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Summary of Expansions and Updates in R&D GREET® 2023

Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory

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Summary of Expansions and Updates in R&D GREET® 2023

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DISCLAIMER

R&D GREET 2023 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 2023) 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 2023 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.

1. INTRODUCTION

The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model was 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), other end-use sectors, and energy systems. Argonne has expanded and updated the model in various areas in R&D GREET 2023. This report provides a summary of the expansions and updates.

R&D GREET 2023 is a part of routine annual R&D GREET updates, which include representation of new fuel pathways and updates to underlying assumptions. Given the explicit reference for GREET in certain tax credit provisions as well as other third-party regulatory implementations, this version of GREET, intended to support RD&D purposes, will be called R&D GREET going forward to avoid confusion and clearly delineate between the versions of GREET. Pathways represented in the tool include those that have been rigorously evaluated and have high certainty; those that are preliminary; those have not recently been evaluated; 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 LCA community and elicit stakeholder feedback. These annual releases are academic in nature and are not necessarily appropriate for use in circumstances where a high level of quantitative certainty or precision is required.

GREET is referenced in numerous independent state and federal compliance and incentive programs (including solicitations, rulemakings, and tax incentives), but it is important to note that this particular release (R&D GREET 2023) may or may not be the version adopted by those 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), but not all regulatory programs that reference GREET have necessarily already adopted a given version of the tool in guidance.

Argonne does not warrant that use of R&D GREET 2023 or any other instance of GREET is consistent with the requirements of any particular regulatory 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.

2. MAJOR EXPANSIONS AND UPDATES IN R&D GREET 2023

2.1. ENERGY PRODUCTS

2.1.1. Hydrogen

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Methane pyrolysis of natural gas (NG) and renewable natural gas (RNG) pathways were implemented for centralized hydrogen production. The life cycle inventory (LCI) data was gathered from pilot plant data provided by industry via personal communication. Pyrolysis of methane results in the production of carbon black, hydrogen, and small amount of coke. Steam is also generated in the process from excess heat recovery. Mass, energy, and market value allocation were implemented as co-product treatment options. If valorized, the steam co-product receives displacement credits as the default option. Steam co-product allocation options for using energy or market value allocation are provided. Mass allocation between hydrogen, carbon black, and coke (with steam export displacement credit) is used as a default option for the methane pyrolysis pathway.

The representation of this pathway depends heavily on the co-product allocation method chosen (mass-, energy-, and market value-based allocations), and there are uncertainties regarding the appropriate default allocation method for solid carbon. The default allocation in R&D GREET 2023 is mass-based allocation. Additionally, the LCI data obtained to date is limited and specific to one type of methane pyrolysis. Additional data representing a broader range of configurations within industry needs to be collected. Argonne has ongoing analysis to resolve these technical uncertainties. Users of R&D GREET 2023 should be aware that the emissions depicted for methane pyrolysis are preliminary, have uncertainty, and may change materially in future versions of R&D GREET.

For RNG-based pathways in R&D GREET 2023, please see discussions in Sections 2.1.4 and 3.3.

In addition, the option for including embodied emissions of electrolyzers was added for hydrogen production via low-temperature water electrolysis (proton exchange membrane [PEM] electrolyzers) and high-temperature electrolysis (solid oxide electrolyzer cell [SOEC] electrolyzers). See Section 2.3.3 for more details.

Publication:

Vyawahare, P., C. Ng, and A. Elgowainy. 2023. *Hydrogen production from methane pyrolysis*. https://greet.es.anl.gov/publication-methane_pyrolysis.

2.1.2. Sustainable Aviation Fuels

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Several sustainable aviation fuel (SAF) production pathways from the International Civil Aviation Organization (ICAO) Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) were added to R&D GREET 2023 (ICAO, 2022). The new pathways include hydroprocessing of tallow, palm fatty acid distillate (PFAD), and used cooking oil to produce hydroprocessed esters and fatty acids (HEFA)-derived SAF; the Fischer-Tropsch (FT) process using eucalyptus and municipal solid waste; and the ethanol-to-jet (ETJ) conversion using sugarcane ethanol (besides corn and cellulosic ETJ).

An energy allocation method was added as an alternative to the existing displacement method for handling fermentation/gasification co-products (i.e., co-generated electricity) of the cellulosic ethanol production pathways in the *EtOH* tab. This change allows the user to apply the energy allocation method throughout all processes in the system boundary if CORSIA pathways are selected, according to the CORSIA guideline for all co-product cases. In addition, corrections were made in the co-product allocation formulas of ETJ and sugar-to-jet pathways to properly account for co-generated electricity.

We also updated the terminology in ETJ pathways in R&D GREET from "standalone" to "integrated" and from "distributed" to "standalone." Previously, R&D GREET ETJ pathways were configured as "standalone" or "distributed" systems depending on the ethanol source. If ethanol production and jet fuel production are co-located using biomass feedstocks, it was called a "standalone" system. On the other hand, if ethanol is imported for SAF production (two separate facilities), the system was called "distributed." However, ICAO CORSIA uses different terminology, which frequently caused confusion. ICAO uses "standalone" and "integrated" systems to refer to the "distributed" and "standalone" systems, respectively, in previous GREET versions. ICAO differentiates the systems based on the heat integration between ethanol and SAF production. If there are two separate systems, ICAO calls it a "standalone" system; on the other hand, if there is a co-located facility, it is called an "integrated" system. Thus, we changed the terminology of the two ETJ designs in R&D GREET to be consistent with ICAO.

R&D GREET's petroleum jet fuel pathways were implemented based on the linear programing modeling of 43 U.S. petroleum refineries (Elgowainy et al., 2014), which reports a CI of 85 gCO_2e/MJ for petroleum jet fuel. In R&D GREET 2023, we added two petroleum jet fuel baseline carbon intensities (CIs) based on ICAO (2022) and Cooney et al. (2017). Both the ICAO and the National Energy Technology Laboratory (NETL) present a CI of 89 gCO_2e/MJ for petroleum jet fuel. Depending on the selection, different petroleum CI values will be used in R&D GREET SAF CI comparisons with petroleum jet CI. Note that only the R&D GREET option gives the modeling capability for users to change input parameters such as energy efficiency and process fuel uses to simulate different refining configurations, while the other two options only present static CI values.

2.1.3. Marine Fuels

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A new NG-to-methanol pathway was added to R&D GREET. The new pathway is distinguished from the previous natural gas-to-methanol pathway in that it includes the production and export of hydrogen as a coproduct (approximately 50% energy share). This pathway was also connected to RNG in new RNG-to-methanol pathways. Users can toggle between RNG sources in the *MeOH_FTD* tab. The available RNG sources are anaerobic digestion of wastewater sludge, food waste, manure, or FOG (fats, oils, and grease); default feedstock is manure.

An additional biomass to methanol pathway was added in which the feedstock is a biomass mix—50% logging residue and 50% clean pine. However, 100% logging residue remains as the default biomass choice for the biomass to methanol pathway via indirect liquefaction. Users can switch it to biomass mix using the toggle in the *MeOH_FTD* tab for the results of the biomass mix-to-methanol pathway.

Fuel consumption (methanol and pilot oil) and emissions (SO_x, NO_x, CO, and CO_2 emissions) test data was received from MAN Energy Solutions for one of their large slow speed two-stroke marine engines operating in methanol dual-fuel mode. Results from International Maritime (IMO) Tier II emissions operation were incorporated into the R&D GREET 2023 *Marine_WTH* (marine well-to-hull) tab to represent operation in international waters. At 80% engine load, the engine operated with 93% methanol and 7% pilot oil (marine gas oil [MGO] 0.1% sulfur), on an energy basis. Although the MAN engine test data achieved higher efficiency (lower specific fuel consumption numbers) than the MGO slow speed two-stroke engine data currently in R&D GREET, it was decided to set the methanol dual-fuel specific fuel consumption values for equivalent engine efficiency to the current R&D GREET baseline data with conventional fuels. This was done to avoid introducing an inconsistency which would lead to unfair comparisons. Within the MAN data, it was found that new methanol dual-fuel engines were operating at an engine efficiency equivalent to new MGO engines. The R&D GREET marine engine efficiencies reflect a lower fleet average specific fuel consumption, which was maintained across the methanol and ammonia pathways (Nerenst, 2023). Although methanol is used with pilot oil, a notional pathway for "fuel only" (methanol-only) was also added to the R&D GREET Excel version to enable the commonly used comparison of individual fuels on an energy basis. The methanol pathway including pilot oil consumption incorporates both the combustion and upstream supply chain emissions of the pilot oil. The toggle to switch between "fuel only" and "with pilot oil" is available in *Marine_WTH* tab.

New ammonia, as a marine fuel, production pathways were added: ammonia production pathway from RNG (via anaerobic digestion of either sludge, swine manure, food waste, or FOG), two pathways for producing ammonia from hydrogen generated through coal gasification with carbon capture and sequestration (CCS) and biomass gasification, and one pathway utilizing hydrogen from PEM electrolysis for ammonia as transportation fuel purposes. These pathways are in addition to the already existing NG-based ammonia pathways, with and without CCS, in R&D GREET. The new pathways were developed by building on the existing ammonia fertilizer pathways with minor modifications, such as adding the previously mentioned hydrogen source switches and adding transportation and distribution of ammonia for use as a fuel. For RNG-based ammonia pathways, we include biogenic CH_4 from the waste-to-RNG process and track the biogenic CO_2 emissions and methane slip from the RNG flaring process (although biogenic CO_2 is not assigned a GHG impact due to the carbon neutrality assumption).

Unlike the use phase of methanol, there was no engine test dataset available for ammonia as a fuel from industry at this moment. Thus, for the R&D GREET 2023 release, we made assumptions for ammonia's use phase based on a literature review (Reiter & Kong, 2008; Yousefi et al., 2022) and industry communications. Major assumptions made for ammonia's use phase are as follows: 1) brake energy conversion efficiency of ammonia is equivalent to that of the baseline marine fuel (or MGO), 2) about 99.94% of engine exhaust N_2O emissions is reduced to N_2, leaving only trace amount of N_2O emissions at the tailpipe (0.00024 gN_2O/kWh-brake work) (Nerenst, 2023), and 3) the additional amount of ammonia used for selective catalytic reduction (SCR) is about 2% of ammonia use in the engine for fuel use (Girard et al., 2007).

Publications (Forthcoming):

Masum, F., E. Tan, C. Kolodziej, and T. Hawkins. 2023. *Life Cycle Assessment of Methanol from Fossil, Biomass, and Waste Sources, and Its Use as a Marine Fuel*. https://greet.es.anl.gov/publication-marine_methanol.

Masum, F., T. Huang, T. Kim, and T. Hawkins. 2023. *Life Cycle Assessment of Ammonia as a Marine Fuel: Implication of Use in Dual Fuel Engines with Pilot Oil*. https://greet.es.anl.gov/publication-marine_ammonia.

2.1.4. Renewable Natural Gas

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While the landfill gas (LFG)-to-RNG pathway was recently updated in R&D GREET, the other RNG pathways are currently being re-evaluated, including RNG production using several types of animal wastes, wastewater sludge, and food waste. The emissions associated with these other pathways in R&D GREET currently have significant uncertainties.

For instance, for RNG from animal wastes, such as dairy cow manure, swine manure, cattle manure, and broiler and turkey waste, it is worth further investigating how much of the methane in biogas from business-as-usual (BAU) waste management systems such as anaerobic lagoons, deep pits, solid storage, dry lots, etc. is currently vented and how much may be destructed via flaring. The fraction of biogenic carbon in solid residues from the BAU waste management and in the digestate from anaerobic digestion (AD) to produce RNG, which is currently assumed to be permanently sequestered, needs to be investigated further. In addition, the methane leakage rate during the biogas clean-up and upgrading processes, which is currently assumed to be 2%, needs to be investigated further. The process energy sources for the biogas upgrading needs to be examined.

For RNG from wastewater sludge, the current BAU management practice is assumed to be on-site AD of the sludge, which produces biogas that is partially combusted to produce heat and power to sustain the AD system, with the remainder of the biogas being flared. This process is assumed to have a methane leakage by 1%, which needs to be investigated further. In addition, the current assumption that 20% of the biogenic carbon in the AD digestate is sequestered when it is applied to land needs to be investigated further. For sludge AD to produce RNG, the AD energy efficiency, upgrading energy efficiency, and process energy sources need to be investigated further. An assumed 2% methane leakage rate during the biogas clean-up and upgrading processes needs to be investigated further.

Given the uncertainties of the key parameters for these RNG pathways, users should be aware that the emissions resulting from pathways that use these feedstocks have high uncertainty, are very preliminary, and may change materially in future versions of R&D GREET as these technical uncertainties are addressed.

2.1.5. Coal Mining Methane Capture and Utilization

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Coal mining releases methane gas trapped by coal extraction and by collapsing overburden seams and rock strata underground. This waste gas from active and abandoned mining operations is a source of GHG emissions, accounting for about 9% of global anthropogenic CH_4 emissions (EPA, 2019). Historically, coal mine methane (CMM) has been released into the atmosphere unmitigated, presenting an environmental hazard, GHG emissions, and a wasted energy source. About 41.5 million tons of GHG emissions (CO_2e) could have been avoided in 2021 through CMM capture, according to the GHG inventory from underground coal mines by the U.S. Environmental Protection Agency (EPA, 2022). EPA only requires active underground mines that emit more than 36.5 million cubic feet per year of methane emissions to report emissions data to the Greenhouse Gas Reporting Program (GHGRP), and abandoned and surface mines are not required to report data (EPA, 2010). Meanwhile, EPA has developed a federal Coalbed Methane Outreach Program (CMOP), working collaboratively with the industry and recognizing that "because CMM would be released through mining activities, the recovery and use of CMM are considered emissions avoidance" (EPA, 2023b).

The accumulation of methane to explosive concentrations presents a critical safety hazard for mine workers, especially in underground mines. All underground metallurgic or thermal coal mines in the U.S. are required to establish and maintain a ventilation plan that is aimed at avoiding harm to people in and around the mine, including the control of methane. Ventilation plans are evaluated and enforced by the Mine Safety and Health Administration (MSHA) through a highly formalized process, and no mine in the US can operate without liberating methane to the atmosphere that, in the absence of a ventilation system, would pose a safety risk. Under MSHA regulations, methane concentrations must be kept below 1% at the working face. Degasification is therefore an integral safety component of the underground mining process (Climate Action Reserve, 2012). Two primary degasification techniques are practiced by mine operators: methane emissions that are vented through mine ventilation shafts (i.e., ventilation), an option that removes CMM as ventilation air methane (VAM), or methane drainage wells designed for the express purpose of removing the methane from the mine and venting it to the atmosphere (i.e., methane drainage). These two degasification techniques are frequently combined to increase the reliability and efficiency of methane control. CMM as discussed here does not consider wells at which methane is removed before mining through a pre-mine drainage system or coal bed methane wells that are extracting NG not associated with mine safety.

For underground longwall mines, post-mining (or gob) boreholes are a common drainage system that releases waste coal gas with a high concentration of methane to the atmosphere (Waste Gas Capture Initiative, 2023). This otherwise released CMM can be captured for beneficial uses such as electricity generation, and enriched to pipeline quality methane gas for various end uses. Studies that used tracer gas tests to measure the migration pathways and the transport times of the CMM exiting the boreholes or entering the ventilation system showed that coal mine waste gas being extracted by boreholes can exit the borehole within days, and the gas would otherwise enter the ventilation system within a couple of weeks if the borehole exhauster stopped production (Mucho et al., 2000; Schatzel et al., 2017; UNECE, 2010). These studies demonstrate that the methane-rich coal waste gas will be liberated from the mines via the ventilation or borehole system within a short period of time if they are not captured.

Prior to 2010, CMM recovery for utilization projects benefited from incentive programs, but with the lack of further incentives, the number of CMM recovery for utilization projects has declined, and many projects have ceased operation due to the large capital infrastructure and operating costs. CMM capture and utilization through gas collection, treatment, and pipeline injection presents an opportunity for diverting the CMM gas to beneficial uses, such as providing an additional source of methane for electricity generation, among others. According to the 2022 Greenhouse Gas Reporting Program (GHGRP) database (EPA, 2023c), of the liberated CMM from drainage/boreholes, which is relatively rich in the methane content, about 67% is captured and utilized for power generation, about 3% is captured for flaring, and about 2% is upgraded for pipeline injection. The remaining about 29% of the CMM from drainage/boreholes is liberated and become fugitive emissions. On the other hand, CMM from VAM has low-methane concentrations. Currently, in the absence of CMM capture and utilization, CMM from VAMs is largely vented directly to the atmosphere. In the meantime, a controlled flare system could present an option to reduce the environmental impact of direct venting.

In an upcoming journal article, Argonne conducts a detailed life cycle GHG emissions analysis of CMM by expanding the R&D GREET model to include capture, processing, distribution, and various utilization stages. The current CMM management practices for coal mining safety management purposes, such as venting and flaring, and their relative shares are discussed. End uses of CMM include electricity generation, methanol production, ammonia production, and hydrogen production. Detailed process-level operational data, including energy and chemical consumption and methane leakage rates for CMM capturing and processing, are collected from actual CMM capturing projects and implemented in R&D GREET. In addition, the impact of blending CMM with fossil NG for these end uses is modeled in R&D GREET 2023.

The information above and R&D GREET modeling of the coal mine methane pathway represents information gathered to date, is preliminary, and is under ongoing internal and technical peer review. While the pathway has been included in R&D GREET 2023 for informational purposes, users should be aware that the emissions depicted are preliminary, have uncertainty, and may change materially in future versions of R&D GREET.

Publication (Forthcoming):

L. Ou, H. Cai, M. Wang, et al. 2023. *Life Cycle Analysis of Coal Mine Methane Capture and Utilization*. https://greet.es.anl.gov/publication-lca_coal_ch4_cu.

2.1.6. Synthetic Natural Gas (Power-to-Gas)

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A new synthetic natural gas (SNG) production pathway, also referred as power-to-gas, was added to the *E-fuel* tab in R&D GREET 2023. SNG is produced from CO_2 and H_2 via the Sabatier reaction; the H_2 is provided from low-carbon renewable or nuclear energy sources, and the CO_2 is captured from point source emitters or the atmosphere. This pathway leverages the established H_2 and CO_2 pathways for e-fuel production in R&D GREET. SNG synthesis typically uses a nickel catalyst supported on alumina (Ni/Al_2O_3) for the methanation reaction. A newly developed Ni/Al_2O_3 catalyst production pathway was developed and linked to the SNG pathway. Mass and energy balance data were obtained from the SNG production engineering process model using Aspen Plus. The heating value and density of SNG were calculated based on the composition of SNG (99.6wt% CH_4 and 0.3wt% CO_2).

The SNG process was modeled to yield a product that can meet current NG pipeline specifications (e.g., maximum water and H_2 content). Assuming SNG is injected or blended into the existing NG pipeline, a new process for SNG transmission and distribution (T&D) was added for stationary combustion use. The SNG T&D process configuration is based on the NG T&D process in R&D GREET; the only change is that that SNG is delivered instead of NG. The amount of CH_4 leakage from transmission pipelines was calculated based on a 0.33 vol% leakage rate over a 680-mile pipeline (similar to the conventional NG leakage rate in transmission pipelines estimated elsewhere for R&D GREET), while the leaked gas has the same components as the delivered gas. SNG pipeline transportation is assumed to follow the current practice of using a reciprocating engine (combusting a fraction of delivered gas) to drive the gas compressor. For the SNG-fired reciprocating engine, we assume the same emission factors for criteria air pollutants (CAP) as the NG-fired engine in R&D GREET and calculate the CO_2 emission factor based on carbon balance using fuel properties.

Water is a byproduct of the methanation reaction. The amount of water generated was subtracted from the amount of water needed for the SNG plant as the net water consumption in R&D GREET water use simulations.

Byproduct steam can potentially be produced from SNG synthesis via heat exchange. We added this exported steam as an option in R&D GREET depending on whether or not the byproduct steam can be sold to a consumer in the vicinity. We set the case of no steam export as the default option. If steam is valorized, it is assumed to displace equivalent steam energy produced from fossil NG combustion in a steam boiler.

Publication (Forthcoming):

K. Lee, P. Sun, A. Elgowainy, K.H. Baek, and B. Pallavi. 2023. *Techno-Economic and Life Cycle Analysis of Synthetic Natural Gas Production from Low-Carbon H_2 and Point-Source or Atmospheric CO_2*. https://greet.es.anl.gov/publication-tea_lca_sng_from_lch2_atmco2.

2.1.7. Fischer-Tropsch Diesel from Landfill Gas via Fischer-Tropsch Synthesis

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We added a pathway for the production of renewable diesel from LFG to the *MEOH_FTD* tab in R&D GREET 2023. This pathway takes syngas derived from LFG via tri-reforming and converts it to Fischer-Tropsch (FT) diesel via FT synthesis using catalytic conversion.

This pathway is an alternative to LFG flaring. The life-cycle emissions of the LFG-derived renewable diesel are influenced by counterfactual emissions credits from avoiding the flaring of the methane component in LFG. There are also co-products in this conversion process: FT naphtha and electricity. Since we have applied the displacement method to handle co-produced electricity for other FT fuel pathways in R&D GREET such as methanol production via FT of natural gas, we also used displacement credits associated with the electricity and FT naphtha production to estimate the overall life cycle emissions of the FT diesel. The pathway also provides R&D GREET users with the option to allocate for the FT naphtha co-product on the basis of energy. The use of waste LFG as feedstock, together with the impact of credits from co-products and counterfactual avoided emissions, make the FT diesel attractive from a life cycle emissions perspective when compared with conventional fossil fuel-based diesel.

Publication:

Poddar, T., G. Zaimes, S. Kar, D. Walker, T. Hawkins. 2023. "Life Cycle Analysis of Fischer-Tropsch Diesel Produced by Tri-Reforming and Fischer-Tropsch Synthesis (TriFTS) of Landfill Gas." *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.3c02162 https://doi.org/10.1021/acs.est.3c02162.

2.1.8. Fischer-Tropsch Fuel Production Integrated with Nuclear Power Generation

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For CO_2-derived FT fuel production integrated with nuclear power generation, we added an option of steam co-product export. We set the case of no steam export as the default option.

2.1.9. Brazilian Sugarcane Ethanol

Xinyu Liu (xinyu.liu@anl.gov) and Michael Wang (mwang@anl.gov)

To foster biofuel production, the Brazilian government introduced RenovaBio, a national biofuel policy. We collected inventory data on sugarcane farming and ethanol production from 67 individual sugarcane mills submitted to RenovaBio in 2019-2020. The collected data included sugarcane farming energy usage rates and share, fertilizer usage rates and share, and energy usage and co-product yields during ethanol processing.

In addition, we derived industry-representative probability density functions (PDFs) for key LCA input parameters with data from individual ethanol plants that are required to disclose to RenovaBio. We updated the Brazilian sugarcane ethanol pathway with the production-weighted average life cycle inventory and the associated PDFs.

Publication:

Liu, X., H. Kwon, M. Wang, and D. O'Connor. 2023. "Life Cycle Greenhouse Gas Emissions of Brazilian Sugar Cane Ethanol Evaluated with the GREET Model Using Data Submitted to RenovaBio." *Environmental Science & Technology* 57 (32): 11814–11822. https://doi.org/10.1021/acs.est.2c08488.

2.1.10. Nuclear Fuel Cycle and Embodied Emissions for Advanced Nuclear Powerplants

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The updated nuclear electricity production in the U.S. in R&D GREET 2023 has three parts. First, the *Uranium* tab has been updated for each step in the nuclear fuel cycle, including material and energy inputs, beginning with the extraction of uranium to the fabrication of nuclear fuel. There are three methods of uranium extraction: open-pit mining, underground mining, and *in-situ* leaching (ISL). The first two methods are followed by a milling process where ore is crushed, and uranium is concentrated into yellowcake. The concentration of uranium in the ore is assumed to be 0.1%, in line with the global average. This uranium is sent to uranium conversion facilities which use either a dry or a wet process to convert the yellowcake into uranium hexafluoride. Both options are provided in R&D GREET 2023, with the default option set to the wet process, as the dry process is only used in the U.S., and its uranium conversion facility was not active in 2022. Uranium enrichment has been updated in R&D GREET 2023 to remove any enrichment capacity for gas diffusion plants, as they are no longer used. Instead, the more energy efficient gas centrifuge method is now used for uranium enrichment. Finally, the enriched uranium is fabricated into nuclear fuel that is transported to light water reactor (LWR) power plants in the U.S. R&D GREET incorporates the global uranium supply chain into the U.S. in the nuclear power pathways. As domestic uranium production has declined steeply in the past decade, the U.S. has relied on uranium imports from countries such as Canada and Kazakhstan to fuel its nuclear power plants. The U.S. also purchases enriched uranium from other countries. The proportion of foreign uranium at each step in the nuclear fuel cycle was determined using publicly available data from Energy Information Administration (EIA, 2022).

Second, the conversion factor for nuclear fuel to electricity from LWRs was updated in R&D GREET 2023 to 6.59 MWh/g U235 to better represent the operating conditions of modern LWRs. The reactor is assumed to have a capacity of 1 GW_e and a burnup rate of 50 GW_t/tonne enriched uranium, and it uses fuel enriched to 4.21%. The tail assay for uranium enrichment is estimated at 0.25%.

Finally, the *Nuclear* tab in R&D GREET2 was updated with the embodied emissions for advanced boiling water reactors and small modular reactors. In addition, embodied emissions for dry cask construction can also be found in the same tab and are used to calculate emissions for spent nuclear fuel disposal for the back-end of the nuclear fuel cycle.

Publication:

Ng, C., P. Vyawahare, Y. Gan, P. Sun, A. Elgowainy. 2023. *Embodied Emissions for Advanced Nuclear Reactors*. ANL/ESIA-23/5. https://greet.anl.gov/publication-embodied_emi_anr

Publications (Forthcoming):

Ng, C., P. Vyawahare, P.T. Benavides, Y. Gan, P. Sun, R. Boardman, J. Marcinkoski, and A. Elgowainy. "Life Cycle Greenhouse Gas Emissions associated with Nuclear Power Generation in the United States." *Journal of Industrial Ecology*. https://greet.es.anl.gov/publication-lca_nuclear_pp_ghg_us.

2.1.11. Saline Algae Production with Protein Co-products

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A new pathway was added that includes saline water microalgae cultivation followed by conversion of the microalgae to fuel and a protein product via protein extraction and hydrothermal liquefaction (HTL). This pathway yields naphtha, ethanol, sustainable aviation fuel, and algal protein concentrate.

The saline water microalgae cultivation aims to reduce competition with freshwater resources. Currently, saline water consumption is not accounted for in fresh water consumption calculations in R&D GREET, and saline water consumption related to water stress will be further discussed in an upcoming publication. There are two main sources of blowdown from saline water systems: One is to maintain salinity below 55,000 mg/L during algae cultivation, and the other is to reduce salinity to 15,000 mg/L before the water enters the centrifuge during the dewatering process via water washing. It is assumed that the blowdown will undergo treatment using the forward osmosis (FO) membrane system and then be injected into deep wells. The FO membrane system and its upstream pathways, including viscose fiber, have been incorporated into the R&D GREET model based on literature (Coday et al., 2015; Zhang et al., 2019).

Several CO_2 sourcing options are available, including high-purity industrial sources as well as power plants. The CO_2 capture energy penalty is estimated through a regression carried out with data from the Integrated Environmental Control Model, for which the detailed methodology may be found in Singh et al. (2022).

The protein extraction and concentration process yields a high-protein co-product with approximately 72% protein content. The production of the protein co-product includes a high-pressure homogenization pretreatment to release intracellular proteins, protein extraction through alkaline solubilization and subsequent solid-liquid separation, acidification of the liquid stream followed by precipitation, and finally, spray drying to create a dry protein concentrate powder. This powder is considered suitable for human consumption. In R&D GREET, the user can select options for the conventional protein source options to be displaced by the algae protein concentrate. Options include whey protein concentrate and soybean protein concentrate, both suitable for human consumption, as well as alfalfa meal and soybean meal used for animal feed. When considering replacements with this high-protein bio-coproduct, the appropriate functional unit—digestible protein, mass, or protein content—can be selected.

Whey protein concentrate is derived from liquid whey, a byproduct of cheese production. Economic value allocation has been employed to account for the impacts of liquid whey in R&D GREET. The uncertainties associated with this substitution arise from fluctuation in market sizes and prices for whey protein concentrate and cheese. Further elaboration of different allocation methods and uncertainties will be provided in a forthcoming report. The preliminary data for liquid whey production encompass milk and cream production, with information sourced from literature (González-García et al., 2013; Kim et al., 2013). The pathways for producing milk and cream have also been incorporated into the R&D GREET model. Soybean protein concentrate is extracted from soybeans, producing the co-products soybean hulls, soy oil, and soybean molasses during the extraction process. Both economic and mass allocation methods have been implemented as options to compute the environmental credits (Philis et al., 2018). LCI data for soybean protein concentrate are available in the *BioOil* Tab of R&D GREET. Data on alfalfa farming and alfalfa meal production, sourced from literature, can be found in the *EtOH* tab of R&D GREET (Long et al., 2015).

Publications:

Singh U., S. Banerjee, and T. Hawkins. 2023. "Implications of CO_2 Sourcing on the Life-Cycle Greenhouse Gas Emissions and Costs of Algae Biofuels." *ACS Sustainable Chemistry and Engineering*. https://doi.org/10.1021/acssuschemeng.3c02082.

Technical report (forthcoming):

Davis, R., T. Hawkins, A. Coleman, S. Gao, B. Klein, M. Wiatrowski, Y. Zhu, et al. *Economic, Greenhouse Gas, and Resource Assessment for Fuel and Protein Production from Microalgae: 2022 Algae Harmonization Update*. ANL/ESIA-23/7. https://greet.es.anl.gov/publication-algae_update_2022.

2.2. VEHICLES

2.2.1. Light-Duty Vehicle (LDV) Fuel Economy and Mass

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The fuel economy (FE) values and mass for light duty vehicles (LDV) were updated in R&D GREET 2023 using the recent simulation results from Argonne's Autonomie vehicle simulation model (Islam et al., 2023). In this R&D GREET update, the fuel economy of midsize sedans, small sport utility vehicles (SUVs), and pickup trucks were updated in the R&D GREET1 model. The update covers multiple fueling pathways and vehicle technologies. The mass of selected vehicle types was also updated in the R&D GREET2 model. This subset of midsize sedans, small SUVs, and pickup trucks only considers internal combustion engine vehicles (ICEV), grid-independent hybrid electric vehicles (HEV), grid-dependent hybrid electric vehicles (PHEV), fully battery electric vehicles (EV), and fuel cell electric vehicles (FCEV) 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. The R&D GREET2 model includes a time series of mass information for the vehicle models. In addition, time-series data are provided for battery power capacity (HEV, FCEV), fuel cell stack power capacity (FCEV), and battery energy capacity (BEV, PHEV). Using those power and energy data from Autonomie modeling, R&D GREET2 allows users to select different battery chemistries with different specific powers/energies than those simulated in Autonomie's runs: R&D GREET approximates the sizes of battery and fuel cell components internally based on its own data and modeling. To determine the vehicle mass, we sized battery and fuel cell weight as noted above and combined that with all other Autonomie-reported weight categories, aside from their reported battery, fuel cell system, hydrogen storage, and fuel weights. We used a R&D GREET2 internal weight estimation of hydrogen storage. 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 2023. The Autonomie model has "low" and "high" technology progression profiles. For the R&D GREET 2023 update, we used the "low" progress scenario to be conservative and representative of baseline technology progress.

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

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The fuel economy values for various classes of medium- and heavy-duty vehicles (MHDVs) were updated in R&D GREET 2023 using the most recent simulation results from the Autonomie model (Islam et al., 2023). Autonomie provided fuel consumption values for the three standard driving cycles for MHDVs specified by EPA for the following vehicle types:

- Class 2 pickup truck and van
- Class 4 pickup and delivery (PnD)/service truck
- Class 6 pickup and delivery (PnD)/box truck
- Class 7 school bus
- Class 8 refuse truck
- Class 8 heavy heavy-duty vocational truck
- Class 8 transit bus
- Class 8 day-cab truck
- Class 8 long-haul truck

For each vehicle type, we considered four powertrain types: conventional ICEV, parallel HEV, BEV, and FCEV. Vehicle types other than Class 8 long-haul trucks are defined as "vocational."

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 Autonomie model provided simulation results for model years 2023, 2025, 2030, 2035, and 2050. This update uses the Autonomie model year 2023 runs to represent all of these model years in R&D GREET, except for 2023, which is used for model year 2020 in R&D GREET. The Autonomie model also provided FE results for "low" and "high" technology progress scenarios. We use the "low" FE values to be conservative.

We also updated the component weights for three MHDVs (Class 6 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 is determined using a combination of Autonomie (Islam et al., 2023) and Argonne's BatPaC models (see Section 2.2.4), and fuel-cell components are sized based on data provided by Strategic Analysis, Inc. For all other components, Autonomie simulation-based results 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 FE updates).

Technical Memo:

Iyer, R.K., and J.C. Kelly. 2023.*Updates to Medium-Duty & Heavy-Duty Vehicle Component Weights*. https://greet.es.anl.gov/publication-MHDV_updates.

2.2.3. Battery Materials—Linking EverBatt and R&D GREET

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Argonne has a separate EverBatt model that computes the energy use and environmental impacts of Li-ion battery recycling (or the production of cathodes and/or cathode precursors via recycling of Li-ion batteries; Argonne National Laboratory, 2023; Dai et al., 2019). In R&D GREET 2023, we integrate these impact outputs from the EverBatt model for recycled Li-ion battery cathodes/cathode precursors, along with the corresponding material and energy inputs and the mass and economic impact allocation factors used for impact calculations. We also provide users the option to modify the shares (%) of virgin and recycled cathodes/cathode precursors used for Li-ion battery production, assuming 100% production from virgin materials as our default case. More details are provided in our technical memo and in the *Battery_Recycling* tab of R&D GREET2.

Technical Memo:

Iyer, R.K., and J.C. Kelly. 2023. *Linkage of EverBatt with R&D GREET*. https://greet.anl.gov/publication-EverBatt_linkage.

2.2.4. Battery Material Composition and Cathodes

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The R&D GREET model typically uses battery energy (kWh) and power (kW) values from Argonne's Autonomie model as inputs to Argonne's BatPaC model (Knehr et al., 2022) to determine the material composition, weight, and specific energy/power of lithium-ion batteries for various vehicles and powertrains. In R&D GREET 2023, we updated these parameters for lithium/Li-ion batteries using the latest results from Autonomie (Islam et al., 2023) and BatPaC 5.1 models (Knehr et al., 2022). The car, SUV, and pickup EV ranges (maximum distance traveled on a single round of EV charging) have been modified to 150/200/300/400 miles (from the previous 200/300/400/500 miles), while the PHEV battery size increases from the 20-mile battery to the 35-mile battery, and still includes the 50-mile battery, in line with the Autonomie updates. The updates span six tabs in R&D GREET2 (*Car, SUV, PUT, Class 6 PnD Trucks, Class 8 Day-cab Trucks*, and *Class 8 Sleeper-cab Trucks*). In addition, we also introduce a new cathode—NMC95 (NMC = nickel manganese cobalt; NMC95 = $LiNi_{0.95}Mn_{0.025}Co_{0.025}O_2$) cathode—per the BatPaC 5.1 model. Inventory details for this cathode are provided in the *Other_Cathodes* tab of R&D GREET2, while its associated battery parameters are updated in the aforementioned six tabs. More information is given in the technical memo for this update.

Technical Memo:

Iyer, R.K., and J.C. Kelly. 2023. *Updates for Lithium-Ion Batteries and Other Components in Light-, Medium-, and Heavy-Duty Vehicles*. https://greet.es.anl.gov/publication-battery_updates.

2.2.5. Agricultural Tractor

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Off-road vehicles contribute approximately 10% of U.S. transportation GHG emissions, almost as much as the aviation sector (DOE et al., 2023). While agriculture equipment constitutes only 21% of off-road energy use, large agricultural tractors have been found to be one of the most significant single vehicle types in terms of fuel consumption and thus GHG emissions. Based on these findings, we implemented a large agricultural tractor into R&D GREET 2023 (both R&D GREET1 [*Tractor_WTW* tab] and R&D GREET2 [*Tractor* tab]) with multiple powertrain options, including an internal combustion engine (ICE), an ICE parallel hybrid, full battery electrification, and a fuel cell. Conventional and low-carbon liquid fuel options are available in R&D GREET 2023 for the ICE and parallel hybrid powertrains. Multiple electricity production pathways are available for the battery electric powertrain. Likewise, several hydrogen production options were implemented for the fuel cell tractor. The selection of energy production pathways is found on the *Tractor_WTW* tab in R&D GREET1. The energy consumption of each tractor powertrain is based on Argonne's Autonomie model (Lajunen et al., 2023). The tractor vehicle cycle was also implemented in R&D GREET2 for each powertrain architecture, allowing users to evaluate the GHG burden of tractor production, use over lifetime, and disposal/recycling. Combining the well-to-wheel results from R&D GREET1 with the vehicle cycle results from R&D GREET2 allows for an evaluation of total tractor cradle-to-grave energy consumption, water consumption, and emissions.

Technical Memo:

Kolodziej, C.P., and J.C. Kelly. 2023. *Implementation of an Agricultural Tractor Cradle-to-Grave Analysis to R&D GREET2023*. https://greet.es.anl.gov/publication-tractor_development.

2.3. MATERIALS

2.3.1. Domestic Lithium Resources

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Lithium (Li) chemicals—lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH)—have conventionally been produced from spodumene ores (primarily in Australia and processed in China) and high Li-content Salar brines (e.g., Chile). The growing demand for Li-ion batteries to decarbonize transportation and other sectors in the U.S. is expected to substantially raise the demand for Li chemicals, necessitating a significant increase in their production and ensuring a robust, secure supply chain. Multiple commercial entities in the U.S. are exploring the production of Li chemicals from low Li-content brines and sedimentary clays—resources that were hitherto considered economically unviable for Li chemical production. At the same time, it is important that the LCA of potential domestic Li chemicals be available in R&D GREET.

R&D GREET 2023 provides a preliminary LCI dataset—material and energy inputs—for Li production from these alternative reserves based on data provided by companies in this domain within the U.S. and North America in their preliminary economic assessment studies. For low Li-content brines, the technology route considered is direct lithium extraction (DLE), which couples the production of Li chemicals with other materials (such as bromine and magnesium chloride) and/or energy sources (geothermal energy or crude oil). Except for the limitation on process emissions (which are not considered due to lack of data), this is the most comprehensive LCI for the production of Li chemicals from these resources. This update helps users analyze and compare the life cycle energy use of Li chemical production from alternative low Li-content brines and clays with those from conventional spodumene and brine reserves. All the updates are made in the *Li_Chemicals* tab of R&D GREET2, while more details are provided in the technical report noted below.

Publication:

Iyer, R.K., and J.C. Kelly. 2023. *Lithium Production in North America: A Review*. ANL/ESIA-23/8. https://greet.anl.gov/publication-Li_production_NA.

2.3.2. Embodied Emissions of Solar PV and Battery Storage

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We used the *Solar_PV* tab in R&D GREET2 to estimate the embodied emissions of the solar PV power infrastructure. To account for the lifecycle emissions embodied in solar PV manufacturing, we analyzed the global supply chain and regional variations in electricity and raw material input for each production step: metallurgical grade silicon production, solar grade polysilicon production, crystalline silicon (cSi) ingot and wafer production, cSi cell production, and cSi PV panel production. For R&D GREET 2023, we updated the global supply chain data for each production step using the cumulative global supply chain data in years 2017–2021. We have also updated the electricity mix and aluminum pathways for the relevant regions.

We also incorporated the LCA pathway to analyze the embodied emissions of battery storage for the solar unviable PV system and generate results for the embodied emissions of average electricity output from the solar PV plus battery system. We incorporated battery discharge time (in hours) and battery storage efficiency to estimate the energy storage size (in kWh) for a solar PV system of specific peak power capacity and used the parameters of inverter loading ratio and inverter storage size ratio to determine the associated inverter size. The estimate of battery storage and inverter size, together with the data of material composition and specific energy of lithium-ion batteries in the R&D GREET database, were then applied to calculate the material inventory and embodied emissions for lithium-ion batteries of different battery chemistry.

In the analysis, we assumed different battery usage scenarios to determine the percentage of electricity released from the battery and the associated emissions burden. Two different battery cycling scenarios—fully cycled twice a day and fully cycled once a day—were incorporated into the model as user options to estimate the electricity delivered by battery storage. The estimate of electricity delivered by battery storage in different battery cycling scenarios compared with the total electricity output of the solar PV system determines the percentage of electricity supplied by the battery system, which was then used to perform emissions calculations for the embodied emissions of average electricity output from the PV plus battery system. We also provide options for replacements of the battery in different battery cycling scenarios based on the number of cycles and different battery chemistries. The material inventory and the associated embodied emissions of the battery system's battery container, battery rack, and cable are also accounted for in the battery LCA.

Publication:

Gan, Yu, Amgad Elgowainy, Zifeng Lu, Jarod C Kelly, Michael Wang, Richard D Boardman, and Jason Marcinkoski. 2023. "Greenhouse gas emissions embodied in the U.S. solar photovoltaic supply chain." *Environmental Research Letter* 18 (10): 104012. https://www.doi.org/10.1088/1748-9326/acf50d.

Publication (Forthcoming):

Gan, Yu, Clarence Ng, and Amgad Elgowainy. 2023. "Considering embodied greenhouse emissions of nuclear and renewable power infrastructures for electrolytic hydrogen and its use for synthetic ammonia, methanol, Fischer−Tropsch fuel production." https://greet.es.anl.gov/publication-facility_ghg_h2_fuels.

2.3.3. Electrolyzers

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Embodied emissions from electrolyzer manufacturing are considered in the overall life cycle of H_2 production for a comprehensive assessment of its life cycle environmental impacts. In R&D GREET 2023, we included these embodied emissions in the life cycle of electrolyzer-based H_2 production, encompassing both electrolyzer stack and balance-of-plant (BOP) components. Three electrolyzer technologies are considered: alkaline, SOECs, and PEMs. Bills of materials (BOMs), energy inputs, and the associated manufacturing impacts of all three technologies are provided in the *Electrolyzer* tab of R&D GREET2. While R&D GREET 2022 provided these details for electrolyzer stacks, we have now provided the same for BOP units of all electrolyzers (except for energy inputs for BOP manufacturing) based on data provided by Strategic Analysis, Inc. These manufacturing impacts are subsequently imported to the *Hydrogen* tab of R&D GREET1 for inclusion in the H_2 life cycle.

Technical Memo:

Iyer, R.K., P. Vyawahare, J.C. Kelly, and A. Elgowainy. 2023. *Electrolyzer Manufacturing Updates in R&D GREET 2023*. https://greet.es.anl.gov/publication-electrolyzer_updates.

2.3.4. Aluminum

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Earlier GREET versions combine extruded and sheet aluminum into wrought aluminum, which is then used in automobiles and other applications. In R&D GREET 2023, we disaggregated the wrought aluminum into automotive extruded and sheet aluminum forms for use in automobiles. We also used the appropriate aluminum forms (both automotive and non-automotive) in R&D GREET 2023 for applications other than the previously aggregated wrought aluminum pathway. Aluminum-related changes span multiple tabs of R&D GREET2 and enable a more accurate characterization of the energy use and environmental impacts for automobiles and other products that use aluminum in various forms. With the removal of wrought aluminum in vehicle components for R&D GREET 2023, we used the existing ratios of stamped automotive sheet and extruded automotive aluminum from that used in wrought previously (62.1% and 37.9%, respectively) for all LDV and MHDV components. For batteries, we assumed non-stamped automotive aluminum sheet use for current collectors.

2.3.5. End-of-Life Recycling

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Historically, the R&D GREET model has used the recycled content method to estimate the life cycle energy use and environmental impacts of recycled materials. In 2022, we added the end-of-life recycling method in R&D GREET for steel and aluminum and evaluated their environmental impacts in both methods. The end-of-life recycling method assigns the production burden of primary material to a product and then uses the quantity of that material that is recovered at the product's end of life to provide a recycling credit to the product.

In R&D GREET 2023, we expanded the use of the end-of-life recycling method to other automotive materials—lead, nickel, magnesium, copper, glass, and platinum—by considering their respective end-of-life recycling rates from the literature. In addition, we updated the recycled content values for these materials to current values for automobiles wherever available. These updates better characterize the resultant environmental outcomes of these materials as well as of the automobiles made using these materials using both methods. The recycled content and end-of-life recycling content methods are provided in the *Mat_Inputs* and *Mat_Sum* tabs and are used to compute the environmental impacts of vehicles in the various vehicle-related tabs of R&D GREET2 (such as *Vehi_Comp_Sum*, *MHDV_Comp_Sum*, and *MHDV_Trailer_Comp_Sum*).

Technical Memo:

Iyer, R.K. and J.C. Kelly. 2023. *End-of-Life Recycling Information for Lead, Nickel, Magnesium, Copper, Glass, Plastic, and Platinum.* https://greet.es.anl.gov/publication-EOL_recycling_info.

2.3.6. Ammonia

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Argonne's previous evaluation of NG-based ammonia production was based on Aspen Plus simulations of ammonia plant processes. Aspen results showed that the acid gas removal (AGR) process using methyl diethanolamine (MDEA) has potential methane emissions from stripper tail gas, and the Aspen Plus simulation did not consider methane mitigation measures such as off-gas combustion (Lee et al., 2022). However, through communication with industrial ammonia plant operators, we confirmed that the tail gas from the industrial AGR process does not contain methane, and even if it does, all the vent gas is combusted to provide process heat and mitigate potential methane impacts. Therefore, we updated the NG-based ammonia production pathway in R&D GREET by assuming no methane emissions from the AGR process.

However, Zhou et al. (2019) measured airborne methane emissions from six NG-based ammonia fertilizer facilities in the U.S. via a mobile sensing approach using a Google Street View car equipped with a high-resolution methane analyzer. They calculated the NG loss rate, which represents the ratio of NG loss over the NG input to ammonia plants. They assumed that the measured methane emissions were representative of emissions during the normal operations of plants, and they estimated the NG input to ammonia plants based on an energy balance approach. According to their study, the industrial average NG loss rate (± standard deviation) was estimated to be 0.34% (±0.20%). If we accounted for such leakage (0.34% on average) for NG-based ammonia production in R&D GREET, well-to-gate GHG emissions of ammonia production would increase by 2.4%.

Although the measurement results implied that an NG-based ammonia plant may have methane leakage, the source of the leakage is uncertain. It could be from ammonia production facilities, the front end of the facilities, such as the pipeline for NG transportation and distribution, or the back end of the facilities, such as a purge gas leak from the plant. It could also be partly from the NG supply chain in the proximity of ammonia plant. Further, the top-down measurement from the atmosphere has not been confirmed from measurements (or lack of measurements) of individual sources inside ammonia plants. For example, the EPA GHGRP (EPA, 2023c) did not report any methane emissions from potential leakages. Therefore, due to limited understanding and the uncertainty of the leakage source, we decided not to include methane emissions for the NG-based ammonia production pathways in R&D GREET 2023, in contrast to R&D GREET 2022, in which Aspen-estimated methane emissions were included. Compared to R&D GREET 2022, the well-to-gate GHG emissions of ammonia production in R&D GREET 2023 were reduced by 14.5%.

NG-based ammonia production produces coproduct steam. In Argonne's evaluation using an Aspen Plus simulation, all the steam produced was assumed to be used for turbines to supply power to compressor units in the ammonia plant (Lee et al., 2022). However, a 2021 International Energy Agency (IEA) report showed that steam can be exported from ammonia plants (IEA, 2021). We confirmed with industry partners that this is the case for the newest ammonia plants. In existing ammonia plant designs, steam is used to drive turbines in the plant. Argonne's Aspen Plus simulation calculated the total NG demand and electricity consumption for conventional NG-based ammonia production to be 32.7 GJ-LHV (low heating value) per tonne of ammonia (Lee et al., 2022), while in the IEA 2021 report, the NG demand and electricity consumption for energy efficient plants were 29.3 GJ-LHV/tonne when steam export is not considered (IEA, 2021), and the Fertilizer Institute's 2005–2013 average from its production cost survey for NG demand and electricity consumption was reported to be 34.7 GJ-LHV/tonne (The Fertilizer Institute, 2013). Therefore, Argonne's simulation result is within the range of the IEA 2021 and the Fertilizer Institute's 2005–2013 survey data. In R&D GREET 2023, we maintain the NG demand and electricity consumption for ammonia production from our Aspen simulation (Lee et al., 2022).

2.3.7. Nickel

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In 2022, we updated the nickel (Ni) production inventory in R&D GREET from sulfidic and laterite ores to reflect their respective contributions to the U.S. Ni supply chain mix. While the sulfidic ore-based inventory was provided for each stage to characterize its corresponding impact, a similar stage-wise segregation was not available for laterite ores.

In R&D GREET 2023, we disaggregated the material and energy inputs for lateritic Ni production to provide a comprehensive understanding of contributions from different stages to its overall environmental impacts. We also considered the sulfur dioxide (SO_x) emissions generated during sulfidic Ni production—a revision to the Ni-related updates in 2022 that provides a more accurate representation of the overall SO_x emissions from this pathway. In addition, we updated the mix of Class I Ni production from both laterite and sulfide ores from the U.S. supply chain to the global supply chain mix. This update provides a more comprehensive assessment of the environmental impacts of both Class I Ni production and subsequent $NiSO_4$ production from this Class I Ni. All updates are made in the *Nickel* tab of R&D GREET2, with more details in the technical memo noted below.

Technical Memo:

Iyer, R.K., S. Shukla, and J.C. Kelly. 2023. *Nickel Updates in R&D GREET 2023*. https://greet.es.anl.gov/publication-Ni_updates_2023.

2.3.8. Steam Cracking Chemicals

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A new allocation method has been added to the *Steam_Cracking* tab in R&D GREET that considers certain outputs of the steam cracking process to be by-products and allocates the impacts of the process and its upstream inputs entirely to the set of "target products" (Plastics Europe, 2012) for steam cracking products and some major plastics precursors. The new allocation method, which has been used in Europe and is referred to as the high-value chemical (HVC) allocation method (Plastics Europe, 2012), is a modification of the mass allocation method that allocates the impacts associated with the use of fuels and energy sources in the crackers to the products with higher commercial value (hydrogen, ethylene, propylene, butadiene, benzene, toluene, styrene, xylene, and ethylbenzene). Consequently, impacts associated with cracker operation are not allocated to the remaining products (methane, ethyne, propyne, butatriene, butene, pyrolysis gasoline, and fuel oil). The allocation methods for steam cracker products in R&D GREET 2023 now include mass, energy, market value, and the high-value chemical.

Publication:

Gracida-Alvarez, U.R., P.T. Benavides, U. Lee, and M. Wang. "Life cycle analysis of recycling of post-use plastic to plastic via pyrolysis." 2023. *Journal of Cleaner Production* 425: 138867. https://doi.org/10.1016/j.jclepro.2023.138867.

2.3.9. Fossil-Based and Bio-Based Chemical Pathways

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We added 13 new pathways to producing chemicals and biochemicals to the *Chemicals* tab in R&D GREET 2023, including eight bio-based and five fossil-based pathways. The fossil-based pathways include: (1) fossil-based isoprene, (2) fossil-based lactic acid, (3) fossil-based maleic anhydride, (4) fossil-based succinic acid, and (5) fossil-based C16-C18 fatty alcohol. The bio-based pathways are composed of (1) bio-based 5-hydroxymethylfurfural (HMF), (2) bio-based 2,5-furandicarboxylic acid (FDCA), (3) bio-based furfural, (4) bio-based palm oil-derived fatty alcohol, (5) bio-based p-xylene, (6) bio-based 1,3-butadiene, (7) bio-based itaconic acid, and (8) bio-based isoprene.

Additionally, three bio-based feedstocks were implemented in R&D GREET 2023, as they are required material inputs for some of the bio-based chemicals. The bio-based feedstocks consist of (1) corn cob, utilized in the production of furfural and now available in the *Animal_Feed* tab, (2) refined palm oil, which is an input in the C16–C18 fatty alcohol process and has been implemented in the *BioOil* tab, and (3) hardwood chips (produced in Maine), which are used in the production of HMF and FDCA and are located in the *Bio_electricity* tab. Data from Hong et al. (2015), Xu et al. (2020), and Xu et al. (2021) were used in the development of the LCIs of corn cob, refined palm oil, and hardwood chips, respectively.

Publication:

Liang, C., U. R. Gracida-Alvarez, T. R. Hawkins, and J. B. Dunn. 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.

2.3.10. Post-Use Plastics-to-Plastics Pathways

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New pathways for converting post-use plastic (PUP) to new plastic via cofeeding of PUP-based pyrolysis oil with fossil-derived feedstock have been added to the *PUP_conversion* tab of R&D GREET1. Building on previous LCA work on pyrolysis of post-use and non-recycled plastic (Benavides et al., 2017, 2022; Gracida-Alvarez et al., 2023) and collaborations with pyrolysis facilities and petrochemical companies in the U.S. and Europe, the conversion of PUP was expanded to include new plastics like high-density and low-density polyethylene (HDPE and LDPE, respectively). R&D GREET was configured to estimate life cycle impacts of transforming PUP in pioneer and N^{th}-plant pyrolysis facilities from two perspectives: the recyclers' and the crackers'. The model incorporated aggregated operational data from eight pyrolysis facilities (seven located in the U.S. and one in Europe) and supplementary simulation data leveraging R&D GREET supply chains for plastics production. The system boundary of the LCA included PUP collection, pretreatment, conversion of PUP to pyrolysis oil, purification of pyrolysis oil, steam cracking of pyrolysis oil that is co-fed with conventional feedstocks to steam crackers, and polymerization of monomers to both HDPE and LDPE plastic. The steam cracking modeling developed in R&D GREET was leveraged to conduct the co-feeding portion of this work as it is shown in the *Steam_Cracking* tab.

Publication:

Gracida-Alvarez, U.R., P.T. Benavides, U. Lee, and M. Wang. 2023. "Life cycle analysis of recycling of post-use plastic to plastic via pyrolysis." *Journal of Cleaner Production* 425: 138867. https://doi.org/10.1016/j.jclepro.2023.138867.

2.3.11. Ni/Al_2O_3 Catalyst

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A new Ni/Al_2O_3 catalyst production pathway was added to the *Catalyst* tab. This catalyst can be used for the Sabatier (methanation) reaction to produce synthetic natural gas (SNG) from H_2 and CO_2. According to Quindimil et al. (2020), the Ni(12 wt%)/Al_2O_3 catalyst is prepared by calcining an impregnated sample of gamma-Al_2O_3 with $Ni(NO_3)_2$ solution. The developed data for $Ni(NO_3)_2$ and gamma alumina production pathways were employed in R&D GREET 2023. According to Wang et al. (2015), the energy consumption for the calcining process is 2 MMBtu/ton catalyst. The catalyst was assumed to be transported 50 miles to its destination via heavy heavy-duty truck fueled by diesel.

2.3.12. Fertilizer and Herbicide

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We updated the LCI for the following final/intermediate fertilizer products: sulfuric acid, phosphoric acid, diammonium phosphate (DAP), and monoammonium phosphate (MAP). The updates are based on the most recent production cost survey conducted by the Fertilizer Institute (Troendle, 2003). We used the five-year average from 1999 to 2003 (the years for which data are available) to update R&D GREET 2023.

Before this update, the GREET model incorporated four types of herbicides: atrazine, metolachlor, acetochlor, and cyanazine (Wang, 1999). In R&D GREET 2023, we incorporated production pathways for three additional herbicides: glyphosate, dicamba, and 2,4-D. These herbicides are widely used for major crops and were not present in the previous versions of the GREET model. To develop production pathways for these, we used inventories gathered from Green (1987). We also introduced one "generic herbicide" type; its inventory was calculated by averaging the data from all common types of herbicides in Green (1987).

We also updated herbicide ingredient mixes for major crops including corn, soybean, and sorghum by collecting data from U. S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS; USDA, 2023).

	Corn	**Willow or Poplar**	**Switchgrass or Miscanthus**	**Sugarcane**	**Soybean**	**Sorghum**
Atrazine	25.4%	0.0%	0.0%	0.0%	0.5%	27.8%
Metolachlor	14.5%	0.0%	0.0%	0.0%	12.9%	17.1%
Acetochlor	17.7%	0.0%	0.0%	0.0%	4.2%	9.7%
Cyanazine	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Glyphosate	31.6%	0.0%	0.0%	0.0%	49.8%	27.6%
2,4-D	2.7%	0.0%	0.0%	0.0%	7.9%	6.8%
Dicamba	1.7%	0.0%	0.0%	0.0%	6.1%	4.8%
Others	6.3%	100.0%	100.0%	100.0%	18.5%	6.2%

In addition, we updated the fertilizer transportation mode share and distance, based on data collected from the Fertilizer Institute (Fertilizer Institute, 2019).

Technical Memo:

Liu, X., and H. Cai. 2023. *Updates in Fertilizer and Herbicide Production Life Cycle Inventory in R&D GREET*. https://greet.es.anl.gov/publication-fertilizer_pesticide_update_2023

3. OTHER UPDATES AND ADDITIONS

3.1. ELECTRICITY GENERATION MIX AND CRUDE OIL MIX

Uisung Lee (ulee@anl.gov)

Electricity generation mixes by U.S. regions were updated based on EIA's Annual Energy Outlook (AEO) for eight North American Electric Reliability Corporation (NERC) regions and three states (Alaska, California, and Hawaii), as presented in Table A-1 (EIA, 2023a). Since EIA does not provide electricity generation projections for Alaska and Hawaii, we maintain the same mixes for future years for those two states (EIA, 2023c). In previous GREET versions, the "pumped storage and others" item in AEO was added to the mix of hydropower generation. In the current AEO, "pumped storage and others" for future years has significant negative values, due to pumping energy losses that result in a net consumer of electricity for pumped storage. We subtracted the net electricity consumption of "pumped storage and others" from the hydroelectric power and updated the electricity generation mix in R&D GREET 2023. The hydroelectric generation category can be net negative in some regions. In this case, we set it zero and normalized the shares of other electricity generation sources accordingly.

We also updated the projection of the regional crude shares through 2050. R&D GREET covers eight regions—U.S. domestic, Canada (oil sands), Canada (conventional crude), Mexico, Middle East, Latin America, Africa, and Other. The projected U.S. domestic share is directly from AEO (EIA, 2023a), and the shares of other regions are based on company-level crude import data by EIA (EIA, 2023b). The regional crude oil shares from 2021 to 2050 are presented in Table B-1. For the shale oil share, Eagle Ford and Bakken contribute 8.0% and 8.7%, respectively, based on EIA (EIA, 2023d, 2023e). The weighted average values of crude oil transportation distances have been updated using company-level import data (EIA, 2023b). The weighted average distances are estimated at 8,588 miles by ocean tankers for offshore countries and 1,698 miles for Canada and Mexico by pipeline.

3.2. WASTE MANAGEMENT OF MUNICIPAL SOLID WASTE

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Landfilling has been included in R&D GREET as the business-as-usual (BAU) management practice of municipal solid waste (MSW) for many years, following the methodologies outlined in the 2006 Intergovernmental Panel on Climate Change (IPCC) guidelines (IPCC, 2006). This update added incineration, composting, and anaerobic digestion to the BAU MSW management practices. We adopted the methodology and data in EPA's Waste Reduction Model (WARM) (EPA, 2023d), together with data from literature and MSW management facilities to estimate GHG emissions from each BAU management practice for major MSW components. Component-level LCA results are provided for each MSW management practice. The U.S. average LCA results for each component are then estimated based on the share of MSW management practices for each component. The old IPCC approach is still available in R&D GREET 2023. An option is provided for users to select the modeling approach for their study. R&D GREET 2023 also added navigation buttons at the top of the *Waste* tab to help users navigate through the module.

This pathway is currently under internal review. Users of R&D GREET 2023 should be aware that the emissions resulting from pathways that use this feedstock are very preliminary, have high uncertainty, and may change materially in future versions of R&D GREET.

Publication (Forthcoming):

Wang, Y., L. Ou, H. Cai, U. Lee, T. Hawkins, and M. Wang. 2023. *Greenhouse Gas Emissions of Business-As-Usual Management Practices for Non-Recycled Municipal Solid Waste in the United States*. https://greet.es.anl.gov/publication-non_recycled_msw_ghg.

3.3. WASTE MANAGEMENT OF ANIMAL MANURE

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We updated animal manure management in R&D GREET 2023 using the latest data released by the U.S. EPA. Two types of data are updated. First, in emissions data, the state-level shares of manure management systems, including anaerobic lagoons, deep pits, liquid/slurry, solid storage, pasture application, dry lot, etc., were updated using the EPA data (EPA, 2023a). The updates were made for all types of animal manure modeled in R&D GREET, including beef cattle, dairy cows, dairy heifers, swine, layers, and broiler and turkey. The national average values of MCFs (Han et al., 2011) and shares of different manure management systems were calculated based on the state-level results and the animal populations for each state (EPA, 2023a; USDA, 2023). Second, we updated parameters related to the estimation of methane emissions from manure management (e.g., methane conversion factors [MCFs]). MCFs determine the methane emission from each manure management system and vary by manure management technologies and climate. MCFs for dry systems were updated using the latest IPCC data (IPCC, 2019). State-level MCFs for liquid systems were updated using the EPA data (EPA, 2023a). Meanwhile, we also revised the ratio of vented methane from animal waste management to 100%, considering that no evidence, including the EPA GHG emission inventory report, has suggested that methane generated from the animal waste management systems mentioned above is captured and flared. Previous versions of GREET used an assumption of 60% venting of recoverable methane. This update represents current practice (CARB, 2023).

Given the uncertainty of these animal manure-based RNG pathways as noted in Section 2.1.4, users should be aware that the emissions resulting from pathways that use this feedstock are very preliminary, have high uncertainty, and may change materially in future versions of R&D GREET.

3.4. CO_2 CAPTURE, COMPRESSION, AND TRANSPORTATION

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We updated the energy requirements for CO_2 capture and compression for the following emission sources: ethanol plants, ammonia plants, NG processing plants, steam methane reforming (SMR) hydrogen plants, cement plants, iron and steel plants, NG-fired power plants, and coal-fired power plants.

The energy requirements for CO_2 capture from these industries were updated based on recent data from two NETL reports (Hughes et al., 2022; Schmitt et al., 2022). For high-purity CO_2 sources from ethanol plants, ammonia plants, and NG processing plants, a capture process is not needed, thus there is zero capture energy use. For mid- and low-purity CO_2 emitted from cement plants, iron and steel plants, NG-fired power plants, and coal-fired power plants, the Shell CANSOLV post-combustion CO_2 capture system was applied to capture CO_2. For hydrogen plants, the Shell ADIP-Ultra pre-combustion CO_2 capture system was applied (Hughes et al., 2022; Schmitt et al., 2022).

CO_2 Sources	Reference	CO_2 Capture System
Ethanol plant	Hughes et al., 2022	n/a (compression only)
Ammonia plant	Hughes et al., 2022	n/a (compression only)
NG processing plant	Hughes et al., 2022	n/a (compression only)
SMR hydrogen plant	Hughes et al., 2022	Shell ADIP-Ultra
Cement plant	Hughes et al., 2022	Shell CANSOLV
Iron and steel plant	Hughes et al., 2022	Shell CANSOLV
NG-fired power plant	Schmitt et al., 2022	Shell CANSOLV
Coal-fired power plant	Schmitt et al., 2022	Shell CANSOLV

CO_2 capture systems (CANSOLV and ADIP-Ultra) require low-pressure steam, which can be generated by NG, waste heat or other energy sources. In R&D GREET 2023, we applied the NG input for CO_2 capture from SMR hydrogen plants, cement plants, and iron and steel plants. Because power plants already produce steam, there is no dedicated fuel use for steam generation for CO_2 capture. Instead, the loss of the net power generation due to steam use for CO_2 capture was converted as additional burden for CO_2 capture.

After CO_2 capture, the CO_2 gas is further compressed to reach the pressure (e.g., 2,200 psi) needed for pipeline transportation. The energy for CO_2 compression was calculated with the thermodynamic compression formula in the *Compression* tab. The compression conditions (the inlet temperature, the inlet and outlet pressures) for each industry were updated based on the two NETL reports (Hughes et al., 2022; Schmitt et al., 2022). The compression conditions can be modified in the *Compression* tab. R&D GREET then calculates the corresponding compression electricity requirement.

When the captured and compressed CO_2 is transported by pipeline, a number of booster pumps will be needed, depending on the transportation distance. A rule-of-thumb assumption of distance between booster stations is 100 miles. The R&D GREET default is one booster pump and a 200-mile pipeline distance. R&D GREET users can manually change the pipeline distance to calculate the corresponding number of boosters and the corresponding electricity requirement. The electricity requirement to operate one booster pump is 8.2 MJ/metric ton of CO_2 with specified conditions: upstream and downstream pressures of 2,200 psia and 1,500 psia, temperature at 25°C, and booster pump energy efficiency of 70%.

3.5. DIRECT AIR CAPTURE

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We updated two direct air capture (DAC) pathways in R&D GREET 2023: high-temperature (HT) absorption-based DAC and cryogenic carbon capture. For HT DAC (high-temperature liquid absorption pathway), we updated the default energy demand (NG and electricity) based on data from Keith et al. (2018). In the current update, the electricity use of a CO_2 compressor is subtracted from the DAC electricity demand, as it is accounted for separately during the compression stage by using the thermodynamic compression formula in R&D GREET. The CO_2 emissions calculations were also updated based on the process data in Keith et al. (2018). All CO_2 produced in the calciner of the reference design is captured. Since CO_2 emissions from NG combustion in the calciner were also captured in the process of the reference design, those captured CO_2 emissions were subtracted from the total emissions for high-temperature DAC. The cryogenic carbon capture column was also updated to provide a note for clarification. In Baxter et al. (2021), the pilot plant was designed for flue gas removal along with CO_2 removal from atmosphere. Thus, we added a note to clarify.

3.6. METHANE LEAKAGE IN NATURAL GAS SUPPLY CHAIN

Andrew Burnham (aburnham@anl.gov)

Methane leakage and CO_2 flaring emissions from the NG supply chain were updated based on newly published data. In R&D GREET 2023, 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, 2023a).

Technical Memo:

Burnham, A. 2023. *Updated Natural Gas Pathways in R&D GREET 2023*. https://greet.es.anl.gov/publication-update_ng_2023.

3.7. LIQUEFIED NATURAL GAS REGASIFICATION

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To estimate the emissions associated with the global usage of imported liquefied natural gas (LNG), we included the LNG regasification process in R&D GREET 2023. This LNG pathway is applied in many regions around the world that lack domestic NG supplies, such as Europe and East Asia (in China, Japan, and South Korea).

There are mainly two types of regasification technologies—open rack vaporizers (ORVs) and submerged combustion vaporizers (SCVs)—used for LNG regasification at the receiving terminal (Agarwal et al., 2017). ORVs use seawater as the heating source to vaporize LNG, while SCVs use heat generated from NG combustion for the vaporization. The choice between the two technologies is mainly determined by the ambient temperature and the geographic location of the LNG terminal (Agarwal et al., 2017; Chu et al., 2006). Generally, most LNG terminals adopt ORV as the primary technology, while LNG terminals with lower ambient temperatures in winter adopt SCV as the secondary technology to provide additional heat (Agarwal et al., 2017; Chu et al., 2006). We obtained the energy consumption rate of ORVs and SCVs from literature (Chu et al., 2006; Li and Chen, 2016) and then calculated the average energy consumption for LNG regasification. See details in the publication listed below. We assumed a 0.1% boil-off rate per day and a five-day stay at the receiving terminal for the LNG to calculate the leakage and venting emissions.

Publication:

Gan, Y., H.M. El-Houjeiri, A. Badahdah, Z. Lu, H. Cai, H., S. Przesmitzki, and M. Wang. 2020. "Carbon footprint of global natural gas supplies to China." *Nature Communications* 11 (1): 824. https://doi.org/10.1038/s41467-020-14606-4.

3.8. BIOPOWER CARBON CAPTURE AND SEQUESTRATION

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We implemented carbon capture, transportation, and sequestration for electricity production from biomass combustion by U.S. states in the *Bio_electricity* tab, using the life cycle inventory of CCS for biopower published by NETL (Buchheit et al., 2021).

Calculation of CO_2 available for CCS is based on existing data in the *Bio*_electricity tab for dry biomass demand per unit electricity produced by state and wood type. To calculate the net carbon fraction in dry biomass, the weighted carbon content per state is used. The assumptions for compression, transportation distance, and booster pump requirements are implemented based on the *E_fuel* tab, where one booster pump is assumed per 200 miles of pipeline distance.

Default values of 95% efficiency of CO_2 capture from flue gas for CCS and a 0.48% ash fraction in biomass are assumed. Calculated from NETL life cycle inventory analysis, the default value of the electricity penalty for CO_2 capture is 1060 MJ/tonne CO_2.

The percentage change in results for resource use and emissions metrics for biopower with and without CCS are relatively larger than those for coal electricity with and without CCS. The main reason for this is that the effect of the parasitic electricity load for biopower CCS is higher than that of coal CCS due to the lower efficiency of electricity generation from biomass. In addition, the efficiency of coal-to-electricity and biomass-to-electricity are parameterized differently. Increases in supply chain emissions for the various chemicals used for CO_2 capture also influence the percentage differences, but to a lesser extent.

Although the NETL report provides flow rates of fly ash and bottom ash as waste streams, we did not include them in the current implementation to maintain consistency with the coal electricity pathways.

3.9. TRUCK PAYLOAD FOR TRANSPORTING CORN TO ETHANOL PLANTS

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In R&D GREET 2023, we updated the payload of a heavy heavy-duty truck to transport corn from the field to an ethanol plant from 15 short tons to 25.2 short tons. This update was based on feedback we received from several Midwestern corn ethanol producers: Corn is hauled to an ethanol plant by a semi-trailer with an average payload of 900–1000 bushels. In this update, we used the more conservative payload of 900 bushels, which translated to 25.2 short tons.

3.10. ANIMAL FEED

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In R&D GREET 2023, several animal feed ingredients have been added to the *Animal_Feed* tab: alfalfa feed for mature cows, alfalfa feed for immature cows, corn silage, and cotton feed. These components serve as feed for cows, ultimately yielding milk as the primary output. Milk, in turn, serves as the primary raw material for both cheese and liquid whey production. Liquid whey, in particular, plays a central role as the primary raw material for producing whey protein concentrate, which is one of the target products to be replaced by algal protein concentrate. Detailed information on algal protein concentrate extraction in biofuel conversion pathways can be found on the *Algae* tab. All inventories are based on dry mass, with data sourced from the literature (Grant & Hicks, 2018). Life cycle inventory data for corn cob (see Section 2.3.9 for details), is also included in this update. We also made some minor revisions (e.g., updates in the time series values and yield of ethanol conversion) in the distiller's dried grains with solubles (DDGS) pathway related to the yield of corn ethanol used to reflect the correct corn ethanol pathway.

3.11. TRANSPORTATION LOSS OF SORGHUM PATHWAYS

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We updated the loss factor of sorghum transportation from 2% to 0% to reflect the current practices in sorghum transportation.

4. R&D GREET MODULES

Several modules have been created with the R&D GREET model to increase R&D GREET user modeling experiences. Below is a summary of the R&D GREET modules released together with R&D GREET 2023.

4.1. R&D GREET MARINE MODULE

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The R&D GREET marine module provides an interactive, user-friendly platform with which to view the life cycle emissions of existing marine fuel pathways in R&D GREET. Users can select from fossil fuels such as heavy fuel oil, marine diesel oil, methanol/ammonia from NG or sustainable marine fuels such as bio-oils, methanol/ammonia from RNG, etc. Upon selecting the fuels, users can choose the feedstock sources (depending on the pathways) and view the results along with the input parameters. Fuel cycle results of pathways are divided into three categories: feedstock, conversion, and combustion. GHG results are shown with more details and with further breakdowns between CO_2, CH_4, and N_2O estimates. It also shows trip-specific results. It allows users to define their own input parameters and view the updated results as the interface connects to the R&D GREET1 Excel version in the background. It allows the users to save and compare results, both from fuel cycle and trip perspective, for up to five pathways or trips. Detailed instructions on how to use the module are included with the marine module.

First introduced in 2022, the marine module was updated with the R&D GREET 2023 release. In this version, NG or RNG to methanol and hydrogen (as a coproduct) pathways were included. The default primary feedstock for the biomass to methanol pathway was changed from logging residue to mixed biomass, which is a combination of 50% clean pine and 50% logging residue. RNG to ammonia pathways were also included. Users can choose the feedstock source for RNG for both methanol and ammonia pathways—the available options are wastewater sludge, swine manure, food waste, and FOG (fats, oil, and grease). Ammonia from hydrogen produced from poplar gasification, coal gasification with CCS, and water electrolysis with renewable electricity are also included. The R&D GREET marine module and a user guide are available at https://greet.es.anl.gov/greet_marine.

4.2. CCLUB (CARBON CALCULATOR FOR LAND USE CHANGE FROM BIOFUELS PRODUCTION)

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The Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB; Kwon et al., 2021) takes a process simulation approach to estimating the soil organic carbon (SOC) changes between various land uses, using the CENTURY model. In CCLUB 2023, Argonne has added agro-ecological zone emission factors (AEZ-EF) as an alternative approach to estimating the SOC changes between various domestic and international land uses. The Californian Air Resources Board (CARB) developed the AEZ-EF for its low-carbon fuel standard (LCFS) program and Purdue University updated it for the ICAO CORSIA program.

Domestic AEZ-EFs representing the SOC changes between major land use categories across the AEZ7 to AEZ16 regions were implemented for major biofuel feedstock production systems, such as corn, corn stover, cellulosic feedstock (e.g., switchgrass and miscanthus), and woody feedstock (e.g., poplar and willow). Domestic and international land use categories include croplands, pasture/hay/grasslands, forests, idle cropland, and expired Conservation Reserve Program (CRP) land.

In addition, Argonne has incorporated the latest 2013 Winrock SOC emission factors for estimating GHG emissions from land use changes related to biofuels.

The CCLUB SOC modeling options now include the following approaches for domestic SOC modeling: 1) CENTURY, 2) AEZ-EF, 3) Winrock, and 4) Woods Hole. For international SOC modeling, it includes the AEZ-EF, Winrock, and Woods Hole approaches. Argonne has implemented the AEZ-EF approach for both domestic and international SOC modeling in the Excel and .net versions of the CCLUB tool.

Technical Memo:

Liu X., H. Cai, M. Wang, and H. Kwon. 2023. Updates to Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB). https://greet.es.anl.gov/publication-cclub_update_2023.

4.3. FEEDSTOCK CARBON INTENSITY CALCULATOR (FD-CIC)

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To model the impacts of Right source, Right rate, Right time, and Right place (4R) practices on N_2O emissions from corn farming, we reduce the nitrogen fertilizer application rate by 14% for 4R practices relative to the fertilizer application rate without 4R practices (Nehring, 2020). N_2O emission reduction from 4R is calculated based on the reduction in nitrogen fertilizer input and the N-N_2O conversion rate in R&D GREET.

We expanded FD-CIC for multi-year LCA of crop production in common crop rotations, including corn-soybean, continuous corn, and corn-corn-soybean. The new multi-year, landscape-based LCA worksheets in FD-CIC can generate two types of results: 1) landscape-based LCA results over the two or three years of crop rotation, in grams of GHG emissions per acre of cropland, and 2) crop-specific LCA results with different crop rotations, in grams of GHG emissions per bushel of a specific crop.

Besides the emission impacts of crop rotations, FD-CIC accounts for GHG emission impacts of other farming practices, such as tillage, cover crop, and manure practices. In a selected crop rotation, the user can specify the tillage practice, including conventional tillage, reduced tillage, and no tillage. The user can also specify whether a cover crop is planted during a crop rotation and/or whether manure is applied to the crop field.

The simulations of county-level soil organic carbon changes related to corn and soybean production from different crop rotations are conducted with the parameterized CENTURY model. The simulated soil organic carbon change results are incorporated in FD-CIC in the form of lookup tables. FD-CIC is available at https://greet.es.anl.gov/tool_fd_cic

4.4. R&D GREET BATTERY MODULE: BETA VERSION

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A beta version of a new battery module has been developed with the release of R&D GREET 2023 to facilitate a user-friendly comparison of the inventory and the environmental impacts of selected battery chemistries available in R&D GREET using a dashboard. Presently, the module can be used to compare eight different battery chemistries: LMO, NMC111, NMC532, NMC622, NMC811, NCA, LFP made via the hydrothermal route, and LFP made via the solid state route. For each battery chemistry, the user can choose the expected range of the electric vehicle: 150 miles, 200 miles, 300 miles, and 400 miles. Therefore, the user can compare the environmental impacts and inventories of 32 different battery choices per kWh (eight at a time) in a transparent, interactive, and user-friendly manner. By changing the default module values, users can also investigate the relative change in the energy demand and emissions of different battery chemistries due to possible technological advancements, e.g., changes in battery specific energy or upstream material production emissions.

Publication:

Shukla S., T. Sykora, J.C. Kelly, and H. Cai. R&D *GREET Battery Module: Beta Version*. https://greet.es.anl.gov/publication-battery_module_2023.

5. 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 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 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.

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APPENDIX A: U.S. ELECTRICITY GENERATION MIX

Table A-1. Electricity generation mixes of the United States, eight NERC Regions, and three states

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
U.S. Mix										
2022	0.3%	38.5%	20.6%	18.9%	0.3%	6.8%	0.4%	10.7%	3.3%	0.4%
2025	0.2%	32.1%	18.7%	19.1%	0.3%	7.3%	0.4%	12.4%	9.0%	0.6%
2030	0.2%	24.7%	8.3%	17.9%	0.2%	6.8%	0.5%	22.0%	18.2%	1.2%
2035	0.2%	20.6%	7.9%	15.9%	0.2%	6.3%	0.5%	23.8%	22.1%	2.4%
2040	0.1%	21.4%	6.8%	13.7%	0.2%	5.8%	0.6%	23.3%	25.3%	2.7%
2045	0.1%	21.4%	6.0%	13.2%	0.2%	5.4%	0.7%	23.0%	27.3%	2.7%
2050	0.1%	21.0%	5.0%	12.6%	0.2%	4.9%	0.7%	22.7%	30.0%	2.7%
Texas Reliability Entity (TRE) Mix										
2022	0.1%	44.5%	13.9%	10.1%	0.0%	0.2%	0.0%	26.4%	4.7%	0.0%
2025	0.1%	32.0%	14.4%	10.1%	0.0%	0.1%	0.0%	28.3%	14.9%	0.1%
2030	0.0%	30.9%	5.6%	9.7%	0.0%	0.0%	0.0%	27.6%	25.9%	0.2%
2035	0.0%	25.8%	6.7%	9.4%	0.0%	0.0%	0.0%	24.9%	32.7%	0.4%
2040	0.0%	27.9%	4.0%	9.0%	0.0%	0.0%	0.0%	23.3%	35.4%	0.5%
2045	0.0%	29.0%	3.5%	8.6%	0.0%	0.0%	0.0%	23.9%	34.4%	0.6%
2050	0.0%	29.0%	2.6%	8.1%	0.0%	0.0%	0.0%	21.6%	37.9%	0.8%
Florida Reliability Coordinating Council (FRCC) Mix										
2022	0.2%	71.3%	10.4%	12.5%	0.2%	0.8%	0.0%	0.0%	4.2%	0.6%
2025	0.2%	64.9%	7.9%	12.8%	0.2%	0.8%	0.0%	0.0%	12.6%	0.7%
2030	0.1%	45.5%	5.9%	11.7%	0.2%	0.6%	0.0%	0.0%	35.4%	0.7%
2035	0.1%	42.2%	6.2%	11.4%	0.2%	0.3%	0.0%	0.0%	38.9%	0.8%
2040	0.0%	40.5%	5.8%	11.0%	0.2%	0.1%	0.0%	0.0%	41.4%	0.9%
2045	0.0%	34.6%	5.5%	10.6%	0.2%	0.0%	0.0%	0.0%	48.1%	1.0%
2050	0.0%	35.2%	5.2%	10.1%	0.2%	0.0%	0.0%	0.0%	48.3%	1.0%

Table A-1. (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Midcontinent ISO (MISO) Mix										
2022	0.2%	30.9%	36.6%	14.2%	0.2%	1.4%	0.0%	15.3%	0.9%	0.3%
2025	0.2%	26.3%	32.9%	14.4%	0.2%	1.6%	0.0%	17.6%	6.6%	0.4%
2030	0.1%	18.7%	11.6%	10.8%	0.1%	1.2%	0.0%	38.6%	18.5%	0.5%
2035	0.1%	15.9%	11.9%	5.8%	0.1%	1.0%	0.0%	44.9%	19.7%	0.6%
2040	0.1%	16.6%	11.0%	4.1%	0.1%	0.8%	0.0%	45.7%	20.8%	0.8%
2045	0.1%	17.1%	9.5%	4.1%	0.1%	0.6%	0.0%	46.5%	21.2%	0.9%
2050	0.1%	16.6%	7.2%	3.8%	0.2%	0.4%	0.0%	47.5%	23.2%	1.0%
Northeast Power Coordinating Council (NPCC) Mix										
2022	0.2%	50.5%	0.7%	23.6%	1.1%	16.0%	0.0%	4.0%	2.0%	1.9%
2025	0.2%	39.0%	0.0%	24.4%	1.2%	17.8%	0.0%	9.7%	4.1%	3.5%
2030	0.1%	28.1%	0.0%	22.9%	1.2%	16.5%	0.0%	19.1%	4.9%	7.2%
2035	0.0%	23.4%	0.0%	21.8%	1.1%	15.7%	0.0%	18.9%	4.7%	14.4%
2040	0.0%	21.3%	0.0%	21.3%	1.1%	15.3%	0.0%	18.5%	4.6%	17.9%
2045	0.0%	21.0%	0.0%	20.2%	1.0%	14.4%	0.0%	17.9%	8.3%	17.1%
2050	0.0%	20.3%	0.0%	18.9%	1.0%	13.2%	0.0%	18.4%	12.1%	16.1%
Pennsylvania, New Jersey, and Maryland (PJM) Mix										
2022	0.1%	43.9%	18.3%	31.1%	0.1%	1.3%	0.0%	3.5%	1.2%	0.4%
2025	0.1%	38.1%	18.0%	31.4%	0.1%	1.4%	0.0%	5.9%	4.4%	0.6%
2030	0.0%	33.4%	11.8%	31.5%	0.0%	1.4%	0.0%	8.6%	10.7%	2.6%
2035	0.0%	27.4%	9.7%	30.2%	0.0%	1.3%	0.0%	13.5%	12.2%	5.7%
2040	0.0%	29.9%	9.4%	26.3%	0.0%	1.1%	0.0%	13.1%	14.9%	5.4%
2045	0.0%	30.8%	9.0%	25.5%	0.0%	1.0%	0.0%	12.9%	15.3%	5.5%
2050	0.0%	28.9%	7.9%	24.6%	0.0%	0.9%	0.0%	14.2%	18.2%	5.2%

Table A-1. (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
SERC Reliability Corporation (SERC) Mix										
2022	0.2%	34.9%	25.5%	31.6%	0.4%	4.6%	0.0%	0.0%	2.8%	0.1%
2025	0.2%	30.0%	22.5%	33.5%	0.3%	4.9%	0.0%	0.1%	8.4%	0.2%
2030	0.1%	20.1%	10.0%	34.3%	0.4%	4.8%	0.0%	2.9%	27.3%	0.3%
2035	0.1%	15.8%	9.9%	31.0%	0.3%	4.3%	0.0%	2.5%	35.8%	0.4%
2040	0.0%	16.8%	8.8%	26.1%	0.3%	3.7%	0.0%	2.3%	41.5%	0.5%
2045	0.0%	16.7%	7.1%	24.5%	0.3%	2.9%	0.0%	2.2%	45.7%	0.5%
2050	0.0%	15.6%	5.5%	23.2%	0.3%	2.3%	0.0%	1.7%	50.9%	0.5%
Southwest Power Pool (SPP) Mix										
2022	0.1%	23.8%	26.2%	5.7%	0.0%	5.5%	0.0%	38.4%	0.3%	0.1%
2025	0.1%	17.9%	24.3%	5.5%	0.0%	5.6%	0.0%	38.2%	8.3%	0.1%
2030	0.0%	10.3%	8.0%	4.9%	0.0%	4.3%	0.0%	55.7%	16.6%	0.2%
2035	0.0%	8.6%	9.0%	1.4%	0.0%	4.6%	0.0%	59.2%	16.8%	0.3%
2040	0.0%	10.5%	8.2%	1.7%	0.0%	4.6%	0.0%	58.2%	16.3%	0.5%
2045	0.0%	11.4%	8.0%	1.6%	0.0%	4.5%	0.0%	57.7%	16.2%	0.6%
2050	0.0%	13.1%	7.5%	1.6%	0.0%	4.4%	0.0%	56.8%	15.8%	0.8%
Western Electricity Coordinating Council (WECC) Mix										
2022	0.1%	30.7%	15.9%	7.9%	0.4%	22.9%	2.1%	11.1%	8.6%	0.3%
2025	0.1%	25.8%	13.2%	6.6%	0.4%	24.5%	2.2%	12.4%	14.3%	0.4%
2030	0.1%	19.0%	5.0%	5.3%	0.4%	23.4%	2.6%	29.8%	13.8%	0.6%
2035	0.1%	15.6%	4.1%	5.0%	0.4%	21.4%	2.9%	29.8%	20.0%	0.8%
2040	0.1%	14.9%	2.1%	3.6%	0.4%	19.7%	3.2%	29.1%	26.1%	1.0%
2045	0.1%	14.6%	1.8%	3.4%	0.3%	18.5%	3.4%	27.6%	29.1%	1.3%
2050	0.1%	15.1%	1.7%	3.2%	0.4%	17.3%	3.8%	26.0%	30.9%	1.6%

Table A-1. (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
California Mix										
2022	0.0%	42.8%	3.4%	8.3%	0.9%	12.5%	3.8%	7.4%	20.3%	0.7%
2025	0.0%	32.7%	0.0%	4.4%	1.0%	14.2%	4.4%	7.8%	34.6%	0.8%
2030	0.0%	30.2%	0.0%	0.0%	1.1%	14.9%	6.6%	7.7%	38.4%	1.1%
2035	0.0%	18.3%	0.0%	0.0%	1.0%	10.7%	6.8%	5.8%	56.3%	1.1%
2040	0.0%	15.4%	0.0%	0.0%	0.9%	8.4%	6.8%	5.2%	62.1%	1.2%
2045	0.0%	9.8%	0.0%	0.0%	0.8%	7.3%	7.2%	5.6%	68.0%	1.3%
2050	0.0%	7.8%	0.0%	0.0%	0.8%	6.5%	8.1%	5.9%	69.5%	1.4%
Alaska Mix										
2022	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
2025	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
2030	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
2035	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
2040	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
2045	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
2050	13.7%	46.7%	11.4%	0.0%	0.6%	25.6%	0.0%	2.0%	0.0%	0.0%
Hawaii Mix										
2022	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%
2025	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%
2030	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%
2035	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%
2040	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%
2045	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%
2050	67.0%	0.0%	11.8%	0.0%	3.1%	1.3%	2.0%	7.2%	5.5%	2.2%

APPENDIX B: U.S. CRUDE OIL MIX

Table B-1. Crude oil share in the United States by 2050

Year	U.S. Domestic	Canada (Oil Sands)	Canada (Conventional Crude)	Mexico	Middle East	Latin America	Africa	Others
2022	80.8%	6.6%	5.0%	1.9%	2.3%	1.9%	0.9%	0.6%
2025	77.6%	7.7%	5.9%	2.3%	2.6%	2.2%	1.1%	0.7%
2030	77.8%	7.6%	5.8%	2.3%	2.6%	2.2%	1.0%	0.7%
2035	77.8%	7.6%	5.8%	2.3%	2.6%	2.2%	1.0%	0.7%
2050	78.1%	7.5%	5.7%	2.2%	2.6%	2.2%	1.0%	0.6%

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