

Summary of Expansions and Updates in R&D GREET® 2025

**Energy Systems and Infrastructure Assessment Division
Argonne National Laboratory**

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INTRODUCTION

The research and development (R&D) version of Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET[®]) model, or R&D GREET, is developed by Argonne National Laboratory (Argonne) with the support of the U.S. Department of Energy (DOE) and other federal agencies. R&D GREET is a life cycle analysis (LCA) model, structured to systematically examine the energy and environmental effects of a wide variety of transportation fuels and vehicle technologies in all transportation sub-sectors (i.e., road, air, marine, and rail) and other end-use sectors, and energy technology systems. Argonne has expanded and updated the model in many areas in R&D GREET 2025. This report provides a summary of the expansions and updates.

R&D GREET is designed as an attributional LCA model, but specific consequential effects for certain pathways are included by default when they are scientifically important and/or highly policy relevant. For example, two major consequential elements – induced land use change (ILUC) for biofuels and avoided emissions for certain RNG-based pathways – are implemented by default in R&D GREET because they are highly relevant to our user base and crucial for a comprehensive evaluation of the environmental effects of these technologies. In a future version of R&D GREET, these consequential elements for biofuels and RNG could be more clearly distinguished from core attributional results. We will consider adding a highly visible toggle that would allow users to turn off or adjust these consequential impacts.

EXPANSIONS AND UPDATES

1. NATURAL GAS UPDATE

Life cycle inventory (LCI) data for natural gas (NG) pathways have been updated with the latest datasets published by Khutal et al. (2025). To streamline implementation, the physical properties of NG were aggregated based on delivery shares, reducing the number of property sets and emission-factor technologies. The method for calculating NG equivalent loss has also been revised to use the methane content of NG, merging methane loss and methane-equivalent loss into a single category. These updates are intended to enhance efficiency in R&D GREET Excel, reduce redundancy and complexity, and simplify R&D GREET.NET implementation. In addition, a dedicated basin-to-region (between supply and demand) NG pathway for hydrogen production has been added in the *NG_Basins* tab. This is similar to the separate region-to-region NG pathway for hydrogen production in the *NG_Regions* tab. The Basins NG option for hydrogen production can be enabled from Table 6.9 in the Inputs tab.

Publications:

Zhou, X., Pandey, I., Martinez, S., Shukla, S., Vyawahare, P., Ng, C., Elgowainy A. (2025). *Updated Natural Gas Pathways in R&D GREET 2024 Rev.1*. https://greet.anl.gov/publication-update_ng_2024_Rev1

Pandey, I., Martinez, S., Shukla, S., Zhou, X., Vyawahare, P., Ng, C., Wang, M., Elgowainy A. *Life Cycle Analysis of Natural Gas Supply Chain in the United States*. https://greet.anl.gov/publication-ng_lca_2025

2. FEEDSTOCK PRODUCTION FOR BIOFUELS

2.1 Herbicide Use for Intermediate Winter Camelina Update

In R&D GREET 2024 Rev.1, the glyphosate application rate was assumed to be 4.8 g/kg oilseed, which, combined with a yield of 1,178 kg/ha, results in a total application of 5,654 g acid equivalent (a.e.)/ha. *Acid equivalent* refers to the amount of the glyphosate active ingredient in its acid form, providing a standardized measure for comparing application rates across different commercial formulations.

This assumed rate, however, exceeded the maximum application rate of Roundup Powermax 3 (1,260 g a.e./ha), a common glyphosate product from Bayer. For this product, growers typically apply only about 50% of the recommended maximum application rate for pre-planting burndown, implying a practical rate of approximately 630 g a.e./ha. ANL consequently reached out to Dr. Berti at North Dakota State University, whose work in 2017 reported a glyphosate application rate of 5.1 kg active ingredient (a.i.)/ha and was a major data source for the previous assumption in R&D GREET 2024 Rev.1. Dr. Berti acknowledged that the reported rate was substantially higher than current agronomic practices and may have reflected older assumptions or different glyphosate formulations. In a recent study that is currently under review, Dr. Berti et al. consider a much lower glyphosate application rate of 1.16 kg a.i./ha for winter camelina, which aligns with typical grower practices and commonly applied glyphosate formulations.

Based on these inputs, R&D GREET 2025 has been revised to adopt a glyphosate application rate of 1.16 kg a.i./ha (≈ 470 g a.i./acre) for winter camelina.

2.2. Canola Farming Life-Cycle Inventory Data Updates

Canola (*Brassica napus* L.) cultivation is a key component of North American agriculture, serving both as a food-grade oil source and a biofuel feedstock. The LCI data for U.S. canola in R&D GREET 2025 are derived from national survey data and an LCA report by (S&T)² Consultants Inc. on Canadian spring canola farming, given the agroecological and management similarities with northern U.S. spring canola systems. Since winter canola accounts for less than 5% of total U.S. canola acreage (U.S. Canola Association, 2024), this dataset is considered representative of the U.S. national average.

In R&D GREET 2024, we updated parameters related to soil N₂O emissions associated with synthetic nitrogen fertilizer and crop residue nitrogen. Notably, the data source for crop residue nitrogen was switched from Janzen et al. (2003) to Thiagarajan et al. (2018), intended to reflect the more recent study. After consulting with Environment and Climate Change Canada (ECCC), responsible for compiling Canada's National GHG Inventory, we reverted the data source to Janzen et al. (2003) in R&D GREET 2025 since ECCC confirmed its representativeness for canola. We also incorporated corrections from the (S&T)² Consultants LCA report regarding on-farm diesel and electricity consumption.

In addition to spring and winter canola, we included intermediate winter canola as an added potential biofuel feedstock. When planted between regular cropping cycles on otherwise fallow land, intermediate winter canola offers co-benefits such as reducing soil erosion, preventing nutrient loss, and providing pollinator habitat, while generating additional revenue from harvested seeds. The LCI for intermediate winter canola is based on third-party field trial data spanning over 4,000 acres and 11 million pounds of crop. This work is in preparation for journal publication (Kwon et al., forthcoming).

2.3. Dedicated Energy Crop Farming Life-Cycle Inventory Data Updates

In collaboration with Oak Ridge National Laboratory, we refined crop production and budget data from the U.S. Department of Energy's *Billion-Ton 2023 (BT23)* report for five dedicated energy crops: biomass sorghum, switchgrass, miscanthus, willow, and poplar. Updates include biomass yields, on-farm diesel use, fertilizer and chemical application rates, and soil N₂O emission parameters. For herbaceous perennial crops (switchgrass and miscanthus) and woody crops (willow and poplar), where multiple harvests occur over several years, all parameter estimates were annualized based on the respective crop lifespans. Specifically, soil N₂O emissions from root residue remaining after the final harvest were included, assuming natural decomposition for all crops. Induced land-use changes and other indirect market-mediate effects were also addressed with GTAP simulation results by Purdue University. This work is currently being prepared for journal publication (Kwon et al., forthcoming).

2.4 R&D Feedstock Carbon Intensity Calculator (FD-CIC)

We expanded R&D FD-CIC to include two primary wheat types—winter and spring wheat—distinguished by growing season, as well as spring canola, the dominant canola type by U.S. acreage. In addition, we updated estimates of soil organic carbon stock changes for corn, soybeans, grain sorghum, and spring canola using the DayCent process-based simulation model, replacing the previous modeling results from the CENTURY model.

Publications:

Kwon, H., Liu, X., Sykora, T., Cai, H., and Wang, M. 2025. “Expansion and Update of the R&D Feedstock Carbon Intensity Calculator (FD-CIC) for R&D GREET 2025.” Energy Systems and Infrastructure Assessment Division, Argonne National Laboratory. ANL/ESIA-24/13

Kwon, H., Liu, X., Cai, H., and Wang, M. “Life Cycle Analysis of Growing Canola for Biofuel Production in the United States”. Forthcoming.

Kwon, H., Langholz, M., Liu, X., Clark, R., Taheripour, F., Cai, H., and Wang, M. “Life Cycle Analysis of Dedicated Energy Crops for Fuel Production in the United States”. Forthcoming.

3. BIOENERGY WITH CARBON CAPTURE AND STORAGE

BioEnergy from woody biomass with Carbon Capture and Storage (BECCS) is a carbon dioxide removal (CDR) technology that provides renewable energy with low emissions. Its energy and CDR performance depend on the type of biomass feedstock used, which is influenced by proximity to the feedstock, configurations of the BECCS system, and life-cycle analysis (LCA) methodology. We completed an LCA of biopower/bioheat BECCS systems using woodchips and pellets from the U.S. southern loblolly pine-based woody biomass. We evaluated life-cycle GHG emissions of two products/services provided by two BECCS systems — an electricity-only and a combined heat and power (CHP) systems. We applied three LCA co-product methods: (1) energy products with carbon capture and storage (CCS) credit, (2) incremental approach, and (3) upstream emission counterbalancing. We demonstrate how LCA methods, feedstock sources, and BECCS system designs shape their life-cycle GHG emissions effects. These options are implemented in R&D GREET 2025. See more details in Do et al. (2025).

Publications:

Do, T.N., Cai, H., Wang, M. (2025). *Life-Cycle Analysis of Bioenergy from Woody Biomass with Carbon Capture and Storage*. Forthcoming.

4. WASTEWATER SLUDGE COUNTERFACTUAL SCENARIOS

A database covering approximately 75% of national sludge flow was developed to quantify shares of sludge flowing through treatment processes to disposal. The most prevalent treatment pathways (representing combined treatment processes and disposal methods) were identified for LCI development and analysis. These pathways constituting ~67% of national sludge flow include:

- 1) Landfilling-disposal pathways
 - AD followed by landfill (11.3%)
 - No treatment landfill (5.5%)
 - Aerobic digestion followed by landfill (0.8%)

- Lime stabilization followed by landfill (0.1%)
- 2) Land application-disposal pathways
 - AD followed by land application (16.2%)
 - AD plus thermal drying followed by land application (7.4%)
 - AD plus composting followed by land application (5.1%)
 - Lime stabilization followed by land application (3.3%)
 - Thermal drying followed by land application (3.1%)
 - AD plus lagoon storage (anaerobic or facultative lagoon) followed by land application (2.6%)
 - Aerobic digestion followed by land application (1.1%)
 - Composting followed by land application (0.6%)
- 3) Incineration-disposal pathways
 - Multiple-hearth incineration (5.1%)
 - Fluidized-bed incineration (5.0%)

AD treatment processes were further delineated by their use of combined heat and power (i.e., “w/ or w/o CHP”).

Emissions from each treatment process (e.g., AD, composting, and thermal drying) and pretreatment steps such as thickening and dewatering, as well as disposal route (e.g., landfill and land application), were calculated using process-specific parameters derived from peer-reviewed literature, technical reports and guidelines.

By default, R&D GREET 2025 models a national sludge-weighted average counterfactual scenario covering approximately 67% of total national sludge flow. Users can also select a plant size range (defined by inlet wastewater flow) and the weighted average will be calculated using weights derived from national sludge flow shares within the chosen range (not available for plants smaller than 5 MGD due to lack of data coverage).

Publications:

Gan, Y., Leonhardt, B.E., Englander, J., Cai, H., et al. (2025). *Lifecycle Greenhouse Gas Emissions Analysis of Business-As-Usual Wastewater Sludge Management Practices*, Forthcoming.

5. ANIMAL MANURE ANAEROBIC DIGESTION PATHWAYS

This update provides the following:

- Updates to business-as-usual (BAU) manure management pathways, which include:
 - Animal populations and national shares of manure management practices for the beef, dairy, swine, and poultry (broilers, layers, and turkeys) sectors.
 - Updating methane conversion factors (MCFs) for anaerobic lagoons, liquid/slurry tanks, and deep pits of BAU manure management practices.

- Adding an estimation methodology for methane emissions from digestate storage after anaerobic digestion.

State and county animal-population data were harmonized with the EPA GHG Inventory and national averages are now weighted by volatile-solids (VS) production rather than headcount to better reflect regional manure generation. A counterfactual method titled “Hybrid” leverages updates to MCFs for lagoons, liquid/slurry tanks, and deep pits using the IPCC (2019) method (including manure temperature and revised activation energy) at the county level and aggregated to states and the nation; regionally specific cleanout schedules were incorporated where available. For the first time, the model explicitly accounts for methane emissions from open digestate storage by estimating the digestate’s residual biomethane potential and applying liquid/slurry MCFs; these storage losses correspond to roughly 3–14% of the biomethane yield, depending on digester type and sector.

For layers, broilers, turkeys, and dairy heifers, BAU updates had negligible effects, but adding digestate storage increased life cycle GHG emissions for CNG in transit buses by about 35–45 kg CO₂e/mmBtu, yielding default values of approximately 100–125 kg CO₂e/mmBtu in R&D GREET 2025. Note that these results depend on reactor type (see Leonhardt et al., 2025).

For beef, BAU updates and digestate storage raised emissions by ~15 and ~35 kg CO₂e/mmBtu, respectively, yielding a default value of approximately 80 kg CO₂e/mmBtu.

For dairy cows, BAU updates and digestate storage increased emissions by ~95 and ~35 kg CO₂e/mmBtu, respectively, yielding a default value of approximately –25 kg CO₂e/mmBtu.

For swine, BAU updates reduced emissions by ~70 kg CO₂e/mmBtu, while digestate storage added ~30 kg CO₂e/mmBtu, yielding a default value of approximately –190 kg CO₂e/mmBtu.

By default, the “Hybrid” method, which augments U.S. EPA Greenhouse Gas Inventory data with regionalized cleanout schedules and updates to MCF modeling parameters in-line with IPCC (2019), is used to represent the counterfactual scenario, but users are free to modify this to other legacy options (“U.S.” - based on the EPA Greenhouse Gas Inventory; “IPCC” - based on IPCC (2006) methods; and “User Defined” which provides the user flexibility within the IPCC (2006) methodology). Within the “Hybrid” approach for the counterfactual, a user input has been included to allow the user to model farm-specific shares of conventional manure management methods (i.e., anaerobic lagoons, solid storage, etc.).

The report below details these updates and suggests areas for further improvement. Counterfactual analysis for waste-derived RNG is advancing rapidly and will undergo regular updates and refinements as more research is conducted.

Publications:

Leonhardt, B.E., Englander, J., Ou, L., Wang, M., Cai, H. (2025). *Updates to Anaerobic Digestion Pathways for Animal Manure in R&D GREET 2025*. Argonne National Laboratory.

6. FOREST RESIDUE NATURAL DECAY COUNTERFACTUAL

Forest residues are abundant and often underutilized sources of bioenergy feedstock. This update accounts for the natural decay of forest residues across the contiguous United States (CONUS) to quantify emissions under a counterfactual scenario in which residues are not utilized. Forest residues are categorized by wood type (softwood and hardwood) and residue type (down dead wood and forest floor), based on the state-level biomass carbon pools. The decay rates are represented by adjusted decay constants (k) calibrated to local climate variables (i.e., temperature, precipitation, and evapotranspiration) for each location. Decay-rate data are compiled for tree species present within each state and weighed by basal area coverage.

The fates of biogenic carbon in forest residue are tracked across multiple pools and fluxes: sequestration in humus/microbial biomass, sequestration in inert organic matter, remaining in residues, and biogenic CO₂ emissions to atmosphere. A net biogenic carbon balance is reported. Two carbon-accounting approaches biogenic CO₂ emissions are implemented: (1) a carbon-neutral approach and (2) an explicit accounting approach coupled with a time-dependent discounted Global Warming Potential (GWP). This framework enables evaluation of the fates of biogenic carbon of forest residues due to natural decay for specific states and regions over an LCA time horizon of 100 years.

Publications:

Medel-Jiménez, F., Kwon, H., Lim, J.Y., Cai, H., Wang, M. (2025). *Evaluation of Forest Residues for Bioenergy Production: The Alternative Fate of Natural Decay and Net Biogenic Carbon Implications Evaluating Decay of Forest Residues for Bioenergy*. Forthcoming.

7. DMR-PRETREATMENT & FERMENTATION OPTION FOR CELLULOSIC ETHANOL PATHWAY

In the EtOH tab, cellulosic ethanol pathways via fermentation have been expanded to include Deacetylation and Mechanical Refining (DMR), alongside the default Dilute Acid (DA) pretreatment.

The DMR pretreatment option is available for corn stover, switchgrass, miscanthus, forest residue, and forage sorghum. The LCI for DMR pretreatment and fermentation to ethanol is based on collaborative work with National Renewable Energy Laboratory for corn stover feedstock (ANL, 2025; Mokwatlo et al., 2024). This includes detailed data on chemical inputs, water consumption, electricity credits, and recovered sodium sulfate salt from wastewater treatment as a co-product. A displacement credit is applied to account for this sodium sulfate salt co-product.

Publications:

Argonne National Laboratory (2025). Personal communications with National Renewable Energy Laboratory on ethanol production using cellulosic sugar produced via deacetylation and mechanical refining pretreatment of corn stover.

8. UPDATE METHANE PYROLYSIS PATHWAY FOR H₂ PRODUCTION

The methane pyrolysis pathways using natural gas (NG) and renewable natural gas (RNG) have been updated for centralized hydrogen production. LCI data were compiled from Aspen Plus process modeling of the methane pyrolysis process developed by Xu et al. (2025). The LCA methodology follows Ng et al. (2025). Methane pyrolysis yields hydrogen and solid carbon (carbon black), with a small amount of coke; excess heat is recovered to produce steam. Co-product treatment options implemented include mass, energy, and market-value allocation, as well as a carbon black displacement option. By default, mass allocation is applied, with steam displacement credits included when steam is valorized. For the steam co-product, alternative energy- or market-value-based allocation options are also provided. When the carbon black displacement option is selected, steam is treated via displacement only.

Additionally, carbon black produced from the furnace black process using heavy aromatic oils has been added to the Chemicals tab. Data for this update was obtained from Rosner et al. (2023), which includes three scenarios. The baseline scenario assumes that all tailgas is flared, while the other two scenarios (can be toggled) assume that a portion of the tailgas is combusted to supply electricity and generate steam for export. We assume that the upstream emissions for heavy oil production are equivalent to residual oil production in R&D GREET.

Publications:

Xu, Y., Sun, P., Elgowainy, A. (2025). *Modeling and Techno-Economic Analysis of Methane Pyrolysis via Arc Plasma For Hydrogen and Carbon Black Production*. https://greet.anl.gov/publication-methane_pyrolysis_tea_2025

Ng, C., Vyawahare, P., Elgowainy, A., Xu, Y., Sun, P. (2025). *Life Cycle Analysis of Methane Pyrolysis for Hydrogen Production*. https://greet.anl.gov/publication-methane_pyrolysis_lca_2025

9. UPDATE OF H₂ FROM CHLORINE PLANTS

Two hydrogen pathways have been updated to more accurately reflect the upstream emissions of brine for the use of chlorine production, of which hydrogen is a byproduct. The associated pathways include “Byproduction of Gaseous H₂ from Chlorine plants” and “Byproduction of Liquid H₂ from Chlorine plants” which both utilize sodium brine produced in the U.S. Previous assumptions equated the upstream emissions of this brine usage with brine production in Chile

associated with Lithium extraction (Kelly et al., 2021). Current conversations with industry personnel suggest that brine is acquired by pumping water through salt caverns on the way to chlorine facilities. This energy is already accounted for in the transportation of resources to the plant. Therefore, the upstream emissions of brine production are now assumed to be negligible. Some share of brine is imported but more research is needed to understand the impacts and share of this pathway.

10. GEOLOGIC HYDROGEN PRODUCTION

Geologic hydrogen from natural reservoirs is an emerging hydrogen supply. This expansion incorporates an LCA pathway to evaluate cradle-to-gate emissions (including both process and embodied impacts) of geologic hydrogen production under six possible scenarios that vary in gas composition, reservoir pressure, and surface processing configurations.

The pathway integrates detailed process-level emissions and resource flows based on data collection from academic and industry stakeholders, as well as field-scale engineering simulations conducted using the Oil Production Greenhouse Gas Emissions Estimator (OPGEE). Scenario-specific parameters include direct material and energy use (e.g., diesel consumption during drilling and exploration; combustion of waste gas, raw gas, and hydrogen for electricity generation powering downhole pumps, gas compression, and processing systems), hydrogen flow rates and throughputs, and fugitive emissions of CO₂ and CH₄. Additionally, the model accounts for amortized embodied emissions associated with infrastructure-related material demands, including steel, cement, and chemical inputs used in drilling and well completion.

Publications:

Yu, G. et al. *Cradle-to-gate Life Cycle Analysis of Energy and Environmental Impacts of Natural Geologic Hydrogen Production*, 2025. Forthcoming.

11. COAL MINE METHANE COUNTERFACTUAL SCENARIO

Coal mine methane (CMM) is emitted from five primary sources, i.e., degasification systems at active underground mines, ventilation systems from active underground mines, abandoned or closed mines, active surface mines, and fugitive emissions from post-mining operations as coal is stored in piles and transported. For CMM from degasification systems that is rich in methane, it is commonly liberated to the atmosphere (i.e. venting) or flared by mine operators. These are considered counterfactual scenarios when such CMM is captured, upgraded, and injected to pipeline for beneficial end uses.

The latest management practices of CMM degasification borehole CMM are reported in EPA's 2023 GHGRP Subpart FF data. It shows that active underground coal mines in the United States liberated a total of about 554,000 metric tons of methane in the drainage CMM in 2023. The mine

operators chose to flare and destroy about 69% of the drainage CMM while venting the remaining about 31% to the atmosphere (See Table 1).

Table 1. Flaring and venting activities to manage drainage CMM from active, underground coal mines in 2023

	2023	
	CH ₄ (MT/yr)	GHG using AR5 GWP 100 (MT CO ₂ e/yr)
CMM Degas Liberated	553,899	16,616,960
CMM Degas Captured and Destroyed	384,084	11,522,509
CMM Degas Vented	169,815	5,094,451
% Vented	30.7%	
% Destroyed (Flared)	69.3%	

To reflect the industry average practice, a weighted average counterfactual scenario of 30.7% venting and 69.3% flaring is implemented in R&D GREET 2025 for diverting drainage CMM from active, underground coal mines to beneficial uses. This default option is added to a binary counterfactual scenario of either 100% flaring or 100% venting that were implemented in R&D GREET 2024. The new default is the common method in R&D GREET to aggregate different counterfactual scenarios into a statistical weighted average assumption for other resources such as manure, food waste, and wastewater sludge when they are diverted from common management practices to beneficial uses.

12. CRUDE OIL MIX UPDATES

The projection of regional crude oil mixes has been updated through 2050. Based on EIA's AEO 2025 (EIA 2025a), domestic crude oil production shares were estimated for 2024 and projected from 2025 to 2050. R&D GREET also includes imports from other world regions—Canada (separated into oil sands and conventional crude), Mexico, Middle East, Latin America, Africa, and Other. Because no projections are available for these regions, their future shares were estimated using the 2024 regional distribution from EIA's company-level crude import data (EIA 2025b). For shale oil, Eagle Ford and Bakken contributed 7.6% and 9.2% of total U.S. crude oil production in 2024, respectively (EIA 2025c; 2025d), and these shares were assumed to remain unchanged through 2050. Canadian oil sand projections were updated using data from the Canada Energy Regulator (2023); because data on synthetic crude oil (SCO) shares from surface mining and in-situ operations are unavailable, the same shares reported in Cai et al. (2015) were assumed. Weighted average crude oil transportation distances were revised using company-level import data (EIA 2025b), with imports from Canada and Mexico transported about 1,735 miles by pipeline and imports from other countries transported an average of 7,175 miles by ocean tanker.

13. ELECTRICITY MIX, GHG, NO_x, AND SO₂ EMISSION UPDATES FOR ELECTRICITY GENERATION

Electricity generation mixes and onsite emission intensities of GHG, NO_x, and SO₂ for 2024 were estimated at multiple U.S. regional levels, including national, North American Electric Reliability Corporation (NERC), state, EPA's Emissions & Generation Resource Integrated Database (eGRID), and DOE National Transmission Needs Study regions. Electricity generation mixes were developed using detailed net generation data from the U.S. EIA's Form 923 (U.S. EIA, 2025e), which reports plant-level electricity generation by EIA fuel type. To derive regional generation mixes, plant-level generation data were aggregated to various regional levels based on plant coordinates and the corresponding geographic boundaries for states, NERC, EPA eGRID, and DOE Needs Study regions. The aggregated generation data by EIA fuel type were then consolidated into the ten power source categories used in the R&D GREET model (Lu et al., 2024). Regional electricity generation mixes were quantified as the fractional contribution of each power source to total regional net generation.

Direct GHG emissions from individual power plants were estimated following the methodology described in Lu et al. (2024). Direct NO_x and SO₂ emissions were obtained from EIA's Emissions by Plant dataset (EIA, 2024). Because plant-level NO_x and SO₂ emissions for 2024 were not yet available, we estimated these emissions by assuming that 2024 emission factors were consistent with 2023 values at the plant level. The resulting plant-level emissions were aggregated by region and normalized by total regional electricity generation to derive onsite GHG, NO_x, and SO₂ emission intensities for power generation across all regions in 2024.

Projections of electricity generation mixes and onsite emission intensities of GHG, NO_x, and SO₂ through 2050 were developed at the national and multiple regional levels using scenario results from EIA AEO 2025 and selected NREL 2024 Standard Scenarios (Gagnon et al., 2024). In addition to the AEO 2025 Reference Case, ten alternative AEO scenarios were incorporated, including Alternative Electricity, Alternative Transportation, High/Low Economic Growth, High/Low Oil Price, High/Low Oil and Gas Supply, and High/Low Zero-Carbon Technology Cost (U.S. EIA, 2025a).

Both the AEO and NREL datasets provide projections of electricity generation by source type and direct emissions of GHG, NO_x, and SO₂ from power generation. For AEO scenarios, their Electricity Market Module (EMM) data were only aggregated to the national and NERC levels due to the large geographic extent of EMM regions, which limit compatibility with other regional definitions. For NREL scenarios, their balancing area (BA)-level projections were aggregated to national, NERC, state, EPA eGRID, and DOE Needs Study regions, with each BA assigned to the region with the greatest geographic overlap. Because both datasets cover only the contiguous U.S., electricity generation mixes and emission intensities for Alaska and Hawaii were held constant at their 2024 levels for future years.

All resulting electricity generation mixes and onsite emission intensities of GHG, NO_x, and SO₂ are compiled in the *Generation_mixes* tab of R&D GREET1 2025. The default R&D GREET 2025 simulation applies the electricity generation mixes from the Reference Case of the EIA AEO 2025.

The default approach for calculating GHG, NO_x, and SO₂ emissions remains consistent with previous releases and follows the method defined in Section 10.1 of the “Input” sheet. The newly incorporated national and regional onsite emission intensities from electricity generation are provided as an optional setting in Section 1 of the *Generation_Mixes* sheet.

14. MARINE MODULE UPDATE

The *Marine_WTH* tab, in previous R&D GREET, is divided and expanded into two tabs—*Marine_Fuel* and *Marine_Trip*. The *Marine_Fuel* tab presents fuel cycle well-to-wake LCA results while *Marine_Trip* tab presents the vessel-specific trip based well-to-wake LCA results.

Significant effort has been made to incorporate the latest vessel, energy converter, fuel consumption, and emission information from the International Maritime Organization’s (IMO) 4th GHG Study. Sixteen new vessel types are added in the *Marine_Trip* tab. Depending on the vessel type, additional data fields—such as vessel size, main propulsion type, engine power rating, and combustion cycle—are included, consistent with the Fourth IMO GHG Study. Operational mode of the trip, fuel consumption, and load calculation were updated based on the report. The fuel consumption calculation also incorporates correction factors for low load, speed–power, weather, and fouling. Additionally, fuel consumption in boilers or steam turbines is also added for the first time, besides fuel use in the main propulsion engine and auxiliary engine.

A detailed description of all the changes, along with instructions on using the updated tabs, is covered in an Argonne Report listed below.

Publications:

Benvenuti, L., Kolodziej, C., Tripathi, S., Benavides, P.T., Wang, M., Masum, F. (2025). *Development of the Well-to-Wake Life Cycle Assessment Model for Marine Fuels in R&D GREET 2025*. Argonne National Laboratory. Report: ANL/ESIA-25/18.

15. VEHICLE LCA UPDATES

15.1. Light-Duty Vehicle Fuel Economy, Mass, and Material Composition Updates

The fuel economy (FE) values and mass for light-duty vehicles (LDVs) were updated in R&D GREET 2025 based on vehicle modeling and simulation by Argonne’s Autonomie model team that evaluated U.S. DOE R&D impacts on vehicle energy consumption (Islam et al., 2023). The assumptions that feed into the Autonomie model are currently undergoing periodic review. Therefore, this earlier version of Autonomie model assumptions have been used in this year’s update. This resulted in output changes (i.e., “updates”) that are not necessarily reflective of technological improvements. These changes in R&D GREET 2025, which cover multiple fuel pathways and vehicle technologies, include the fuel economy of midsize sedans (Cars), small

sports utility vehicles (SUVs), and pickup trucks (PUTs). The mass and component mass shares of selected vehicle types were similarly changed in R&D GREET2 2025. This subset of midsize sedans, small SUVs, and pickup trucks considers internal combustion engine vehicles (ICEVs), grid-independent hybrid electric vehicles (HEVs), grid-dependent plug-in hybrid electric vehicles (PHEVs), fully battery electric vehicles (EVs), and fuel cell electric vehicles (FCVs) for each of the class types.

The time-series tables for fuel economy for vehicles extending to 2050 can be found in the *Car_TS*, *LDT1_TS*, and *LDT2_TS* tabs of R&D GREET1 2025. R&D GREET2 includes a time series of mass information for the vehicle models. The Autonomie model provided simulation results for model years 2023, 2025, 2030, 2035, and 2050. We assigned model year 2023 to model year 2020 in R&D GREET 2025. Islam et al., (2023) has “low” and “high” technology progression profiles. For the R&D GREET 2025 update, we used the “low” progress scenario to be conservative and representative of baseline technology progress.

In addition, the material composition of vehicle systems for Conventional Type 1 vehicles was updated, including Car, SUV, and PUT. The updates are based on aggregate details of vehicle parts within powertrain and size class from A2MAC1 vehicle teardown data (A2MAC1 2025) for three vehicle powertrains: ICEVs, HEVs, and EVs, reflecting the current state of the vehicle market. This update focuses on updating the Body, Powertrain, Transmission, and Chassis systems while retaining the composition of the Generator, Traction Motor, Electronic Controllers, and Fuel Cell Onboard Storage based on their recent updates. The findings for this analysis were also used to update aspects of the PHEV and FCV component systems. Material composition data for ICEVs, EVs, and HEVs for Cars, SUVs, and PUTs are from validated real-life vehicles in the market. PHEVs and FCVs are assumed to share a common Body, Transmission, and Chassis (without batteries) with HEVs since they have a similar configuration. More details are provided in the memo below.

Publications:

Shen, K., Pandey, R., Kelly, J.C. (2025). *Update of Light-Duty Vehicle Material Composition in the R&D GREET[®] Model*. Argonne National Laboratory.

15.2. Medium- and Heavy-Duty Vehicle Fuel Economy, Mass, and Material Composition

The fuel economy values for various classes of medium- and heavy-duty vehicles (MHDVs) were updated in R&D GREET 2025 based on vehicle modeling and simulation by Argonne’s Autonomie team (Islam et al., 2023). We also updated the component weights for three MHDVs – Class 6 pickup-and-delivery (PnD) truck, Class 8 regional day-cab truck, and Class 8 long-haul sleeper-cab truck across four powertrains (diesel, conventional hybrid, electric, and fuel-cell hybrid). As indicated in the section just above, Autonomie Model assumptions are currently undergoing periodic review. Therefore, this earlier version of Autonomie Model assumptions have been used. This resulted in output changes (i.e., “updates”) that are not necessarily reflective of

technological improvements We employed the duty cycle and vocation-specific weighting factors specified by EPA (EPA, 2016) to estimate the weighted average FE across major duty cycles for each MDHV and powertrain option in the R&D GREET model. Detailed calculations on how the weighting is performed are available in Liu et al. (2021). The coverage of the vehicle MYs included MY 2023, 2025, 2030, 2035, and 2050 based on Autonomie simulations. We assigned the vehicle MY 2023 simulation results in Islam et al. (2023) to MY 2020 vehicles in R&D GREET 2025 updates and assigned the “low” technology progression scenario results from Islam et al. (2023) to update the fuel economy and vehicle component weight values in R&D GREET 2025, to be conservative and representative of baseline technology progress.

Battery sizing is determined from Islam et al. (2023), and fuel-cell components are sized based on data provided by Strategic Analysis, Inc. For all other components, data from Islam et al. (2023) are used. These updates have been made in the respective MHDV tabs (*Class 6 PnD Trucks*, *Class 8 Day-cab Trucks*, and *Class 8 Sleeper-cab Trucks*) in R&D GREET2 (for component weight updates) and the *HDV_TS* tab in R&D GREET1 (for fuel economy updates). More details are provided in the memo below.

Publications:

Shen, K., Iyer, R.K., Kelly, J.C. (2025). *Updates to Medium-Duty & Heavy-Duty Vehicle Component Weights*. Argonne National Laboratory.

15.3. School and Transit Buses

Vehicle-cycle and fuel-cycle data for Class 7 School Bus and Class 8 Transit Bus were added to R&D GREET 2025 in two new tabs, namely, *Class_7_School_Bus* and *Class_8_Transit_Bus*, respectively. School and transit buses are available in different sizes and classes. In R&D GREET 2025, we consider a conventional Type C school bus (Class 7) and a standard 40-foot transit bus (Class 8). Two powertrains – EV and EV – were considered for both school and transit buses. A detailed vehicle-cycle inventory was collected for both buses, following a bottom-up approach. For both buses, the weights of individual component systems and total vehicle (bus) weight are based on Islam et al. (2023), which provides these weights as results from Argonne’s Autonomie modeling. These are complemented with component weights and material composition details from multiple sources, including product catalogs and manufacturers’ manuals, subject to differences in component system definitions between Argonne’s Autonomie and R&D GREET models. Two lithium-ion battery cathode chemistries are considered: NMC811 and LFP (NMC = nickel-manganese-cobalt; LFP = lithium-iron-phosphate). Battery capacity is obtained from Islam et al. (2023), while battery weights and bill-of-materials are determined by inputting battery capacity values from Islam et al (2023) into Argonne’s BatPaC 5.2 model (Knehr et al., 2022). The outline for both bus-related tabs in R&D GREET Excel version follows a similar layout to that used for the *Tractor* tab. More details are provided in the technical report below.

Publications:

Pandey, R., Iyer, R.K., Kelly, J.C. (2025). *Vehicle-Cycle Inventory for Type C School Buses & Intra-City Transit Buses*. Argonne National Laboratory.

16. UPDATES TO BATTERY COMPOSITION AND CONSTITUENT MATERIAL PRODUCTION

16.1. Lithium-Ion Batteries – Updates to Bill of Materials

R&D GREET uses battery energy (kWh) and power (kW) values from simulations conducted with Argonne’s Autonomie model as inputs to Argonne’s BatPaC model to determine the bill of materials (BOMs) and specific energy and power values of lithium-ion batteries (LIBs) for different vehicle classes and relevant powertrains. In R&D GREET 2025, inputs from the latest publicly available simulation results for vehicle modeling conducted by the Autonomie team (Islam et al., 2023) are used within the latest publicly available version of the BatPaC model (BatPaC 5.2) (Knehr, et al., 2022, Argonne, 2024) for this update. Battery parameters (BOM and specific energy and power values) were updated for the following vehicles:

- a. Light-duty vehicles (LDVs):
 - Vehicles covered:
 - Car
 - Sports utility vehicle (SUV), and
 - Pick-up truck (PUT)
 - Powertrains covered:
 - Conventional hybrid electric vehicles (HEVs)
 - Plug-in hybrid electric vehicles (PHEVs) with vehicle range of 35 and 50 miles for battery-driven component
 - Battery electric vehicles (BEVs) with an all-electric range of 150, 200, 300, and 400 miles; and
 - Fuel-cell electric vehicles (or FCVs)
 - Batteries covered (cathode chemistries covered):
 - NMC (nickel manganese cobalt – 111, 532, 622, 811, and 95)
 - LFP (lithium iron phosphate)
 - NCA (nickel cobalt aluminum); and
 - LMO (lithium manganese oxide)
- b. Medium- and heavy-duty vehicles (MHDVs):
 - Vehicles covered:
 - Class 6 pickup-and-delivery (PnD) truck
 - Class 8 regional day-cab truck; and
 - Class 8 long-haul sleeper-cab truck
 - Powertrains covered:
 - HEVs
 - BEVs; and

- FCVs
- Batteries covered (cathode chemistries):
 - NMC (111, 532, 622, 811, and 95); and
 - LFP

Battery-related updates for these different vehicle types with associated powertrains are provided in their respective tabs in R&D GREET2 (i.e., Car, SUV, PUT, Class 6 PnD Trucks, Class 8 Day-Cab Trucks, and Class 8 Sleeper-Cab Trucks).

Publications:

Iyer, R.K., Pandey, R., Shen, K., Kelly, J.C. (2025). *Updates to Lithium-Ion Battery Material Composition for Vehicles for R&D GREET 2025*. Argonne National Laboratory.

16.2. Battery Recycling and Lithium Chemical Updates

R&D GREET 2025 incorporates data from Argonne’s EverBatt model on the life-cycle inventory (LCI) and resultant impacts of LIB recycling (Iyer and Kelly, 2023). In R&D GREET 2025, these inventory and impact values are updated to account for the respective conversion of elements in ionic form to their cathode precursor forms for use in cathode manufacturing (e.g., Ni^{2+} to NiSO_4 , Co^{2+} to CoSO_4 , and Li^+ to Li_2CO_3 and $\text{LiOH}\cdot\text{H}_2\text{O}$). These updates are made to the Battery_Recycling tab in R&D GREET2.

Additionally, the LCIs of domestic Li-chemical production in the United States have been updated for specific projects to account for the most recent publicly available information, based on techno-economic feasibility studies published for these projects. The relevant updates are made in the Supplementary Section of the Li_Chemicals tab in R&D GREET2.

Publications:

Iyer, R.K., Kelly, J.C. (2025). *Updates to U.S. Lithium Chemical Production and Lithium-Ion Battery Recycling for R&D GREET 2025*. Argonne National Laboratory.

16.3. Battery Assembly

A detailed battery assembly process is developed to calculate assembly energy and incorporated in R&D GREET 2025, based on a recent publication from Argonne’s BatPaC team (Knehr et al., 2024). Battery assembly energy is calculated based on generalized correlation equations developed in Knehr et al. (2024). A total of 12 parameters related to cathode chemistry, cell capacity, and assembly plant production capacity are used in correlation equations.

The cathode chemistries covered include:

- a. NMC111 (lithium nickel manganese cobalt oxide) or $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$
- b. NMC532 or $\text{LiNi}_{0.5}\text{Mn}_{0.3}\text{Co}_{0.2}\text{O}_2$
- c. NMC622 or $\text{LiNi}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}\text{O}_2$
- d. NMC811 or $\text{LiNi}_{0.8}\text{Mn}_{0.1}\text{Co}_{0.1}\text{O}_2$
- e. NMC95 or $\text{LiNi}_{0.95}\text{Mn}_{0.025}\text{Co}_{0.025}\text{O}_2$
- f. NCA (lithium nickel cobalt aluminum oxide) or $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$
- g. LFP (lithium iron phosphate) or LiFePO_4

The powertrains covered include:

- a. Plug-in Hybrid Electric Vehicle (PHEV)
- b. Battery Electric Vehicle (BEV)
- c. Hybrid Electric Vehicle (HEV)
- d. Fuel Cell Electric Vehicle (FCEV)

We updated the energy consumption for battery assembly across multiple vehicle types, including light-duty vehicles (LDVs), medium- and heavy-duty vehicles (MHDVs, which encompass freight vehicles and buses), tractors, and solar photovoltaic (PV) systems. LDVs include multiple powertrains with different configurations. For PHEVs, 35-mile and 50-mile battery capacities are considered, while for BEVs, 150-mile, 200-mile, 300-mile, and 400-mile battery capacities are considered. For MHDVs, we consider three powertrains: BEV, HEV, and FCV. All of these powertrains are modeled for 6 different cathode chemistries: NMC111, NMC532, NMC622, NMC811, NMC95, and LFP. The battery assembly for MHDV BEV batteries is modeled similarly to that of 400-mile BEVs used in LDVs, while the batteries used in HEVs and FCVs are modeled similarly to their LDV counterparts. Similarly, the energy required for battery assembly is updated for tractors. NMC622 battery chemistry is considered for BEV, HEV, and FCV powertrains. The BEV battery is modeled similarly to the BEV 400-mile battery in LDVs, while HEV and FCV batteries are modeled in the same way as in LDV counterparts. We have also added battery assembly-related energy consumption modeling for Class 7 school bus and Class 8 transit bus in R&D GREET 2025. Two cathode chemistries are included in the model: NMC811 and LFP, and only the BEV powertrain is considered. The battery for these buses is modeled similarly to the BEV 400-mile battery in LDVs.

For all relevant vehicle-powertrain configurations across the aforementioned vehicle categories, users have the flexibility to select battery cathode chemistry, assembly plant production capacity, BEV mile-range, and choice of electricity grids, including five global grids (US, China, Japan, Korea, Europe), four single energy source grids (coal, hydro, wind, natural gas), and the remaining eleven U.S. electric grids. The relevant updates are made in *Battery_Assembly*, *GREET1_Import_Export*, *Battery_Sum*, *MHDV_Battery_Sum*, *Tractor*, and *Solar_PV* tabs in R&D GREET2. More details are available in the technical memo below.

Publications:

Pandey, R., Iyer, R.K., Kelly, J.C. (2025). *Updates to Energy Required in Lithium-Ion Battery Assembly for R&D GREET 2025*. Argonne National Laboratory.

16.4. Graphite

The LCI of battery-grade synthetic graphite (SG) was updated in the R&D GREET 2025. New processes have been incorporated in the model, including industry-level production of calcinated petroleum coke, graphite block, graphite crucibles, and SG. The LCI updates are based on a mix of data sources, including literature publications and communication with industrial experts.

Two pathways of SG were built to reflect advancements in the SG industry over the past decade, using datasets from Wang et al. (2025) and Pandey et al. (2025). To support these pathways, calcined petroleum coke (CPC) production was added based on Edwards et al. (2020). Using a market allocation approach, we developed the life-cycle inventory for CPC produced from petroleum coke and lime.

In the Wang et al. (2025) pathway, SG is produced using uncalcined petroleum coke, CPC, uncalcined oil-based needle coke, graphite crucibles, and ethylene tar pitch. The process comprises five stages: pre-treatment, coating & granulation, graphitization, carbonization, and post-treatment. In the Pandey et al. (2025) pathway, SG is produced using CPC, graphite crucibles, metallurgical coke, and coal tar pitch, following six stages: milling, graphitization, micronizing/spheroidizing, coating (kneading), coating (thermal treatment), and packaging. Users may specify the relative shares between these pathways as well as the electricity mix used in SG production to enable scenario analysis. Feedstock options are also configurable for both pathways, such as crucible uses.

Corresponding graphite crucible production pathways were also implemented. In the pathway aligned with Wang et al. (2025), graphite crucibles are produced primarily from graphitized coke, a byproduct of the graphitization process that uses calcined petroleum coke as a principal input. Material inputs and the process energy mix are based on personal communication with an industry expert (Carrere, 2024), with energy inputs supplemented by Wang et al. (2025). In the pathway aligned with Pandey et al. (2025), graphite crucibles are produced from graphite block; graphite block production relies on calcined petroleum coke, coal tar pitch, and metallurgical coke, all of which are parameterized in R&D GREET 2025. More details are provided in the publications below.

Publications:

Shen, K., Iyer, R.K., Kelly, J.C. (2025). *Update of Synthetic Graphite Life Cycle Inventory in the R&D GREET® Model*. Argonne National Laboratory.

Pandey, R., Gracida-Alvarez, U.R., Iyer, R.K., Kelly, J.C. (2025). *Energy, greenhouse gas, and water life cycle analysis of synthetic graphite anode production in the United States*. Environmental Science: Advances, DOI: [10.1039/D5VA00171D](https://doi.org/10.1039/D5VA00171D).

16.5. Battery Module

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Within R&D GREET 2025, the Battery Module has been updated to reflect the latest data within R&D GREET, including battery bill of material parameters and material life cycle inventory data. Additionally, the internal calculation procedures within the module have been updated to reflect the modifications to battery assembly documented above. Finally, to support advanced users, features have been added to allow selection of a specified R&D GREET2 backend dataset and allow for deeper control of backend data and analysis. The controls are as follows and can be input into the Immediate Window within Visual Basic in Excel for select features as described:

- *UnhideGREET2 True* unhides the R&D GREET2 workbook,
- *UnhideGREET2 False* hides the R&D GREET2 workbook,
- *UnhideSheets True* unhides the backend worksheets,
- *UnhideSheets False* hides the backend worksheets,
- *LoadGREET2Form* reopens the form to choose a R&D GREET2 form to load.

Most users will not need to utilize these additional features.

17. STEEL UPDATE, INCLUDING IRON ORE MINING AND PROCESSING, ELECTRICAL STEEL, HIGH-STRENGTH STEEL, AND ADVANCED HIGH-STRENGTH STEEL

For the R&D GREET model steel sector, the LCI data was updated for two categories largely, iron ore mining and processing from several regions and manufacturing of several steel types/grades.

For the ore mining and processing, we developed and incorporated new pathways for imported ores from Canada and Brazil and added an option to select ore sources. In the U.S. steel industry, more than 90% of iron ore (48 MMT) was supplied from domestic deposits in 2024, the remainder (2.6 MMT) was imported from Brazil (47%), Canada (30%), Sweden (13%) and other countries (10%) (USGS, 2025). Brazil has two major iron ore mine regions: Minas Gerais for low grade hematite and Pará for high grade hematite. Data for mining, processing, and delivery to ironmaking plants in the U.S. Midwest were compiled for both regions. We also added an option to choose the ratio of Brazilian ore feedstock between the two regions. More details are provided in the memo below (Lee et al., 2025).

In addition, we updated the LCI for U.S. blast furnace (BF)-grade pellets based on published literature (ORNL, 2000; Industrial Technologies Office, 2015), adding flexibility to select ore shares between U.S domestic taconite ore (the primary domestic ore deposit) and Canadian hematite ore. Previous R&D GREET releases assumed a 50/50 mix of U.S. taconite pellets and Canadian hematite pellets for BF-grade ore feedstock. In this update, we added an option to specify

that ratio for the BF-grade ore supply. Furthermore, previous R&D GREET versions selected coke as the primary energy source for pelletization of BF-grade ore because pelletization was treated as part of an integrated steel mill. We added an option of NG fuel for pelletization of BF-grade U.S. taconite. This is because when pelletization occurs near the mining site, NG is often used as process fuel. The updates in the BF-grade pellets impact all downstream iron and steelmaking pathways that use this feedstock.

The energy consumption of steel sheet stamping has been updated for virgin steel produced via blast furnace-basic oxygen furnace (BF-BOF) route, and a new hot stamping process has been incorporated into R&D GREET 2025. The share of stamping and hot stamping can also be customized when modeling steel sheet forming.

A comprehensive production pathway for non-oriented electrical steel (NOES) has been added. The bill of materials (BOM) for the upstream input, ferrosilicon, and its production via submerged arc furnace (SAF) were built in R&D GREET 2025. Silicon steel is then modeled using the established ferrosilicon together with existing datasets for steel, cast aluminum, and the electric arc furnace (EAF) process. Finally, NOES production from silicon steel is established through sequential pickling, cold rolling, annealing, and coating processes. In addition, the feedstock composition for three hot-rolled and six cold-rolled high-strength steel (HSS) have been incorporated into R&D GREET 2025, along with six advanced high-strength steel (AHSS).

The LCI updates are based on a few literature sources, including previous studies (Zang et al. 2023), DOE reports on steel production (Jamison et al. 2015), and a preprint collaborative study between Argonne National Laboratory and the University of Michigan (UM) on U.S. automotive steel and aluminum production (Heidari et al. 2024). More details are provided by Shen et al. (2025).

Publications:

Shen, K., Iyer, R.K., Kelly, J.C. (2025). *Update of Steel Life Cycle Inventory in the R&D GREET® Model*. Argonne National Laboratory.

Lee, K., Ganguly, A., Zhou, R., Chaudhari, U.S., Lu, Y.R., Sun, P. (2025). *Updates to the Life Cycle Inventory for Iron Ore Mining and Processing in the R&D GREET® Model*. Argonne National Laboratory.

18. CHEMICAL AND CATALYST UPDATES

18.1 Platinum Over Strontium Titanate (Pt/STO) Catalyst Implementation

A new Platinum over strontium titanate (Pt/STO) catalyst production pathway has been added to the “Catalyst” tab in R&D GREET 2025 based on analyses by Ferdous et al. (2025). This catalyst is utilized for the hydrogenolysis of post-consumer plastics to obtain lubricating oils from upcycled plastics (LOUPs), which can be used as substitutes for conventional base oils.

The catalyst support consists of STO nanocuboids, synthesized through the reaction of strontium hydroxide octahydrate dissolved in acetic acid with titanium tetrachloride dissolved in ethanol under alkaline conditions. The solid product formed in this reaction is separated via centrifugation and undergoes subsequent treatments with vacuum, ozone, water, and nitrogen. Platinum is then deposited onto the support through solution-phase deposition using dodecane as the solvent. Following deposition, the catalyst is washed with toluene and pentane, dried, and subjected to nitrogen and hydrogen reduction.

Additionally, production pathways for key chemicals such as strontium hydroxide octahydrate, titanium tetrachloride, and dodecane have also been incorporated into R&D GREET 2025. These pathways are based on data reported by Tsang et al. (2016), Caramazana-Gonzalez et al. (2017), and ESIG (2021), respectively.

Publications:

Ferdous, S., Gracida-Alvarez, U.R., Ferrandon, M., Delferro, M., Benavides, P.T., and Urgun-Demirtas, M. (2025). *Techno-economic and life cycle analyses of the synthesis of a platinum–strontium titanate catalyst*. *Catalyst Science & Technology* 15 (15): 4419-4429. <https://doi.org/10.1039/D5CY00189G>.

18.2 Bio-Ethylene from Corn Ethanol (cofeeding pathway)

A new pathway for the production of bioethylene from corn ethanol has been added to R&D GREET 2025 based on the study by Benavides et al. (2025). This pathway involves fluid catalytic cracking (FCC) of a co-fed mixture of corn ethanol and vacuum gas oil (VGO). However, accelerated mass spectrometry C-14 quantification determined that ethylene is exclusively derived from corn ethanol and not from VGO.

The FCC process produces water, coke, and light-end gases, which include a variety of products such as ethylene and ethane. Catalyst coke generated during the process is utilized as an internal energy source, while ethane from the light-end gases is separated and subjected to steam cracking to increase the ethylene yield. The pathway implemented in R&D GREET 2025 considers only the C-14 testing yields case, where 0.46 kg of ethylene is produced per kg of corn ethanol.

In addition to ethylene, the steam cracking process generates other gaseous products, including hydrogen, propylene, butane, isobutane, butylene, butadiene, acid gas, pyrolysis gas, and fuel gas. Fuel gas is also used as an internal energy source for the process. Due to the presence of these co-products, a mass allocation factor of 0.78 was applied to the light-end gases used as feedstock and the flue gas (both internally produced and externally sourced) from the ethane separation and steam cracking process to allocate the environmental impacts of the process to ethylene. The inventory data implemented in R&D GREET 2025 already reflects the application of this allocation factor.

The pathway implemented in R&D GREET 2025 considers only the baseline scenario for corn ethanol production. Alternative scenarios for corn ethanol production, as discussed by Benavides

et al. (2025), can be evaluated by modifying the parameters in the Ethanol tab within R&D GREET 2025.

Publications:

Benavides, P.T., Gracida-Alvarez, U.R., Richa, K. Port, J. and Hawkins, T.R. (2025). *Cradle-to-Gate greenhouse gas emissions of the production of ethylene from U.S. Corn ethanol and comparison to fossil-derived ethylene production*. Bioresource Technology 430: 132565. <https://doi.org/10.1016/j.biortech.2025.132565>

18.3 Maleic Anhydride Update

The LCI data for the production of fossil-based maleic anhydride has been updated to include CO₂ emissions from the incineration of the off-gases generated during the oxidation of N-butanes (Althaus, 2007; Liang et al., 2023). These off-gases primarily consist of unreacted butane. These emissions, omitted in earlier versions of R&D GREET, have now been incorporated for the completeness of the inventory data.

Publications:

Liang, C., Gracida-Alvarez, U.R., Hawkins, T.R., and Dunn, J.B. (2023). *Life cycle assessment of biochemicals with clear near-term potential*. ACS Sustainable Chemistry & Engineering 11 (7): 2773-2783. <https://doi.org/10.1021/acssuschemeng.2c05764>.

19. TITANIUM AND TITANIUM DIOXIDE BOM UPDATE

Key updates to the titanium section in the R&D GREET 2025 version are as follows:

- updates on the supply chain of titanium sponge, titanium powder, and titanium dioxide (TiO₂) produced in the United States (US) including the shares between domestic and import and the mix of country of origin for the imported titanium resources;
- addition of natural rutile pathway as another upstream pathway for producing titanium chloride (TiCl₄) and its integration in the existing titanium sponge metal production pathway in combination with the titanium slag (Ti-slag) pathway;
- addition of TiO₂ production pathway including the TiCl₄ production from two different routes (i.e., from Ti-slag based on ilmenite resources and from natural rutile) and the Chloride process to oxidize the TiCl₄ to TiO₂.

Details of methods and approach used are presented in the technical memo (Kim et al. 2025).

Publications:

1. Kim, T., Kelly, J.C. (2025). *Summary of Titanium Section Updates in R&D GREET 2025 – Supply Chain, Natural Rutile Pathway, and Titanium Dioxide Production Pathway*. Argonne National Laboratory: Lemont, IL.
2. Kim, T., Kelly, J.C. (2025). *Life Cycle Analysis on United States Titanium Dioxide and Titanium Metal Products Based on Global Titanium Supply Chain Datasets*. Forthcoming.

20. BUILDING MODULE EXPANSION: HIGH PERFORMANCE THERMAL WATER HEATERS

A cradle-to-grave life-cycle analysis of high-performance thermal water heaters (HPTWHs) was conducted in a multifamily residential setting, with emissions at each life-cycle stage accounted for using the R&D GREET Building module. Embodied GHG emissions, operational GHG emissions, and end-of-life GHG emissions were included in the assessment. Air pollutants, water consumption, and total energy use were also evaluated, providing a comprehensive assessment of environmental and energy impacts. The systems analyzed comprised natural gas water heaters, electric resistance water heaters, air-source HPTWHs, distributed HPTWHs, and drain-source HPTWHs. Environmental impacts and energy use associated with electricity and natural gas consumption were quantified over a 28-year study period, with annual operational refrigerant leakage and end-of-life emissions from HPTWHs accounted for. This is implemented in the Building Module of R&D GREET 2025.

Publications:

Naquash, A., Morales, M., Malhotra, M., Sykora, T., Worek, W., Nawaz, K., Rendall, J., Cai, H. (2025). *Life-Cycle Analysis of Environmental Impact and Energy Use of High-Performance Thermal Water Heating Technologies for Multi-family Buildings*. Forthcoming.

21. UPDATE TO EMBODIED EMISSIONS FOR NUCLEAR POWERPLANTS

This update provides formulas instead of deterministic values to calculate energy consumption associated with the construction and decommissioning of nuclear power plants, as well as spent fuel management in R&D GREET 2025. This allows the energy consumption of these processes to change with relevant operating parameters of the nuclear powerplant.

Publications:

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Argonne does not warrant that the results presented in this report are consistent with the requirements of any particular regulatory or incentive program. Users interested in specific programs are encouraged to review guidance specific to those programs.

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