumptions including vehicle weights by components

EPA MOVES Model

A model used to calculate criteria air pollutant (CAP) emission factors in R&D GREET except for CO_2 (VOC, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$)

CO_2 Emissions in R&D GREET: Carbon Balance

CO_2 emissions are calculated with using carbon content of fuel and carbon containing emissions (i.e., VOC and CO)

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Medium and heavy-duty vehicles (MHDVs) in R&D GREET

Types of MHDVs in R&D GREET

Combination trucks (long-haul and short-haul), different classes of vocational vehicles, heavy-duty pick up trucks and vans, refuse trucks, and different types of buses

Types of MHDV Technologies in R&D GREET

Spark-ignition engine vehicles, CIDI engine vehicles, HEVs, BEVs, and FCVs

Types of Fuels for MHDVs in R&D GREET

Diesel, biofuels, CNG, LNG, electricity, and hydrogen

Results for MHDVs in R&D GREET

Results will be located on the “HDV_WTW” and “HDV_TS” tabs

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Types of medium and heavy-duty vehicles (MHDVs)

Combination Long-haul Trucks

A truck tractor with one or more trailers, drives more than 200 miles per day, and has a sleeper cab

Class 8b: > 60,000 lb gross vehicle weight rating (GVWR)

Combination Short-haul Trucks

A truck tractor with one or more trailers, drives 200 miles or less per day, and does not have a sleeper cab

Class 8b: > 60,000 lb GVWR

Heavy Heavy-duty Vocational Vehicles

A commercial vehicle typically used in construction

Class 8: > 33,000 lb GVWR

Medium Heavy-duty Vocational Vehicles

A commercial vehicle typically used for regional deliveries

Class 6-7: 19,500-33,000 lb GVWR

Light Heavy-duty Vocational Vehicles

A commercial vehicle typically used for regional deliveries

Class 2b-5: 8,500-19,500 lb GVWR

Heavy-duty Pick up Trucks and Vans

Trucks and vans designed for commercial use

Class 2b-3: 8,500-14,000 lb GVWR

Refuse Trucks

A truck designed to collect garbage

Class 8a: 33,000-60,000 lb GVWR

School/transit buses/inter-city Buses

A bus designed to transport individuals to school, within a city, and between a city respectively

GREAT PLAINS INSTITUTE
Argonne NATIONAL LABORATORY
U.S. Department of ENERGY

Non-Road Vehicles in R&D GREET

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Rail in R&D GREET

Units for Rail in R&D GREET

Per ton-mile, per passenger-mile, and per energy unit (mmBtu/MJ)

Inputs for Rail in R&D GREET

Found on “Rail_PTW” tab

Vehicle Types for Rail in R&D GREET

Freight and passenger: intercity (Amtrak), commuter, light transit, and heavy transit

Fuel Types for Rail in R&D GREET

Gasoline, diesel, biodiesel, renewable diesel, renewable gasoline, dimethyl ether (DME), CNG, LNG, LPG, Fischer-Tropsch diesel (FTD), electricity, and hydrogen

Results for Rail in R&D GREET

Found on “Rail_WTW” tab

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Marine in R&D GREET

Units for Marine in R&D GREET

Per million tonne-km or per defined trip

Inputs and Results for Marine in R&D GREET

Combined and found on “Marine_WTH” tab

Vessel Types for Marine in R&D GREET

Bulk, container-large, and tanker-VLCC

Trip Types for Marine in R&D GREET

Domestic-domestic, domestic-CA, CA-CA, domestic-international, CA-international

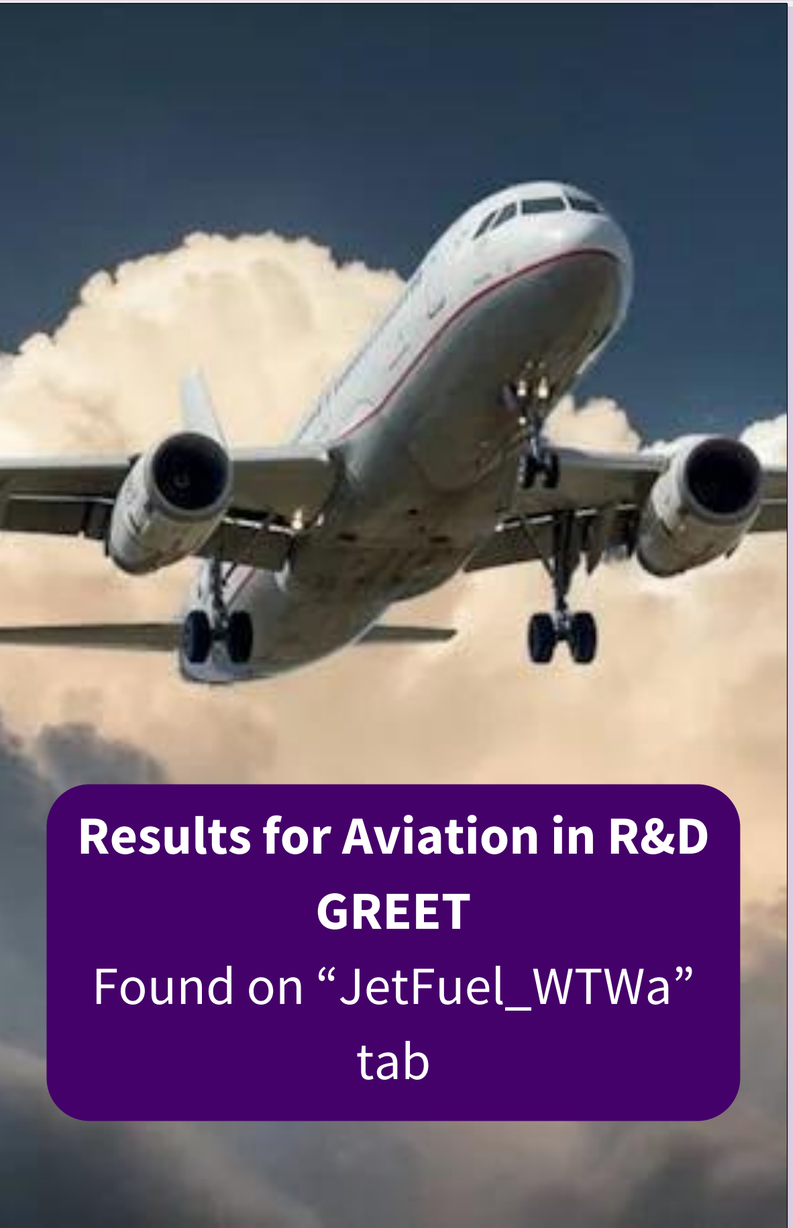
Regions for Marine in R&D GREET

Pacific, Atlantic, Gulf of Mexico, and Great Lakes

Fuel Types

HFO/MGO/MDO, FT-diesel (NG, biomass, biomass/coal, biomass/NG), methanol, LNG, RD, SVO, biodiesel, pyrolysis oil, marine bio oils, e-methanol, eFT fuel, and ammonia

Aviation in R&D GREET



Results for Aviation in R&D GREET

Found on “JetFuel_WTWa” tab

Units for Aviation in R&D GREET

Per passenger-km or per kg-km

Inputs for Aviation in R&D GREET

Found on “SAF_Interface,” “JetFuel_WTP,” and “JetFuel_PTWa” tabs

Aircraft Types for Aviation in R&D GREET

Passenger and freight - single aisle, small twin-aisle, large twin aisle, large quad, and regional jet

Fuel Types for Aviation in R&D GREET

Petroleum jet and sustainable aviation fuels from various sources

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

R&D GREET Capabilities

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

R&D GREET results include several metrics

Energy use

- **Total energy**: fossil energy and renewable energy
- **Fossil energy**: petroleum, natural gas, and coal
- **Renewable/other energy**: biomass, nuclear energy, hydro-power, wind power, and solar energy

Air pollutants

- VOC, CO, NO_x, PM_{10}, $PM_{2.5}$, and SO_x
- Estimated separately for total and urban
- Results can help address environmental justice impacts

Greenhouse gases

- CO_2, CH_4, and N_2O
- CO_2e of the five (combined with their global warming potentials)

Water consumption

- Water consumption by different stages of technology supply chains

R&D GREET scenarios

Each fuel has its own suite of specific inputs the user can change, located on the “inputs” or within the “fuel-specific” tabs

Some Common Inputs

Target year for simulation

Vehicle types and technologies

Technology shares and options

Efficiencies

Electricity grid region

Fossil fuel production infrastructure

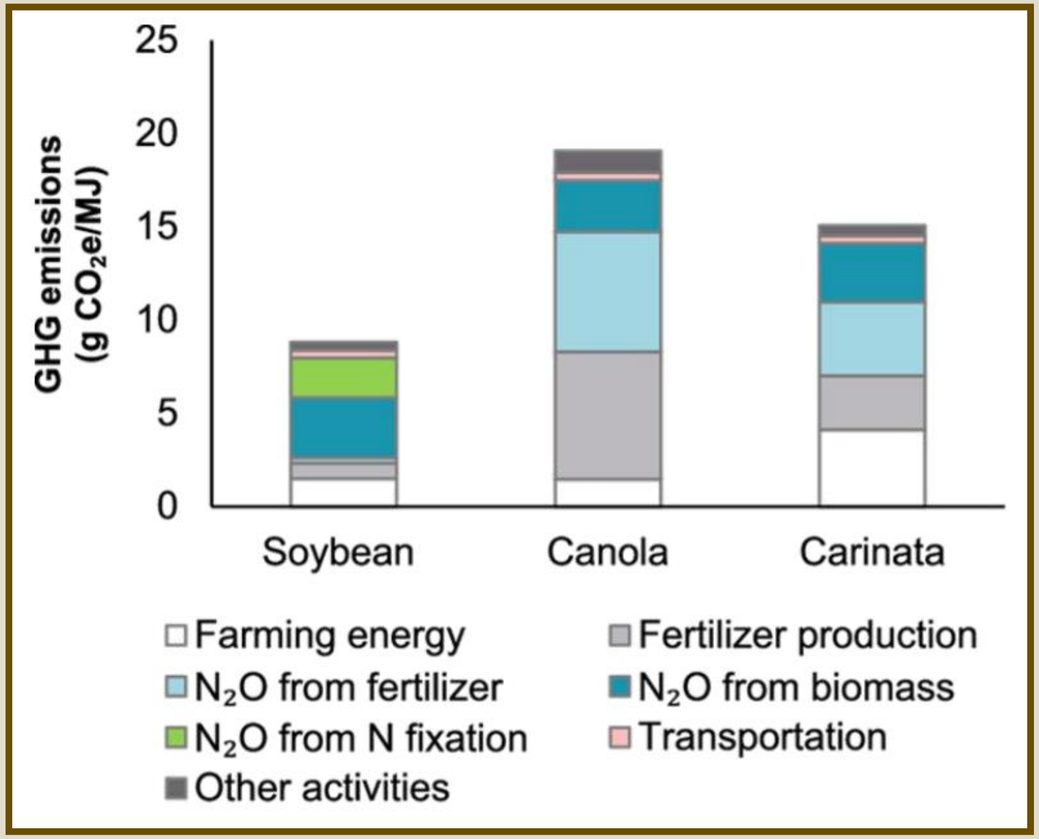
Emission factors

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

Contributions from each parameter on net emissions



- Zu et al., 2022, Environmental Science and Technology

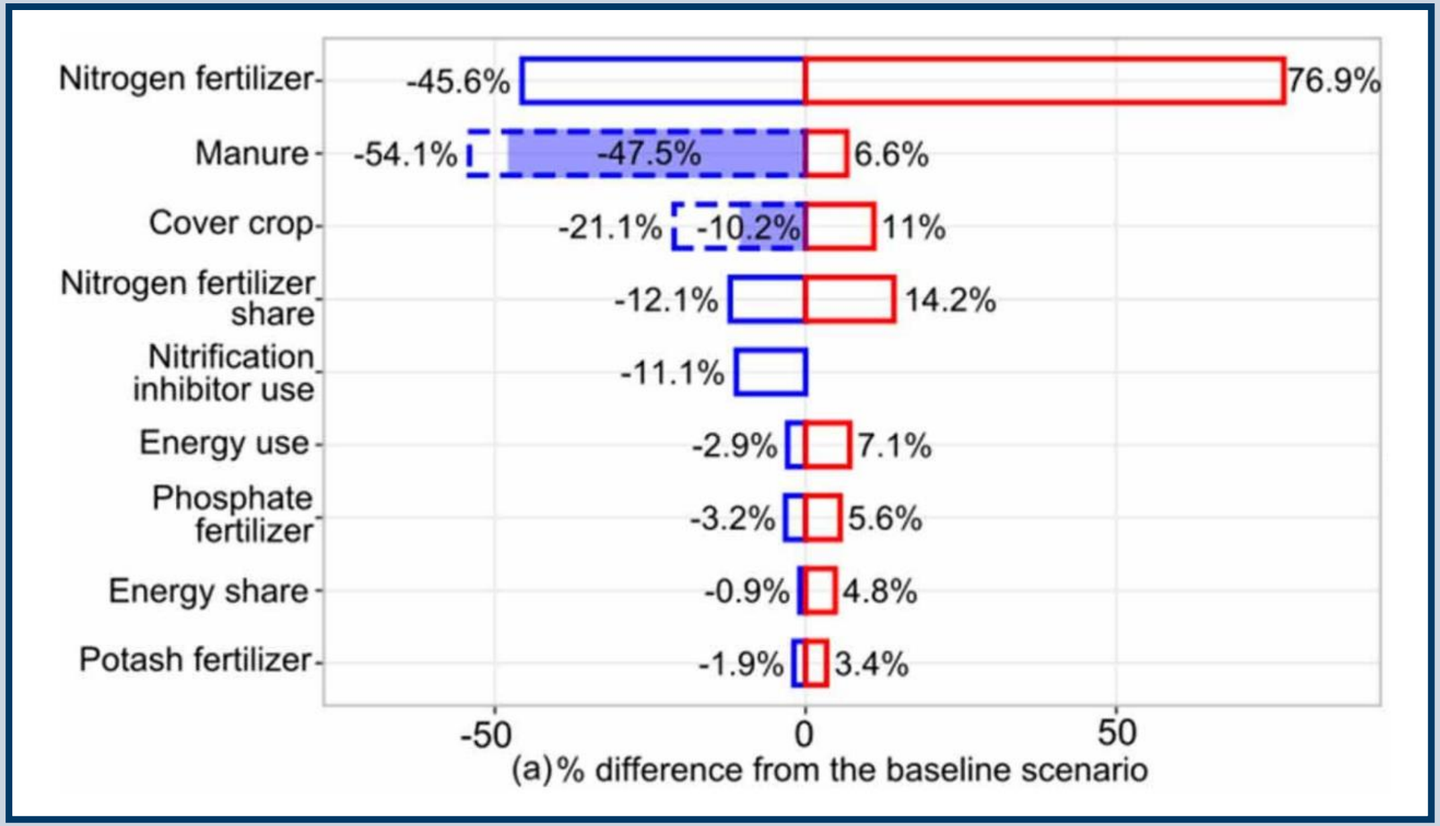
Results can be presented at the **process-level** showing the contribution of major parameters

R&D GREET 1 identifies **hotspots** and **opportunities** for technology improvements

GREAT PLAINS INSTITUTE
Argonne NATIONAL LABORATORY
U.S. Department of ENERGY

R&D GREET stochastic simulation and sensitivity analysis

GHG Sensitivity Analysis



Sensitivity Analysis in R&D GREET

Reveals the impact of each parameter

Stochastic Simulation in R&D GREET

Assigns a probability distribution function, specifies the number of samples and the sampling technique, propagates the uncertainties, and statistically analyzes the outputs

- Liu et al., 2021, Environmental Research Letters

GREAT PLAINS INSTITUTE | Argonne NATIONAL LABORATORY | U.S. Department of ENERGY

Questions?

hcai@anl.gov

golson@gpisd.net

Visit https://greet.anl.gov/

Contributors

Gabrielle Olson, Branden Leonhardt,

Longwen Ou, Uisung Lee, and Hao Cai

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY

THANK YOU

GREAT PLAINS INSTITUTE

Argonne NATIONAL LABORATORY

U.S. Department of ENERGY