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Summary of Expansions and Updates in R&D GREET® 2024

Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory

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Summary of Expansions and Updates in R&D GREET® 2024

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Systems Assessment Center
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DISCLAIMER

R&D GREET 2024 is being released, consistent with Argonne National Laboratory's routine annual R&D GREET update process. Consistent with annual updates since 1995, R&D GREET (also historically called "ANL GREET") includes representation of new fuel pathways and updates to underlying assumptions. Pathways represented in the tool include two major categories: A) those that have been rigorously evaluated and have high certainty; and B) those that are preliminary, which could include pathways that have not recently been evaluated; those where there is still a gap in the science or data, and/or those that are currently under internal or external peer review. Argonne's annual releases of R&D GREET are comprehensive in order to inform the life cycle analysis technical community and elicit stakeholder feedback. These annual releases are meant to share the early-stage perspectives in life-cycle analysis, particularly in preliminary form, so as to gather feedback from the academic and technical expert community and determine where additional research, analysis and data are needed. 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. Inclusion of a pathway or module in R&D GREET does not necessarily represent U.S. Government concurrence for any specific use, but instead is intended to gather technical feedback and advance the science of life-cycle analysis. 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 this particular release (R&D GREET 2024) is not the version used by any of these specific programs. Numerous versions of GREET are currently publicly available (including versions that have been formally adopted in rulemakings, referenced in rulemaking documents, and referenced in solicitations), and others are likely to become adopted. But each of these derivatives of the R&D GREET model will reflect the specific statutes and parameters of those programs and will have a unique interface (e.g. see https://energy.gov/eere/greet for examples). Stakeholders seeking to use a GREET model for purposes of compliance with a given regulatory program should review guidance specific to that program to ascertain the appropriate version of GREET to use. Argonne does not warrant that use of R&D GREET 2024 or any other instance of GREET is consistent with the requirements of any particular regulatory or incentive program. Users interested in specific programs that reference GREET are encouraged to review guidance specific to those programs if and when it is available to determine appropriate means of compliance and contact the relevant responsible agencies for those specific policies or programs.

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 major transportation 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 various areas in R&D GREET 2024. This report provides a summary of the expansions and updates.

MAJOR EXPANSIONS AND UPDATES IN R&D GREET 2024

1. ENERGY PRODUCTS

1.1. HYDROGEN

Jo Zhou, Ishan Pandey, Pradeep Vyawahare, Clarence Ng, and Amgad Elgowainy

1.1.1. Water Consumption Factor Updates for Hydrogen Production Pathways

The water consumption factors (WCF) of several hydrogen production pathways were updated using data from existing literature and publicly available reports. The pathways include steam methane reforming (SMR) with and without CCS, autothermal reforming with CCS, low temperature electrolysis (LTE) of water using proton exchange membrane (PEM) and high temperature electrolysis (HTE) with solid oxide electrolyzer cell (SOEC), gasification of biomass and coal, and by-product hydrogen from the chlor-alkali process and steam cracking of natural gas liquids. The primary change was to the WCF of both electrolysis pathways i.e., LTE and HTE, which were updated to include both process and cooling water. We note that many of the hydrogen pathways have WCFs that are consistent to those reported in the literature. More information regarding this effort and the corresponding updates can be found in the following technical report.

Publication:

Zhou, X., Pandey, I., Vyawahare, P., Ng, C., Elgowainy A. (2024). *Updated Water Consumption Factors of Hydrogen Production Pathways.* https://greet.anl.gov/publication-wcf_updates_2024

1.1.2. Expansion of Energy Sources for High Temperature Electrolysis (HTE) with Solid-Oxide Electrolyzer Cell (SOEC)

Pradeep Vyawahare, Clarence Ng, and Amgad Elgowainy

The thermal and electrical energy source options for hydrogen production from HTE with SOEC (HTE-SOEC) were expanded to include other renewable electricity sources such as Geothermal Flash, Hydroelectric, Wind, and Solar Power in R&D GREET. Given the potential of renewable energy integration with the HTE-SOEC, the pathway was expanded to provide users with wider range of options.

1.1.3. Hydrogen Transportation

R&D GREET includes three transportation modes for hydrogen via pipeline, liquid hydrogen trucks, and compressed gaseous hydrogen tube trailers. The transportation distance for each mode is user defined. The default payload for liquid hydrogen truck is 4 tons and for tube trailer is 1 ton. The liquid hydrogen transport is preceded by liquefaction and cryogenic storage while the tube trailer is loaded via compression from 300 pounds per square inch (psia) to 7,500 psia.

1.2. CLEAN FUELS

Michael Wang, Hao Cai, Xinyu Liu, Hoyoung Kwon, Ulises Gracida, Saurajyoti Kar, Thai Ngan Do, Longwen Ou, and Thomas Sykora

Life cycle inventory (LCI) data for key processes of selected clean fuel pathways have been updated and added with latest data from public databases and literature. These clean fuel pathways encompass 1) ethanol production via fermentation, using the US corn, sorghum, and a combination of the two crops; 2) biodiesel production via transesterification, using the US soybean, spring canola, domestic and imported used cooking oil, tallow, distiller corn oil, and intermediate oil crops including camelina, carinata, and pennycress, and possibly a blend of vegetable and waste oil sources; 3) renewable diesel (RD) and sustainable aviation fuel (SAF) production via the hydroprocessed esters and fatty acids conversion processes (HEFA) using the US soybean, spring canola, domestic and imported used cooking oil, tallow, distiller corn oil, and intermediate oil crops including camelina, carinata, and pennycress, and possibly a blend of vegetable and waste oil sources; 4) SAF (and RD) production via alcohol to jet (ATJ), using domestic ethanol sources, Brazilian sugarcane ethanol, and possibly a blend of ethanol sources; 5) RD and SAF via gasification and Fischer-Tropsch (FT), using corn stover, switchgrass, miscanthus, willow, and poplar; 6) cellulosic ethanol via pretreatment, enzymatic hydrolysis, and fermentation, using corn stover, switchgrass, miscanthus, willow, and poplar; and 7) renewable natural gas (RNG) production via anaerobic digestion and upgrading, using animal manures of major types, wastewater sludge, and landfill gas (details are in the section below).

These updates and expansions are implemented in corresponding tabs of R&D GREET where the aforementioned pathways are modeled. In addition, a new "Clean Fuels" tab is created to summarize key data and assumptions for simulating these pathways.

Publication:

Wang, M., Cai, H., Liu, X., Kwon, H., Gracida, U., Kar, S., Do, T.N., Ou, L., Sykora, T, Elgowainy, A. *Life Cycle Analysis of Greenhouse Gas Emissions of Clean Fuels with the R&D GREET 2024 Model*. (2025). Systems Assessment Center, Energy Systems and Infrastructure Analysis Division, Argonne National Laboratory. ANL/ESIA-24/21.

1.3. RENEWABLE NATURAL GAS

Hao Cai, Longwen Ou, Yu Gan, Juin Yau Lim, Uisung Lee, Amgad Elgowainy, and Michael Wang

Counterfactual scenarios of diverting waste streams for RNG production and methane leakage during upgrading of biogas and landfill gas to pipeline quality RNG, both of which were identified as key analytical issues that drive uncertainties of life cycle GHG emissions of RNG production pathways in R&D GREET 2023, were further investigated in 2024. The effort on counterfactual scenarios re-evaluated business-as-usual management practices of animal manures of different types and typical components of municipal solid waste, as well as the associated GHG emissions. In addition, the methane leakage rate, as well as the process energy requirement during biogas clean-up and upgrading processes was investigated further for common upgrading technologies adopted in the RNG industry. Argonne has implemented expansions and updates related to these key issues for the RNG pathways in R&D GREET 2024. Argonne summarized the details of these analyses in two journal articles that are forthcoming.

Publications:

Yixuan Wang, Longwen Ou, Hao Cai, Uisung Lee, Troy Hawkins, Michael Wang. Business-as-Usual Municipal Solid Waste Management in the United States: Greenhouse Gas Implications. ACS Sustainable Resource Management (Submitted).

Juin Yau Lim, Yu Gan, Hao Cai, Longwen Ou, Uisung Lee, Amgad Elgowainy, Michael Wang. Waste-to-Renewable Natural Gas Production: Greenhouse Gas Emissions of Upgrading Technologies. ACS Sustainable Chemistry and Engineering (In-preparation).

1.4. MARINE FUELS

Farhad H. Masum, Lívia M. M. Benvenutti, and Troy R. Hawkins

Three new biomass-to-methanol pathways were added from agricultural feedstocks. Among them, two are perennial grass feedstocks—switchgrass and miscanthus, and one is agricultural waste feedstock—corn stover. Logging residue remains as the default feedstock for biomass to methanol pathway. The feedstock choices among biomass types can be found in the MeOH_FTD tab of R&D GREET (under Table 2).

For waste-based RNG to methanol and ammonia pathways, counterfactual credits for avoiding conventional waste management related emissions are switched from study-specific to GREET default counterfactual scenarios (see above RNG section). These credits are more conservative, and as a result, final well-to-wake GHG emissions are reduced compared to the R&D GREET 2023 estimates.

The feature to enable capturing of carbon dioxide from process emissions during ammonia production was added (as in other sections of R&D GREET). Default result shows emissions with no carbon capture. Toggle to enable carbon capture for natural gas to ammonia production can be found in Marine_WTH tab of R&D GREET (under Table 1.1). Toggle to enable carbon capture for RNG to ammonia production can be found in Ag_Inputs tab of R&D GREET (Table 1.4). Carbon capture rate is based on what was in the ammonia section of R&D GREET. Electricity use for carbon capture and storage is assumed with the US average grid. The amount of electricity required for carbon capture and storage is available in the compression tab of R&D GREET.

A trip profile was created based on NO_x technical code (NTC)'s E2/E3 test cycle[1], which is adopted by International Maritime Organization (IMO). This trip profile describes what percentage of the trip was conducted under which engine load. According to the IMO trip profile, engine load of 25%, 50%, 75%, and 100% is 15%, 15%, 50%, and 20% of the total trip, respectively. Both methanol and ammonia's pilot fuel consumptions, as well as their consumption as primary fuels, were calculated based on this trip profile.

Based on feedback from engine manufacturers and other industry stakeholders, pilot fuel ratio was increased from 5% to 25% for dual fuel engines using ammonia as the primary fuel and marine diesel oil as the pilot fuel. These estimates reflect more realistic assumptions related to pilot fuel use. Due to the lack of data, the same ammonia to pilot fuel ratio has been considered for all engine loads.

1.5. COAL MINING METHANE CAPTURE AND UTILIZATION

Longwen Ou and Hao Cai

Argonne conducted a life cycle GHG emissions analysis of post-mining drainage coal mine methane (CMM) from active, underground coal mines that can be captured and utilized for beneficial end uses. The system boundary includes capture, processing, distribution, and various utilization stages. The impacts of two current CMM management practices, venting and flaring, were evaluated. End uses of CMM include hydrogen production, ammonia production, methanol production, and electricity generation. Process-level operational data, including energy and chemical consumption and methane leakage rates for CMM capturing and processing, were collected from actual CMM capturing projects and implemented in R&D GREET.

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[1] An E2/E3 test cycle defines a specific set of operating conditions for measuring emissions of a marine diesel engine. Here, E2 is used for constant-speed main propulsion engines and E3 represents a cycle for propeller-law operated engines. Both E2 and E3 are defined under the ISO 8178 standard for exhaust emission measurements.

Publication:

L. Ou, H. Cai. (2024). *Life-Cycle Greenhouse Gas Emissions of Capture and Utilization of Methane-Rich Drainage Gas from Active Underground Coal Mines in the United States*. https://greet.anl.gov/publication-LCA_coal_mine_methane

1.6. VEHICLES

1.6.1. Light-Duty Vehicle Fuel Economy and Vehicle Component Weight

Taemin Kim and Jarod C. Kelly

The fuel economy and vehicle component weight for light duty vehicles (LDV) were updated in R&D GREET 2024 using the simulation results from the most up-to-date vintage of Argonne's Autonomie tool, Autonomie 2024 (Islam et al., 2023). For R&D GREET 2024 update, all three LDV types in R&D GREET are updated for their fuel economy: passenger cars (i.e., midsize sedans), light-duty truck 1 (i.e., small sport utility vehicles, or SUVs), and light-duty truck 2 (i.e., pickup trucks, or PUTs). Fuel economy values in miles per gallon (MPG) are updated for the baseline vehicles for each LDV class: spark-ignition (SI) gasoline internal combustion engine vehicles (ICEVs) and compression-ignition direct injection (CIDI) diesel ICEVs. Fuel economies for other vehicle technologies using different powertrains [i.e., hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs)] or fuels (e.g., high ethanol blends, compressed natural gas, biodiesel, renewable diesel, etc.) are updated in relative changes with respect to their baseline (i.e., SI gasoline ICEVs or CI diesel ICEVs). These updates are made in the "Car_TS", "LDT1_TS", and "LDT2_TS" tabs in R&D GREET1 2024 for passenger cars, SUVs, and PUTs, respectively. The updated fuel economy values span from model year (MY) 2020, 2025, 2030, 2035, and 2050 for all three vehicle types.

For all three types of LDVs in R&D GREET, total vehicle weight, battery capacity for HEVs, PHEVs, BEVs, and FCEVs, fuel cell stack size (in kW) for FCEVs, and mass composition of different parts of vehicles (i.e., powertrain, transmission, chassis, traction motor, generator, electronic controller, vehicle body, etc.) are updated using the Autonomie 2024 simulation results. These updates are made in the "Car", "SUV", and "PUT" tabs in R&D GREET2 2024 for passenger cars, SUVs, and PUTs, respectively. For battery and fuel cell stack size, the updates are made in time series spanning from 2020, 2025, 2030, 2035, and 2050. R&D GREET2 2024 allows users to select different battery chemistries with different specific power and /energy densities than those simulated in Autonomie: GREET approximates the sizes of battery and fuel cell components internally based on its own data and modeling. We assigned the vehicle MY 2024 simulation results in Autonomie 2024 to MY 2020 vehicles in R&D GREET 2024 updates and used the "low" technology progression scenario results in Autonomie 2024 to update the fuel economy and vehicle component weight values in R&D GREET 2024, which is consistent with the conservative approach we have been taking for annual updates so far.

1.6.2. Medium- and Heavy-Duty Vehicle (MHDV) Fuel Economy and Component Weight

Taemin Kim, Rakesh Krishnamoorthy Iyer, and Jarod C. Kelly

The fuel economy and vehicle component weight for medium and heavy-duty vehicles (MHDVs) were updated in R&D GREET 2024 using the simulation results from the most up-to-date vintage of Argonne's Autonomie tool, Autonomie 2024 (Islam et al., 2023). Table 1 presents the list of MHDV types subject to fuel economy updates for R&D GREET 2024 based on the Autonomie 2024 simulation results. Vehicle component weight updates are done for class 8 long-haul and short-haul combination trucks and class 6 pick-up and delivery trucks. For each of the vehicle types presented in Table 1, four powertrain technologies, conventional ICEVs, HEVs, BEVs, and FCEVs, are updated for their fuel economy. Vehicle component weights are also updated for the four powertrain technologies for class 8 short- and long-haul combination trucks and class 6 pick-up and delivery trucks. We employed the duty cycle and vocation-specific weighting factors specified by EPA (EPA, 2016) to estimate the weighted average fuel economy 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 2024, 2025, 2030, 2035, and 2050 based on Autonomie 2024 simulations. We assigned the vehicle MY 2024 simulation results in Autonomie 2024 to MY 2020 vehicles in R&D GREET 2024 updates and assigned the "low" technology progression scenario results from Autonomie 2024 to update the fuel economy and vehicle component weight values in R&D GREET 2024, which is consistent with the conservative approach we have been using for annual updates so far.

Table 1. Summary of MHDV classification in R&D GREET 2024 and a crosswalk with the vehicle classification by EPA and Autonomie

EPA gross vehicle weight rates (GVWR) classification	Vehicle types defined in R&D GREET 2024	Vehicle types defined in Autonomie 2024
Class 2	Heavy duty pick-up trucks and vans	Class 2 Vans
Class 4	Light-heavy duty vocational trucks	Class 4 Service vehicles
Class 6	Medium-heavy duty vocational trucks	Class 6 Box vehicles
Class 7	School buses	Class 7 School buses
Class 8	Heavy-heavy duty vocational trucks	Class 8 heavy vocational trucks
	Long-haul combination trucks	Class 8 sleeper cabs
	Short-haul combination trucks	Class 8 day cabs
	Refuse trucks	Class 8 refuse trucks
	Transit buses	Class 8 transit buses

We updated the component weights for three MHDVs [Class 6 pick-up 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). Battery sizing and material composition were determined using a combination of Autonomie results (Alhajjar et al. 2025) and Argonne's BatPaC modeling results, and fuel-cell components are sized based on data provided by Strategic Analysis, Inc. For all other components, Autonomie simulation results were used. These updates were 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 2024 (for component weight updates) and the *HDV_TS* tab in R&D GREET1 2024 (for fuel economy updates). More details are provided in the memo below.

Publications:

Islam, E.S.; Prada, D.N.; Vijayagopal, R.; Mansour, C.; Phillips, P.; Kim, N.; Alhajjar, M.; Rousseau, A (2023). *Detailed Simulation Study to Evaluate Future Transportation Decarbonization Potential*; ANL/TAPS-23/3; Argonne National Laboratory: Lemont, IL.

Iyer, R.K., Kelly, J.C. (2024). *Updates to Medium-Duty & Heavy-Duty Vehicle Component Weights for R&D GREET 2024.* https://greet.anl.gov/publication-mhdv_2024_update.

1.6.3. Non-CO_2 Air Pollutant Emission Rate Updates Using MOVES4 Simulations

Taemin Kim and Jarod Kelly

All non-CO_2 air pollutant emissions rates associated with LDVs and MHDVs were updated in the R&D GREET 2024 using the simulation results from the most up-to-date version of the US Environmental Protection Agency (EPA) MOtor Vehicle Emissions Simulator (MOVES) model, MOVES4. The emissions species subject to this year's update include methane (CH_4), nitrous oxide (N_2O), volatile organic carbon (VOC), carbon monoxide (CO), nitric oxide (NO_x), black carbon (BC), and organic carbon (OC). In R&D GREET model, these emissions are defined to have either long-term or short-term climate impacts (i.e., warming or cooling). The emissions rates for different types of vehicles, fuels, and powertrain technologies are defined in the time series in R&D GREET. The 2024 update covers the vehicle MYs of 2020, 2025, 2030, 2035, and 2050. The updated air emissions rates are in the time series tables in "Car_TS", "LDT1_TS", "LDT2_TS", and "HDV_TS" tabs of R&D GREET 2024 for passenger cars, SUVs, PUTs, and MHDVs, respectively. One of the key updates is that the N_2O emissions rates for diesel-run MHDVs now address the potential N_2O generation from selective catalytic reduction (SCR) aftertreatment systems. MOVES4 starts to take into account this emission source and we updated our N_2O emissions based on the MOVES simulation results. Results show significant increase in N_2O emissions rate in heavier class (especially Class 7 and above) MHDVs compared to previous versions of R&D GREET.

Publication:

Kim, T.; Kelly, J.C. (2024). *Summary of Non-CO2 Climate Related Emissions Rate for Hybrid- and Plug-in Hybrid Electric Vehicles*; Argonne National Laboratory: Lemont, IL. http://greet.es.anl.gov/publication-non_co2_hev_phev

1.6.4. Battery Materials— Updates of Battery Bill of Materials

Rakesh Krishnamoorthy Iyer, Ramsharan Pandey, and Jarod C. Kelly

The R&D GREET model uses battery energy (kWh) and power (kW) values from Argonne's Autonomie model as inputs to Argonne's BatPaC model to determine the bill of materials (BOM) and specific energy/power densities of lithium-ion batteries (LIBs) for different vehicles and powertrains. In R&D GREET 2024, we used inputs from the latest version of Autonomie model, Autonomie 2024, as provided in (Alhajjar et al. 2025), and BatPaC 5.2 for this update. Battery parameters (BOM and specific energy and power densities) were updated for the following vehicles:

a. LDVs: car, SUV, and PUT
    - Conventional hybrid electric vehicles (or HEVs)
    - Plug-in hybrid electric vehicles (PHEVs, with the extended driving range solely using batteries being 35-miles and 50-miles)
    - Battery electric vehicles (BEVs, with an all-electric range of 150 miles, 200 miles, 300 miles, and 400 miles); and
    - Fuel-cell electric vehicles (FCEVs)

b. MHDVs: Class 6 PnD trucks, Class 8 regional day-cab truck, and Class 8 long-haul sleeper-cab truck
    - HEVs
    - BEVs; and
    - FCEVs

Battery parameters for these vehicle types are provided in their respective tabs (Car, SUV, PUT, Class 6 PnD Trucks, Class 8 Day-cab Trucks, and Class 8 Sleeper-cab Trucks).

Technical Memo:

Iyer, R.K., Kelly, J.C. (2024). *Updates for Lithium-Ion Batteries and Other Components in Light-, Medium-, and Heavy-Duty Vehicles for R&D GREET 2024.* https://greet.anl.gov/publication-battery_2024_update.

2. OTHER UPDATES AND ADDITIONS

2.1. METHANE LEAKAGE OF NG SUPPLY CHAIN

Andrew Burnham

Methane leakage and CO_2 flaring emissions from the NG supply chain were updated based on newly published data. In R&D GREET 2024, we updated the CH_4 leakage rates for both the hybrid top-down and bottom-up approach and the EPA GHG inventory bottom-up approach. The hybrid approach continues to use production scaling factors from Rutherford et al. (2021) and processing and transmission scaling factors from Alvarez et al. (2018), modifying the most recent EPA GHG inventory CH_4 emissions data (EPA, 2024a).

Since these scaling factors were developed, other studies have published more top-down estimates of methane emissions across the supply chain (e.g. Sherwin et. al., 2024). Information from these studies is not reflected in the scaling factors used for the R&D GREET national average, but may be in future releases.

Publication:

Burnham, A. (2024). *Updated Natural Gas Pathways in R&D GREET 2024*. https://greet.anl.gov/publication-update_ng_2024.

2.2. UPDATES OF ELECTRICITY GENERATION MIXES

Zifeng Lu

The electricity generation mixes for 2022 and 2023 were updated at multiple regional levels, including national, North American Electric Reliability Corporation (NERC), state, EPA Emissions & Generation Resource Integrated Database (eGrid) (EPA, 2024b), and DOE National Transmission Needs Study (U.S. DOE 2023) regions. These updates were based on detailed net electricity generation data from the U.S. Energy Information Administraton's (EIA's) Form-923 (U.S. EIA, 2024), which reports generation by plant and EIA fuel type within the U.S. power industry. To derive regional electricity generation mixes, plant-level generation data by EIA fuel type were first aggregated to different regions according to plants' coordinates provided in EIA Form-923 along with geographical definitions for states, NERC, EPA eGRID, and DOE Needs Study regions. The aggregated data by EIA fuel type were then further summarized into the 10 power source categories used by the R&D GREET Model. Regional electricity generation mixes were calculated by determining each power source's percentage share of the corresponding regional net generation. In some instances, a power source's net generation within a region was negative due to the presence of hydroelectric pumped storage (HPS) facilities, which consume more electricity than they produce. In such cases, the net generation for the power source was set to zero, with the shares of other sources adjusted accordingly.

In prior versions, R&D GREET offered electricity generation mix projections through 2050 only at the national and NERC levels, based on the Reference Case from the EIA's Annual Energy Outlook (U.S. EIA, 2023). In R&D GREET 2024, electricity mix projections were expanded substantially. It now includes multiple scenarios from EIA AEO 2023 and NREL 2023 Standard Scenarios, representing alternative and deeply decarbonized electric grids through 2050 across national, NERC, state, EPA eGRID, and DOE Needs Study regional levels. Alongside the

Reference Case, all 15 alternative EIA AEO 2023 scenarios have been included, covering high/low economic growth, high/low oil price, high/low oil and gas supply, varying costs of zero-carbon technologies, and different levels of Inflation Reduction Act (IRA) uptakes (U.S. EIA, 2023). Additionally, 10 NREL 2023 Standard Scenarios representing deeply decarbonized grids were selected. These scenarios include Mid-case, Mid-case 95% CO_2 reduction by 2050, Mid-case 100% CO_2 reduction by 2035, as well as scenarios with high/low electricity demand growth, high/low natural gas price, high/low renewable energy cost, and continued IRA tax credits without expiration (Gagnon et al., 2023). For the NREL scenarios, balancing-area-level (BA-level) electricity generation by source type was aggregated to the relevant regional levels, with each BA mapped to the region that had the greatest percentage area overlap. For the AEO scenarios, their Electricity-Market-Module-level (EMM-level) electricity generation was aggregated at the NERC level only, due to the broad area of EMM regions and the challenges of aligning them with other regional definitions. Both the AEO and NREL scenarios provide projections solely for the continental U.S., so electricity generation mixes for Alaska and Hawaii were held constant at their 2023 levels in future years. These generation mixes are now in the "Generation_mixes" tab of R&D GREET1 2024.

Publication:

Lu, Z., A. Elgowainy, P. Vyawahare, and C. Ng. (2024). "*Development of Life Cycle Greenhouse Gas Emission Intensities of Electricity by National Transmission Needs Study Region.*" Lemont, IL: Argonne National Laboratory. https://greet.anl.gov/publication-ele_ci_needs

2.3. UPDATE TO THE NUCLEAR FUEL CYCLE AND INFRASTRUCTURE EMBODIED EMISSIONS

Clarence Ng, Pradeep Vyawahare, Pahola Thathiana Benavides, Yu Gan, Pingping Sun, Amgad Elgowainy

The update to nuclear electricity production in the U.S. focused on the back end of the nuclear fuel cycle. Embodied emission data associated with construction of concrete pads for the temporary storage of nuclear waste in dry casks were added. Data for decommissioning of the nuclear power plant and from spent fuel management were also incorporated. This includes energy consumption and waste disposal of low and intermediate level nuclear waste. An option to include or exclude the embodied emissions for a permanent nuclear waste repository was added. The repository is assumed to be located in the Yucca Mountain and the life cycle inventory data used for its construction and operation were taken from designs published by the Department of Energy in 2002.

Publication:

Ng, C., Vyawahare, P., Benavides, P. T., Gan, Y., Sun, P., Boardman, R., Marcinkoski, J., Elgowainy, A. (2025). Life Cycle Greenhouse Gas Emissions associated with Nuclear Power Generation in the United States. Journal of Industrial Ecology. *Accepted.*

2.4. OCEAN TANKER CARGO PAYLOAD UPDATE AND BACKHAUL ASSUMPTION CHOICES

Taemin Kim, Christopher Kolodziej, and Hao Cai

The ocean tanker cargo payload for each commodity relevant to international marine transportation was updated based on the datasets available in more recent literature and databases. The commodities listed in the R&D GREET "T&D" tab, section 1 (Cargo Payload by Transportation Mode and by Product Fuel Type) are categorized into the five groups: i) liquefied natural gas (LNG); ii) liquefied propane gas (LPG); iii) crude oil or unrefined oil products (e.g., crude oil and residual oil); iv) petroleum or refined products (e.g., gasoline, diesel, jet fuel, etc.); and v) chemicals (e.g., ethanol, methanol, dimethyl ether, etc.). The average ocean tanker size reported in the 4^{th} International Maritime Organization (IMO) greenhouse gas (GHG) study for the LNG, LPG, and chemical tankers is used to update the ocean tanker cargo payload for the LNG, LPG, and chemical commodity groups in R&D GREET 2024. For the cargo payload of refined petroleum products, the Automatic Identification System (AIS) vessel tracking database is used to estimate the average payload of the petroleum product tankers in operation as of August 2024. For crude oil tanker cargo payload, the datasets for size distribution of all oil tankers (i.e., crude oil tankers and petroleum product tankers) reported in the 4^{th} IMO GHG study are used to estimate the average payload for crude oil tankers. In this process, it is assumed that crude oil tankers take account for about 70% of all oil tankers based on a previous publication.

For all ocean tanker types, the default assumptions of backhaul travel are kept the same for R&D GREET 2024. Meanwhile, for backhaul assumptions of chemical and refined product tankers, an alternative user choice of a backhaul travel is implemented in the R&D GREET 2024 to accommodate different backhaul scenarios available for those tankers.

Publication:

Kim, T.; Kolodziej, C.; Cai, H. (2024). *Summary of Transportation and Distribution Section Update in R&D GREET 2024 – Ocean Tanker Size and Backhaul Assumptions*; Argonne National Laboratory: Lemont, IL.

2.5. COMPRESSION PRESSURES OF NATURAL GAS AND GASEOUS HYDROGEN FOR VEHICLE ON-BOARD STORAGE

When NG and gaseous hydrogen are used onboard storage in vehicles, they need to be compressed at refueling stations. NG compression for compressed natural gas (CNG) vehicles, the discharge pressure at the outlet of a NG compressor at the refueling station in R&D GREET is 4,800 psia for vehicle onboard storage rated pressure of 3,600 psia at 15 ^{o}C temperature. The high discharge pressure at the compressor outlet is to drive the flow against the rising onboard pressure (associated with temperature increase due to heat of compression) during fueling. The increase in vehicle onboard storage pressure at the end of fueling can be up to 1.25 times the rated tank pressure, i.e., up to 4,500 psia. Thus, R&D GREET assumes the compressor discharge pressure at 4.800 psia to be slightly higher than the maximum CNG onboard storage pressure to overcome the pressure drop in the lines between the compressor and the CNG dispenser.

Similarly, for 10,000 psia (or 700 bar) hydrogen vehicle onboard storage, the hydrogen pressure increases up to 1.25 times the rated tank pressure, i.e., up to 12,500 psia (or 875 bar). Thus, R&D GREET assumes the discharge pressure of hydrogen compressor to be slightly higher at 14,000 psia to overcome the pressure drop between the compressor and the hydrogen dispenser.

2.6. ANIMAL FEED

Saurajyoti Kar, Hao Cai, and Michael Wang

We evaluated life cycle GHG emissions of new diets for swine and poultry production based on the United Soybean Board. We also updated the life cycle results for live weight swine and poultry production based on the new diets and supply chain estimates of diet production.

Publication:

Saurajyoti Kar, Hao Cai, Michael Wang. (2024). Life Cycle Analysis of New Diets for Swine and Poultry Production in the United States. Argonne National Laboratory: Lemont, IL.

3. R&D GREET MODULES

3.1. CARBON CALCULATOR FOR LAND USE AND LAND MANAGEMENT CHANGE FROM BIOFUELS PRODUCTION (CCLUB)

Hoyoung Kwon, Xinyu Liu, Saurajyoti Kar, Hao Cai, and Michael Wang

We updated/expanded CCLUB to address induced land use changes (ILUC) and other indirect effects of clean fuel production pathways. First, we updated one of the CCLUB's emission factor (EF) models - Agro-Ecological Zone Emission Factors (AEZ-EF) – with the key elements of the IPCC 2019 emission inventory guidelines (IPCC, 2019) and added a new peat oxidation EF of 38 Mg CO_2e/ha/yr (Zhao et al., 2021). Second, we implemented new domestic soil organic carbon (SOC) and nitrous oxide (N_2O) EFs for three feedstocks (i.e., corn, soybean, and grain sorghum) derived from the DayCent model (a daily time-step version of CENTURY) (Del Grosso et al., 2008) that has supported the U.S. EPA's national GHG Inventory report for decades. Finally, we included the GHG emissions from the changes in indirect effect activities from GTAP-BIO ILUC modeling. These indirect GHG emissions are calculated based on changes in production of non-feedstock crops and livestock that were simulated by GTAP-BIO for 19 global regions and GHG EFs associated with the two activity categories developed using IPCC approaches. More details are available in the CCLUB technical report (Kwon et al., 2024).

Publication:

Kwon, H., Liu, X., Kar, S., Cai, H., and Wang, M. (2025). Expansion of Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) to Address Induced Land Use Changes and Other Indirect Effects of Clean Fuel Production for R&D GREET® 2024. Energy Systems and Infrastructure Analysis Division, Argonne National Laboratory. ANL/ESIA-24/22.

3.2. R&D GREET BATTERY MODULE

Siddharth Shukla, Tom Sykora, Jarod C. Kelly, and Hao Cai

An updated version of the battery module has been developed with the release of R&D GREET 2024 to facilitate a user-friendly interaction with the battery inventory of R&D GREET. The module can be used to investigate the energy and environmental impacts associated with nine battery chemistries available within R&D GREET: LMO, NMC111, NMC532, NMC622, NMC811, NMC95, NCA, LFP made via the hydrothermal route, and LFP made via the solid-state route. For each battery chemistry, users can select the expected range of an electric vehicle: 150 miles, 200 miles, 300 miles, and 400 miles. The environmental impact results for the chosen battery chemistry and vehicle range are displayed using intuitive and user-friendly graphics. Additionally, the new battery module allows users to investigate the variation in battery life cycle emissions due to changes in key supply chain and upstream process-related decisions. These decisions include the source of lithium carbonate and lithium hydroxide, energy consumed in producing cathode and its precursor, and energy consumed for battery assembly. Users can also modify emissions from key materials used in batteries like graphite, aluminum, steel, and nickel sulfate due to possible upstream process modifications. The resultant module has been informed through feedback from industry and academic partners to be a more useful and flexible tool than the previous version.

3.3. GREET RAIL MODULE

Md Rakibul Alam, Nazib Siddique, and Amgad Elgowainy

The following changes were made in the R&D GREET 2024 Rail Module (*Rail_PTW* and *Rail_WTW* tabs of GREET1).

Following the US EPA mandate on using ULSD for rail locomotives, ULSD is now set as the default fuel option in the Rail Module (100% ULSD as default in Rail PTW; users can adjust the percentage of blend of USLD with conventional diesel). To reflect ULSD in emission results in Rail WTW, the formulas for SO_x and CO_2 emissions from fuel consumption in rail locomotives were updated. Other pollutant emissions were directly taken from the Association of American Railroads (AAR) field test results of locomotives using ULSD.

Energy and emissions data for various individual fuels were added for intercity and commuter rail modes. These include:

- Biodiesel
- Renewable Diesel
- Dimethyl Ether (DME)
- Fischer-Tropsch Diesel (FTD)
- Liquefied Natural Gas (LNG)
- Liquefied Petroleum Gas (LPG)
- Hydrogen

In the US, intercity and commuter rail services use diesel (ULSD) and electricity. For these rail modes, we updated the R&D GREET 2024 to estimate energy and emission results for fuel combinations such as:

- Biodiesel and Electricity
- Renewable Diesel and Electricity
- DME and Electricity
- FTD and Electricity
- LNG and Electricity
- LPG and Electricity
- Hydrogen and Electricity

For such combinations of two different fuels, energy and emission estimates consider a weighted average of individual fuel types. The share of total miles traveled by these different fuel types are considered as the weights. Users can adjust these fuel shares within the rail network to model customized scenarios.

The load factor represents the ratio of vehicle occupancy to its capacity. For passenger rail, it is calculated as the ratio of passenger-distance unit to seat-distance unit. This factor plays a significant role when considering energy and emissions per passenger-distance unit (e.g., passenger-mile). To account for this, for passenger trains, a load factor input was added to the R&D GREET 2024 (in *Rail_PTW* tab) including intercity and commuter rail services. The energy and emissions formulas in the Rail WTW tab were updated to incorporate this load factor input, providing more accurate assessments. Users can also adjust these values to model various scenarios.

3.4. GREET BUILDING MODULE

Michele Morales, Tom Sykora, and Hao Cai

Supported by the Building Technologies Office of the DOE Energy Efficiency and Renewable Energy Office, the R&D GREET building module was first introduced in 2021. In the 2024 version we made the following updates and expansions:

- Updated the existing user manual entry feature from the Building Materials tab to support use of environmental product declarations (EPD) focusing on data from A1-A3 product stage which encompasses the embodied impacts from raw materials, transportation and manufacturing building materials. This feature allows users to enter A1-A3 product stage data manually from EPDs and then customize other life-cycle stages by using process energy types and transportation data from R&D GREET1 2024 and R&D GREET2 2024 as well as other open sources. This allows for complete and accurate assessment of the construction and installation, use, maintenance, repair, replacement, and refurbishment, deconstruction and demolition, waste transportation, waste processing, disposal, and Re-X stages.
- Improved the Aggregated LCProfiles structure in a separate tab to serve as the full database for both building material LCA and whole building LCA. In this database, the life-cycle results are categorized by life-cycle stage, namely: raw material supply, raw material transportation, manufacturing, finished product transportation, construction and installation, use, maintenance, repair, replacement, and refurbishment, deconstruction and demolition, waste transportation, waste processing, disposal, and Re-X. This new structure supports selection of different system boundaries for whole building LCA such as cradle-to-gate, cradle-to-construction, cradle-to-use, cradle-to-grave, and cradle-to-cradle.
- We expanded the database of the R&D GREET Building module with a total of 40 window configurations, of which the thermal performance varies from a U-factor of 0.40 to a U-factor of 0.15.
- Created an "EPD" database in the Aggregated LCProfiles tab that holds the life-cycle results for aggregated A1-A3 data manually entered by the user.
- Expanded the Whole Building LCA tab including a new user interface:
    - Added a sensitivity analysis dashboard to help visualization of alternative solutions.
    - Added an option to aggregate or disaggregate Bill of Materials Data to support whole building LCA with a specific system boundary and to disaggregate LCA results with more detail. This allows the user to generate aggregated or disaggregated data. Disaggregated data generates results for every life cycle stage, per material per year. Results will be displayed for every life cycle stage up to the system boundary. Aggregated data generates results at the system boundary, per material per year.
    - Enabled users to create refrigerant scenarios to account for the GHG emissions of refrigerants manufacturing, yearly refrigerant leakage from equipment, and leakages during equipment decommissioning.

- Updated Whole Building Emissions dashboard (Dashboard_WB tab) showing operational time-series emissions and breakdown of operational emissions by energy source.

4. HELP, TUTORIALS, AND PRESENTATION MATERIALS

The R&D GREET website (https://greet.anl.gov/) presents all of our publications, including technical reports, technical memos, journal articles (those with open access from individual journals), and journal article abstracts (those without open access from individual journals). These serve as technical documentation of R&D GREET development and applications.

As in the past, users can email inquiries, questions, and comments to greet@anl.gov. To streamline our responses to questions, we suggest using one of the topic areas in your email subject line. Please indicate if you use the R&D GREET Excel version or the .net version.

- R&D GREET1: Oil/gas fuel pathways LCA
- R&D GREET1: Biofuel/waste fuel pathways LCA
- R&D GREET1: Electricity modeling LCA
- R&D GREET1: Hydrogen modeling LCA
- R&D GREET1: Electro-fuel modeling LCA
- R&D GREET1: Plastics/chemicals LCA
- R&D GREET1: Vehicle operations LCA
- R&D GREET2: Vehicle cycle LCA
- R&D GREET Marine LCA
- R&D GREET Aviation LCA
- R&D GREET Rail LCA
- R&D GREET Building LCA
- R&D GREET Farm-level biofuel feedstock LCA (FD-CIC).

To help users navigate inside the model, R&D GREET tutorial video clips are available at https://greet.es.anl.gov/homepage2. In addition, presentation materials from past R&D GREET user workshops (https://greet.es.anl.gov/workshops) are available to help users understand the structure of R&D GREET models, technical approaches, and general coverage.

5. REFERENCES

Alhajjar MA, Prada DN, Philips P, Islam E, Kim N, Mansour C, et al. Evaluation of Energy Consumption and Cost Reduction Potential of Light-, Medium-, and Heavy-Duty Vehicles (2024-2050). Argonne, IL: 2025.

Alvarez, R.A., D. Zavala-Araiza, D.R. Lyon, D.T. Allen, Z.R. Barkley, A.R. Brandt, K.J. Davis, et al. (2018). "Assessment of methane emissions from the U.S. oil and gas supply chain." Science 361 (6398): 186-188. https://doi.org/10.1126/science.aar7204

Del Grosso, S. J., Halvorson, A. D., & Parton, W. J. (2008). Testing DAYCENT Model Simulations of Corn Yields and Nitrous Oxide Emissions in Irrigated Tillage Systems in Colorado. *Journal of Environment Quality*, *37*(4), 1383. https://doi.org/10.2134/jeq2007.0292

Gagnon, P.E, A. Pham, W. Cole, S. Awara, A. Barlas, M. Brown, P. Brown, V. Carag, S. Cohen, A. Hamilton, J. Ho, S. Inskeep, A. Karmakar, L. Lavin, T. Mai, J. Mowers, M. Mowers, C. Murphy, P. Pinchuk, A. Schleifer, B. Sergi, D. Steinberg, and T. Williams. 2023. *"2023 Standard Scenarios Report: A U.S. Electricity Sector Outlook.*" Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-87724.

IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

Islam, E.S., Prada, D.N., Vijayagopal, R., Mansour, C., Phillips, P., Kim, N., Alhajjar, M., Rousseau, A. (2023). *Detailed Simulation Study to Evaluate Future Transportation Decarbonization Potential*; ANL/TAPS-23/3; Argonne National Laboratory: Lemont, IL.

Rutherford, J.S., E.D. Sherwin, A.P. Ravikumar, G.A. Heath, J. Englander, D. Cooley, D. Lyon, M. Omara, Q. Langfitt, and A.R. Brandt. 2021. "Closing the methane gap in US oil and natural gas production emissions inventories." Nature Communications 12 (1): 1–12. https://doi.org/10.1038/s41467-021-25017-4.

Sherwin, E.D., J.S. Rutherford, Z. Zhang, Y. Chen, E.B. Wetherley, P.V. Yakovlev, E.S.F. Berman, B.B. Jones, D.H. Cusworth, A.K. Thorpe, A.K. Ayasse, R.M. Duren, and A.R. Brandt. US oil and gas system emissions from nearly one million aerial site measurements. *Nature*, 627(8003):328-334. https://doi.org/10.1038/s41586-024-07117-5.

U.S. DOE. 2023. "*National Transmission Needs Study.*" Washington, D.C.: U.S. Department of Energy.

U.S. EIA. 2023. "*Annual Energy Outlook 2023*." Washington, DC: U.S. Energy Information Administration.

U.S. EIA. 2024. "*EIA-923 Power Plant Operations Report 2023*." Energy Information Administration. Accessed April 3, 2024. https://www.eia.gov/electricity/data/eia923/.

U.S. EPA. 2024a. “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2022.” https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

U.S. EPA. 2024b. “*The Emissions & Generation Resource Integrated Database: eGRID Technical Guide with Year 2022 Data*”. Washington, DC: U.S. Environmental Protection Agency.

Zhao, X., Taheripour, F., Malina, R., Staples, M. D., & Tyner, W. E. (2021). Estimating induced land use change emissions for sustainable aviation biofuel pathways. *Science of The Total Environment*, *779*, 146238. https://doi.org/10.1016/j.scitotenv.2021.146238

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