ANL/ESD-21/16

Summary of Expansions and Updates in GREET® 2021

Energy Systems Division

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Summary of Expansions and Updates in GREET® 2021

prepared by
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Systems Assessment Center, Energy Systems Division, Argonne National Laboratory

October 2021

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ACKNOWLEDGMENTS

The GREET development efforts at Argonne National Laboratory have been supported by several programs of the Energy Efficiency and Renewable Energy (EERE) Office of the U.S. Department of Energy (DOE), including the Vehicle Technologies Office (VTO), the Bioenergy Technologies Office (BETO), and the Hydrogen and Fuel Cell Technologies Office (HFTO). Recently, EERE's Building Technology Office (BTO) began to support expansion of GREET to the building sector. Further, DOE's ARPA-E SMARTFARM program has been supporting in-depth LCA of biofuel feedstocks. Argonne National Laboratory's work was supported by the DOE under contract DE-AC02-06CH11357. The views expressed in the report do not necessarily represent the views of the DOE or the U.S. Government.

1. INTRODUCTION

The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model has been developed by Argonne National Laboratory (Argonne) with the support of the U.S. Department of Energy (DOE). GREET is a life-cycle analysis (LCA) tool, structured to systematically examine the energy and environmental effects of a wide variety of transportation fuels and vehicle technologies in major transportation sectors (i.e., road, air, marine, and rail) and other end-use sectors, and energy systems. Within the transportation sector, GREET covers road, air, water, and rail transportation sub-sectors. Recently, GREET was expanded to cover the building sector. Historically, GREET includes LCA of various materials such as steel, aluminum, cement, and different plastic types. Argonne has expanded and updated the model in various sectors in GREET 2021, and this report provides a summary of the release.

2. MAJOR EXPANSIONS AND UPDATES IN GREET 2021

2.1. Energy Products

2.1.1. Corn Starch Ethanol

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The U.S. corn ethanol industry has significantly evolved in the past two decades. In order to examine the changes in corn farming and corn starch ethanol production, we have conducted a retrospective analysis evaluating the changes from 2005 to 2019. The analysis covers updates in both corn farming activities (e.g., corn grain yield, fertilizer/energy inputs) based on the data from the United States Department of Agriculture (USDA) and corn grain ethanol production (e.g., ethanol yield and energy inputs) based on industry biorefinery benchmarking data. The results show that corn grain yield has increased while fertilizer inputs per acre have remained constant, which led to a decrease in fertilizer intensities per bushel of corn harvested. In addition, increased corn grain ethanol yield and reductions in energy use have reduced the life-cycle greenhouse gas (GHG) emissions per megajoule (MJ) of corn grain ethanol produced and used. Based on the results of this study, we have updated the time-series values of relevant parameters for the corn ethanol pathway in GREET 2021. Due to a lack of 2020 data, 2019 values are used for 2020 corn farming and corn grain ethanol production. For details, see Lee et al. (2021).

Publication:

- Lee, U., Kwon, H., Wu, M., & Wang, M. (2021). Retrospective analysis of the US corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions. *Biofuels, Bioproducts and Biorefining*. doi.org/10.1002/bbb.2225

In addition to industry benchmarking data, supplementary data from the USDA was used for estimating the yields of Distiller's Grains with Solubles (DGS) and corn oil. Since 2015, the

USDA started surveying domestic ethanol mills monthly. For 2019, average co-product yield from dry mill plants is calculated using the Grain Crushings and Co-Products Production Annual Summary 2020 report published by the USDA (USDA, 2021a). Both USDA statistics and industry survey data show good match for corn oil yield. For DGS, after careful evaluation including detailed mass-balance analysis, we concluded that USDA statistics are more representative and thus we use USDA's DGS yield in lieu of industry benchmark data.

In GREET 2020, CO_2 emissions from starch fermentation in ethanol plants were calculated using a carbon balance approach with the estimates of carbon inputs in corn and carbon outputs in ethanol, DGS, and corn oil (Wang et al., 2020). However, this approach relies on the assumption that carbon contents of these parameters DGS yields are accurate. Since ethanol mills produce DGS with varying moisture content, estimating the exact mass of DGS from industry survey data is challenging. On the other hand, experimental data indicate that fermentation CO_2 emissions is near stoichiometry (Badino Jr & Hokka, 1999). Thus, in GREET 2021 we replaced the carbon balance approach with a stoichiometry approach: one mole ethanol will yield one mole CO_2 (2.85 kg CO_2/gallon of ethanol) for fermentation CO_2 estimation.

2.1.2. Corn Fiber Ethanol

Hui Xu (hui.xu@anl.gov) and Yuan Li (yuan.li@anl.gov)

The corn fiber ethanol pathway in GREET 2020, as documented in Qin et al. (2018), was hard coded, thus assumptions on base or starch corn ethanol yield is no longer valid for recent ethanol data updates. In GREET 2021, corn fiber ethanol pathway was reconfigured to link corn grain ethanol with corn fiber ethanol interactively: marginal changes in yields of grain ethanol, fiber ethanol, and corn oil, reductions in DGS volume, and savings on heating demand for DGS drying (due to lower DGS volume) are based on baseline corn grain ethanol yield. More details on the original corn fiber ethanol pathway development can be found in Qin et al. (2018). A manuscript documenting life-cycle analysis of low-carbon ethanol refining options, including fiber ethanol pathway, is in preparation.

Publication: *In preparation*

2.1.3. Biodiesel and Renewable Diesel from Vegetable Oil, Tallow, and Fatty Acids

Hui Xu (hui.xu@anl.gov) and Longwen Ou (oul@anl.gov)

We updated and expanded biodiesel (BD) and renewable diesel (RD) pathways (Table 1) in GREET 2021. In addition to updating existing pathways, we added carinata to BD/RD, palm fatty acid distillate (PFAD) to BD, and tallow to RD pathways. Current biodiesel conversion data is based on a 2016 industry survey. In collaboration with the National Biodiesel Board (NBB), Argonne surveyed domestic biodiesel and renewable diesel producers to get updated energy/mass balance and materials input data for production of BD (including both vegetable oil and high fatty acid oil [FFA] oil pathways) and RD. The 2021 industry survey collects operational data for years 2018 and 2019. Feedstock production data for soy oil and canola oil are also updated (see the feedstock production section below for more details). Through a collaboration with the North American Renders' Association (NARA), Argonne conducted a separate industry survey in 2021 to survey domestic animal fat and used cooking oil (UCO) renders, covering operation data for years 2018 and 2019. For UCO, collection and logistic data is also collected through the 2021 industry survey supported by NARA. Completed UCO to BD and RD pathways will be released towards end of calendar year 2021 with a manuscript that documents the datasets and key LCA results.

Table 1. BD and RD Pathways Updated in GREET 2021 Release

Feedstock type	**Feedstock preparation**	**Biomass processing**	**Biofuel conversion**	
	Farming or collection	**Oil extraction or rendering**	**BD**	**RD**
Crops				
Soy oil	↗	↗	↗	↗
Canola oil	↗	—	<->	<->
Corn oil	N/A	—	↗	↗
Carinata	—	—	●	●
Residues/byproducts				
PFAD	—	—	●	—
Tallow			<->	●
UCO	●	●	●	●

— Using existing GREET database.
● New pathways to be added to GREET through this project.
↗ Updating existing pathways by using more recent data.
<-> Benefits from soy oil and other pathway updates.
N/A Not applicable.

Publication: In preparation

2.1.4. Supply Chain Sustainability Analysis (SCSA) Fuel Pathways: Renewable Gasoline, Diesel, and Hydrocarbon Fuel Pathways from Lignocellulosic Biomass and Municipal Wastewater Sludge

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We include the SCSA results of the 2020 state of technology (SOT) of six biofuel production pathways via a range of conversion technologies. The SCSA takes the life-cycle analysis approach to identify energy and environmental sustainability hotspots that could be mitigated through improved process materials and energy conversion efficiencies. The SCSA results provide guidance to BETO ongoing R&D efforts to achieve multiple performance targets including sustainability. Additionally, the SCSA tracks and demonstrates the progress of energy and environmental performances of the individual biofuel pathways that undergo continuous development.

In GREET 2021, we add detailed material and energy balances as well as SCSA results of the 2020 SOT cases of 1) renewable high octane gasoline via indirect liquefaction (IDL) of woody lignocellulosic biomass (in the Pyrolysis_IDL tab); 2) renewable gasoline and diesel via ex-situ catalytic fast pyrolysis of woody lignocellulosic biomass (in the Pyrolysis_IDL tab); 3) renewable diesel via hydrothermal liquefaction (HTL) of wet sludge from a wastewater treatment plant (in the renewable natural gas [RNG] tab); 4) renewable hydrocarbon fuels via biochemical conversion of herbaceous lignocellulosic biomass (in the integrated biorefinery [IBR] tab); 5) renewable diesel via HTL of a blend of algae and corn stover (in the Algae tab); and 6) renewable diesel via combined algae processing (in the Algae tab). We present the SCSA results with different co-product handling methods including a process-level allocation method, a displacement method, and a biorefinery-level method to provide a complete picture of the emission performances of fuel products and non-fuel co-products for pathways with a significant amount of co-products.

Technical report:

- Cai, H., L. Ou, M. Wang, R. Davis, A. Dutta, Harris, K., Wiatrowski, M., Tan, E., Bartling, A., Klein B., Hartley, D., Lin, Y., Roni, M., Thompson, D., Snowden-Swan, L. and Zhu, Y. "Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2020 State-of-Technology Cases." Argonne National Laboratory. Technical Report. ANL/ESD-21/1. 2021. https://greet.es.anl.gov/publication-2020_update_renewable_hc_fuel

2.1.5. Performance-Enhancing Biofuel Blends Based on Co-Optima Fuel Pathways

Troy Hawkins (thawkins@anl.gov), Pahola Thathiana Benavides (pbenavides@anl.gov) George G. Zaimes (gzaimes@anl.gov), Longwen Ou (oul@anl.gov), Taemin Kim (tlkim@anl.gov), and Hao Cai (hcai@anl.gov)

New and modified pathways for performance enhancing biofuels

For the GREET 2021 release, we have added eight pathways for fuels for use in engines co-optimized with drop-in biofuel blends to improve engine efficiency performance and reduce engine-out emissions. One pathway produces methanol from biomass gasification, which is blended with a petroleum gasoline blendstock and designed to improve engine efficiency for light-duty multi-mode (MM) engines. The other seven pathways, representing a combination of biochemical and thermochemical conversion technologies, produce bio-blendstocks capable of reducing engine-out emissions for mixing-controlled compression ignition (MCCI) engines in heavy-duty vehicles. These MCCI fuels are diesel-like bio-blendstocks blended with petroleum diesel. All eight pathways and their implementation in the GREET 2021 model are presented in Table 2.

Table 2. Summary of Co-Optima Pathways Implemented in the GREET 2021

Pathway name	Engine type	Implementation tabs in GREET 2021	Reference
Biomass to methanol	Multimode	MeOH	Gaspar et al. 2019 Benavides et al., 2021
Isoalkane derived from volatile fatty acids (VFAs) from food waste	MCCI	RNG	Bartling et al. 2021 Gaspar et al., 2021
Fatty Alkyl Ethers (FAE) from three feedstock: soybean oil, yellow grease, and a combination of the two	MCCI	Bio_Oil	Bartling et al. 2021 Gaspar et al., 2021
Fatty Acid Fusel Esters (FAFE)	MCCI	IBR	Bartling et al. 2021 Gaspar et al., 2021
Yellow grease to HEFA	MCCI	RNG	Ou et al., 2021
Swine manure to renewable diesel	MCCI	RNG	Ou et al., 2021

Methanol production

Details of the LCA for the methanol production pathway can be found in the publication by Benavides et al. (2021). Methanol is produced by the synthesis of gas from biomass gasification in an indirectly heated gasifier.

Publication:

- Benavides P.T., Bartling A., Steve Phillips S., Singh A., Zaime G., Hawking T.R., Jones S., Wiatrowski M., Tan E., Kinchin C. 2021. Identification of Key Cost and Environmental Impact Drivers in Techno-economic and Life-cycle Analysis of Biomass-Derived Fuel for Advance Engines (forthcoming).

Use of a gasoline–methanol blend in a light-duty internal combustion engine vehicle with a multi-mode combustion engine

The vehicle types in GREET were also updated to include a new light-duty (LD) internal combustion engine vehicle (ICEV) with a multi-mode combustion engine using a blend of conventional gasoline and up to 30% methanol. The use of the gasoline–methanol blend in connection with the multi-mode combustion engine results in fuel economy improvements relative to conventional vehicles. The parameters required for estimating the fuel economy gain are presented in the Fuel Specifications worksheet (Fuel_Spec). Users can choose the blending level from two options (i.e., 20% and 30%) in Table 12.1 in the Inputs tab.

Calculation of fuel economy improvements

Another important update for the GREET 2021 release for co-optima fuels and engines is the engine efficiency gain calculation based on the merit function approach (Gaspar et al., 2021). These calculations were implemented for the use of a gasoline–methanol blend in a LD-ICEV with a multi-mode engine and the calculations were updated to include the fuel economy based on fuel properties for performance-enhancing fuels implemented in the GREET 2020 release in connection with LD-ICEVs with boosted spark ignition (BSI) engines (Wang et al., 2020). The merit function estimates the engine efficiency gain for an alternative fuel blend with gasoline used in a LD-ICEV with a BSI engine relative to the baseline gasoline fuel (i.e., E10) used in a conventional LD-ICEV.

The list of co-optima fuels implemented in the current version of GREET using the merit function approach to address their engine efficiency gain is as follows: i) isobutanol for BSI vehicles; ii) aromatic rich hydrocarbon (ARHC, or also known as Bioreformate in Gaspar et al., [2019] for BSI vehicles); and iii) biomass gasification-derived methanol for MM vehicles. The merit function results (i.e., relative engine efficiency gain) in the Fuel_Specs tab are linked to Table 12.4 in the Inputs tab and are used to calculate fuel economy gain for each co-optima fuel/vehicle pair.

Isoalkane production pathway

Isoalkanes produced from VFAs with carbon lengths ranging from C3-C8 are produced via arrested methanogenesis from a variety of wet wastes feedstocks such as food waste. Once recovered, the VFAs are upgraded to Isoalkanes catalytically via ketonization, condensation, and hydrogenation processes. For the pathway implemented in GREET 2021, we used food waste as the feedstock. Key assumptions about typical waste management of food waste and the associated methane emissions and biogenic carbon sequestration can be found in the Waste Management (Waste) tab in GREET 2021. Food waste is typically landfilled. The GHG emission implications of shifting food waste from landfill to MCCI fuel production are considered in determining the life-cycle GHG emissions of the food waste-derived MCCI bio-blendstock. The properties of the final product (i.e., lower heat value, carbon content, molecular weight, density) are reported by Gaspar et al. (2021) and implemented in the Fuel_Specs tab.

Fatty alkyl ethers production pathway

Fatty alkyl ethers derived from fatty acid are similar to the fatty acid methyl ester or FAME biodiesel but with one oxygen in the ether state. They are produced from triglyceride-rich feedstocks including soybean oil, waste yellow grease, and or a combination of both (e.g., 60:40 soybean oil to yellow grease). These pathways also produce glycerol as a co-product. We apply a market-value based allocation to allocate the energy, emissions, and water consumption burdens between the diesel bio-blendstock and glycerol, a default co-product handling method for biodiesel pathways in GREET. These variations of fatty alkyl ethers are implemented in the Bio_Oil tab and the properties of the final fuel can be found in Gaspar et al. (2021).

Fatty acid fusel esters (FAFEs) production pathways

Fatty acid fusel esters (FAFEs) are long-chained ester that can be produced via conversion of corn stover to sugars using deacetylation and mechanical refining (DMR) process and biologically upgraded to fusel alcohol followed by an esterification reaction with soybean oil. Glycerol, sodium sulfate, and electricity are co-products of this process; therefore, we apply a market-based allocation method to allocate the emission and energy burdens based on the relative market values of the main product and co-products. The FAFE pathway is implemented in the integrated biorefinery (IBR) tab and the properties of the final fuel can be found in Gaspar et al. (2021). Note that the indirect land-use change (ILUC) impacts of soybean oil production are included in the analysis for blendstocks (e.g., FAME and FAFE) which use cultivated soybean oil as the feedstock.

Renewable diesel production pathways

The last two MCCI bio-blendstock pathways are waste-to-fuel pathways: yellow grease to hydroprocessed esters and fatty acids (HEFA, or biodiesel) and renewable diesel produced by swine manure hydrothermal liquefaction (HTL). Yellow grease, i.e., rendered used cooking oil (restaurant grease), can be converted to HEFA via a series of conversion steps including hydrotreating, deoxygenation, isomerization, and hydrocracking. This process also produces a small amount (~5%) of propane. We used energy-based allocation to allocate the energy, emissions, and water consumption burdens between the diesel bio-blendstock and propane co-product. Swine manure can be used to produce a diesel bio-blendstock via HTL. The swine manure is first processed in a distributed HTL plant to produce biocrude. The biocrude product is then transported to a centralized upgrading plant where the biocrude is processed in the presence of hydrogen to produce a diesel-range bio-blendstock. We also considered management of the HTL aqueous and solid waste streams of HTL. For the aqueous waste, we considered a catalytic hydrothermal gasification (CHG) process to convert all the organics to CO_2 and CH_4 (Jones et al., 2014). Nitrogen available as dissolved ammonia in the aqueous waste was assumed to be stripped using quicklime. The solid waste from the HTL process, which includes biochar, ashes, and residue biocrude, goes to landfill. In addition, the solids from ammonia stripping are rich in $CaCO_3$ are also landfilled. We accounted for the carbon sequestration effect of landfilling the solid waste. We also considered the emissions from conventional swine manure management systems and accounted for them as emission credits for the diesel bio-blendstock because these emissions would be avoided when swine manure is diverted from conventional management systems to renewable diesel production.

Emissions control benefits of performance-enhancing diesel-like bio-blendstocks

These performance-enhancing bio-blendstocks are capable of reducing engine-out NO_x and PM emissions when used in co-optimized mixing-controlled, compression-ignition (MCCI) engines. The effect is particularly significant when coupled with the Ducted Fuel Injection technology (Nilsen et al., 2019). The effect of this decrease is to reduce the amount of urea required for controlling NOx emissions via selective catalytic reduction (SCR) in heavy-duty vehicles. In this GREET update, we consider use of these MCCI fuels in Class 8 freight trucks as described by Ou et al. (2019). We assumed that the urea consumption could range from 1.8% to 3.4% of the diesel fuel consumption by the MCCI Co-Optima Class 8 freight truck, depending on the reduction levels of engine-out NO_x and PM emissions, in comparison to a urea consumption rate equivalent to 3.8% of the diesel fuel consumption for a conventional Class 8 freight truck. The reduction in urea consumption is translated to reduction in energy use, GHG emissions, and air pollutant emissions associated with the urea supply chain, as well as the CO_2 emissions from urea hydrolysis that takes place in the SCR. The tailpipe NO_x and PM emission factors for the MCCI Co-Optima Class 8 freight truck remains the same as those of the conventional counterpart following tailpipe emissions controls.

These new pathways were added as an outcome of research performed under The Co-Optimization of Fuels & Engines Consortium (Co-Optima), a DOE-sponsored consortium project including nine DOE laboratories and numerous university and industry partners. The

Co-Optima consortium conducts fundamental research to develop biomass-derived blendstocks with favorable fuel properties and advanced engine technologies that could harness the potential of such bio-blendstocks to improve engine efficiency and reduce emissions. Co-Optima leverages a suite of computation and engineering models to evaluate optimal combinations of bio-blendstock options and engine configurations for use in light-duty and heavy-duty vehicles. The WTW results for all MCCI co-optima pathways are implemented in HDV_WTW tab.

Publications:

- Bartling A., Benavides P.T., Phillips S., S., Singh A., Hawking T.R., Jones S., Wiatrowski M., Tan E., Kinchin C. Ou L., Biddy M., Tao L., Young A., Brown K., Li S., Zhu Y., Snowden-Swan L., Chirag R, 2021. Environmental, Economic, and Scalability Considerations of Selected Bio-Derived Blendstocks for Mixing-Controlled Compression Ignition Engines *(forthcoming).*
- Ou L., Tao L., Phillips S., Hawkins T., Singh A., Snowden-Swan L., Cai H. 2021. Techno economic analysis and life-cycle analysis of renewable diesel fuels produced with waste feedstocks. Under review. ACS Sustainable Chemistry & Engineering *(forthcoming).*

2.1.6. Sustainable Aviation Fuels

We have added eight sustainable aviation fuel (SAF) production pathways using the data in the CORSIA supporting document released by International Civil Aviation Organization (ICAO) (ICAO, 2019). CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) is an international carbon offsetting scheme that aims to achieve carbon neutral growth in international aviation emissions above 2020 levels. We have expanded the available SAF production pathways in GREET 2021 using the datasets available in the CORSIA supporting document (ICAO, 2019) for two SAF production technologies (synthesized iso-paraffins [SIP] and iso-butanol alcohol-to-jet [ATJ]). The new pathways are listed in Table 3.

Table 3. Newly Added Sustainable Aviation Fuel Production Pathways in GREET 2021

Conversion technologies	Feedstocks
Synthesized Iso-Paraffins (SIP)	Sugarcane
	Sugarbeet
Iso-butanol Alcohol-to-jet (ATJ)	Sugarcane
	Agricultural residues
	Forestry residues
	Corn grain
	Herbaceous energy crops
	Molasses

Publication:

- Prussi, M., Lee, U., Wang, M., Malina, R., Valin, H., Taheripour, F., ... & Hileman, J. I. (2021). CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. *Renewable and Sustainable Energy Reviews*, *150*, 111398. doi.org/10.1016/j.rser.2021.111398.

2.1.7. Co-Processing of Bio-Feedstocks in Petroleum Refineries

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A new co-processing module has been incorporated in GREET 2021. This module is intended to examine the impact of co-processing of bio-feedstocks in petroleum refineries. We have been analyzing energy/GHG emissions effects of co-processing renewable feedstocks in petroleum refineries. The results are used to estimate the amount of renewable fuel volume and carbon intensities of co-processed fuels. We used linear programming (LP) modeling of petroleum refineries to develop energy and mass balances of co-processing of renewable feeds in hydrotreaters, hydrocrackers, and fluidized catalytic crackers of conventional petroleum refineries. We have examined three renewable feedstocks (soy oil, used cooking oil, and tallow) to hydrotreater and hydrocracker along with a case inserting pyrolysis oil into fluid catalytic cracker, all with 10% by volume of renewable feedstocks for each unit.

While the co-processing module is completed in the current release of GREET 2021, parametric assumptions are still undergoing research and review. We plan to update the current placeholder parametric assumptions with actual assumptions in a new version of GREET after releasing a forthcoming report/paper documenting all key parameters and analysis results.

2.1.8. Direct Air Capture and Cryogenic Carbon Capture Pathways for Carbon Dioxide for Algae Cultivation

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In the Algae tab, we have incorporated two CO_2 sources, thereby providing more options for carbon capture and utilization for algae cultivation. Specifically, low-temperature adsorption-based direct air capture (DAC) of CO_2 and cryogenic carbon capture pathways are incorporated in accordance to the E_fuels tab (Section 3.2.4). The primary energy requirements of carbon capture for the low-temperature DAC and cryogenic carbon capture system utilizing waste heat are estimated to be 1,361 Btu/kg CO_2 and 991 Btu/kg CO_2, of electricity, respectively. In both cases, the sorbent requirement is 3 g/kg CO_2. Utilizing natural gas instead of waste heat in low-temperature DAC system results in significant emissions as an additional 6,398 Btu/kg CO_2 of natural gas is required besides 1,361 Btu/kg CO_2 of electricity for the DAC system.

2.1.9. Feedstock Production for Biofuels

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Farming inputs and on-farm energy consumption

Fertilizer/chemical inputs are critical to agricultural production, but their upstream manufacturing and on-farm application are the main sources of agricultural GHG emissions (e.g., direct and indirect N_2O emissions). On-farm energy is consumed in field preparation, tilling, fertilizer/chemical application, and harvesting on each farm. Common energy types used on farms include diesel, gasoline, natural gas, liquefied petroleum gas, and electricity. Historically, GREET's reference life-cycle inventory (LCI) data at the national level have been updated with the data from the USDA's major survey programs, the National Agricultural Statistics Service (NASS), the Economic Research Service (ERS), and the Office of the Chief Economist reports. This year's update employs a similar approach with data that are mostly accessible through the NASS Quick Stats database (USDA, 2021b). We made an additional request for on-farm energy use data, which is not publicly available, to USDA ERS. The ERS-generated special tabulations based on the Agricultural Resource Management Survey costs and provides us data for corn in 2016 and soybean in 2018. We also extracted the energy use in grain sorghum farming from the National Sorghum Grower's technical report and tool (National Sorghum Grower, 2021). Besides the above-mentioned feedstocks, we update the LCI data for Canadian canola production based on a LCA report by $(S\&T)^2$ Consultants Inc.

N_2O emissions from crop residues of bio-oil feedstock

Crop residues returned to soils are significant sources of N_2O emissions from field. While including the emissions from various feedstocks for biofuels, GREET did not account for them from many bio-oil feedstock due to the lack of data. This time we update/include the N_2O emissions from crop residues of palm full fruit bunch, canola, jatropha, and camelina ($(S\&T)^2$ Consultants Inc.) and of carinata (Alam et al., 2021) (Table 4).

Table 4. Farming Energy Use, Fertilizer Use, and N_2O Emissions from Bio-oil Feedstock

	Soybean (per bushel)	Palm full fruit bunch (FFB) (per wet ton)	Canola (per wet metric tonne)	Jatropha (per wet kg)	Camelina (per wet kg)	Carinata (per wet kg)
Farming Energy Use: Btu	13,724	154,528	528,667	1,320	961	1,491
Fertilizer Use						
Grams of Nitrogen	43.7	5,297.4	51,648.0	34.0	37.0	23.7
Grams of P_2O_5	207.8	3,565.6	15,919.0	13.0	15.0	3.3
Grams of K_2O	329.6	9,830.8	4,163.0	37.4	10.0	0.5
Grams of $CaCO_3$	0.0	0.0	0.0	0.0	0.0	0.0
Pesticide Use						
Grams of Herbicide	19.43	28.52	417.00	0.00	0.00	0.00
Grams of Insecticide	0.28	137.53	39.00	0.00	0.00	0.20
N content of above and below ground biomass: grams[1]	557	9400×MT2T = (0.77×0.012 + 0.04×0.004) ×1E6 ×MT2T	24280 = (2.31×0.008 + 0.58×0.010) ×1E6	35 = (0.75×0.035 + 0.25×0.035) ×1000	65.2 = (3×0.02 + 0.4×0.013) ×1000	20.75 = (7000×0.0079+ 700×0.004) / 2800
N_2O emissions from N fixation: grams N_2O	7.3					
N_2O emissions: N in N_2O as % of N in N fertilizer	1.374%	1.374%	1.040%	1.374%	1.374%	1.374%
N_2O emissions: N in N_2O as % of N in Biomass	1.264%	1.264%	0.940%	1.264%	1.264%	1.264%

[1] FFB, Canola, Jatropha, and Camelina: Ratio of above ground residue weight to weight of crop or product harvested × N content of above ground residue in a fraction of dry mass + Ratio of below ground biomass weight to weight of crop or product harvested × N content of below ground residue in a fraction of dry mass); Carinata: (Aboveground biomass × N content of above ground residue + Belowground biomass × N content of below ground residue) / yield; MT2T is a unit conversion factor of metric tonne to U.S. ton.

GREET® open-source database

We expanded the database (https://greet.es.anl.gov/databases) by including 1) on-farm energy consumption at the U.S. state-level (USDA ERS) and 2) soil organic carbon changes due to forest harvesting and biomass removal (James et al., 2021).

Biomass harvested

For many feedstocks, farming inputs and on-farm energy consumption were parametrized as for unit of biomass harvested. In GREET 2021, we disaggregated the information into biomass yield per acre (Table 5), farming inputs per acre, and fuel consumption per acre so that users can have a better understanding of the GREET's estimates for modification to their own farming data.

Table 5. Biomass Yields Used in GREET LCA for Biofuel Feedstock Production

Biomass	Yield	Unit	Reference
Willow	28.2	dry tons/acre	The BC1 2040 scenario from the U.S. DOE's Billions-Ton Study (Langholtz et al., 2016)
Poplar	42.9		
Switchgrass	5.8		
Miscanthus	8.6		
Clean Pine	55		
Forage Sorghum	11.7		
Sugarcane	86.7	wet metric tonnes/hectare	(Seabra et al., 2011)
Sweet Sorghum	76		(Cai et al., 2013)

Nitrogen management practices for corn farming

We include two different nitrogen management practices for corn farming, namely enhanced efficiency fertilizer and 4R (Right time, Right place, Right form, and Right rate) as options to evaluate the on-field N_2O reductions due to the practices and their relevant CI impacts on corn ethanol pathways. More detailed descriptions of these practices can be found in the Feedstock Carbon Intensity Calculator (FD-CIC) technical report (Liu et al., 2021).

Feedstock Carbon Intensity Calculator (FD-CIC)

The FD-CIC has been developed as an expansion of the GREET feedstock carbon intensity (CI) module with interactive features and in-depth simulations of feedstock CI potentially at the farm field level. We expand the FD-CIC's capabilities by adding soybeans, sorghum, and rice besides corn. The reference LCI data of rice at the national level was compiled from the NASS Quick Stats database and ERS's special tabulations for rice in 2013. Similar to corn, the FD-CIC calculates the farm-level CI for these feedstocks by allowing user-defined farm-level farming inputs and incorporating the GHG intensities of these inputs from default simulation results of GREET. Additionally, we update indirect N_2O emission factors (EF) associated with synthetic nitrogen and crop residues and include new N_2O EFs disaggregated by climate types (either wet or dry) in the tool. More detailed information can be found in the FD-CIC technical report (Liu et al., 2021).

Publication:

- Lee, U., Kwon, H., Wu, M., & Wang, M. (2021). Retrospective analysis of the US corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions. Biofuels, Bioproducts and Biorefining. 15:1318–1331. doi.org/10.1002/bbb.2225

Technical Report:

- Liu, X., Kwon, H., & Wang, M. (2021). Feedstock Carbon Intensity Calculator (FD-CIC), Users' manual and technical documentation. Energy Systems Division, Argonne National Laboratory. ANL/ESD-21/12. https://greet.es.anl.gov/publication-fd-cic-tool-2021-user-guide

2.1.10. Conventional Waste Management and Waste-to-Energy Pathways

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The waste-to-energy (WTE) pathways in GREET consider the impact of avoided emissions from business-as-usual (BAU) cases that represent conventional waste management practices as well as emissions associated with waste-derived fuel production and use. In order to examine the impact of conventional BAU waste management practices, we have split the RNG tab into two separate tabs in GREET 2021, Waste and RNG, mainly because the current RNG tab includes both fuel production and avoided BAU cases, which makes it difficult to assess the impact of avoided BAU scenarios. Now, the Waste tab includes various conventional waste management practices, while the RNG tab presents the waste-derived fuel production processes. It is expected that the separation would enable users to transparently investigate the impact of various waste management practices.

In addition, we have updated the carbon accounting method in the Waste and RNG tabs to be consistent with other tabs in GREET. While we consider biogenic carbon emissions as carbon neutral in all the tabs in GREET and only account for fossil carbon emissions, previous GREET WTE pathways did not differentiate fossil and biogenic carbon emissions because the evaluating of WTE pathways considers the BAU cases and the impacts of carbon sources are offset between the BAU cases and WTE pathways. However, we observed that having different carbon accounting methods made it difficult to compare with other fuel production pathways. Thus, we revised the Waste and RNG tabs to use the same carbon accounting method; biogenic carbon emissions are carbon neutral, biogenic carbon sequestration is negative carbon emission; fossil carbon emissions are positive carbon emissions, and fossil carbon sequestration is carbon neutral. Since biogenic CH_4 emissions have their carbon uptake of CO_2, we have used the global warming potential of 27.3 for biogenic CH_4 emissions, not the value of 30 for fossil CH_4 emissions.

Lastly, we have identified a carbon accounting error in WTE pathways, caused by accounting for the difference in carbon sequestration between the fuel production and avoided BAU cases rather than CO_2 emissions. This has been corrected in GREET 2021.

2.1.11. Biopower

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With support from USDA, Argonne developed a new bio-electricity module that enables regionalized, life-cycle analysis of forest residues to bio-electricity pathways in different regions of the United States. This module supports modeling for 12 states: Washington, California, Idaho, Arizona, Minnesota, Indiana, New York, Maine, Tennessee, North Carolina, Georgia, and Louisiana. In each state, potential forest residue biomass supply may include pulpwood, logging residues, wood chips, pellets, and sawmill residues. In the default setting, regional biomass supply for a hypothetical 20 MW bio-electricity facility is estimated using the Land Use and Resource Allocation (LURA) model by University of Idaho. Results from LURA and data on regional forest management, harvesting, and processing are implemented in GREET for life-cycle analysis. In the released version, users can change options and enter user-defined feedstock type(s), share of each feedstock type, and hauling distance(s) for customized regional analysis. More details on bio-electricity module development and key LCA results can be found in Xu et al. (2021).

Publication:

- Xu H., Latta G., Lewandrowski J., Lee U., Wang M. Accepted. Regionalized Life Cycle Greenhouse Gas Emissions of Forest Biomass Use for Electricity Generation in the United States. *Environmental Science & Technology.* doi:10.1021/acs.est.1c04301.

2.1.12. Cellulosic Ethanol

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Based on discussion with National Renewable Energy Laboratory (NREL), we have created three major updates of the parameters of various cellulosic ethanol production pathways in GREET 2021: ethanol yield, co-produced electricity, and material inputs. The feedstocks of cellulosic ethanol include corn stover, switchgrass, miscanthus, forest residue, willow, poplar, forage sorghum, and the biogenic portion of municipal solid waste (MSW).

In previous GREET versions, we projected that the ethanol yield would be increased to 85 gal of ethanol per dry ton of feedstock in 2015 and 90 gal/dry ton in 2020. After communication with the NREL TEA team, we now assume that the current cellulosic ethanol yield is around 80 gal/dry ton in 2020, which may be increased to 85 gal/dry ton by 2030 through technology development.

For the material inputs and co-produced electricity, the updates are based on two NREL process engineering modeling reports (Humbird et al., 2011; Tao et al., 2014) and personal communication with the TEA experts from NREL. Table 6 shows the datasets of the NREL 2011 design case, the NREL 2012 SOT case, and GREET 2020. Between the 2011 design case and 2012 SOT case, the recent advance in cellulosic technology makes the 2012 SOT case a more representative case for the cellulosic technology of today, while the yield was estimated lower than the current SOT. Thus, we have updated a set of inputs based on the NREL 2012 SOT case with adjusted cellulosic ethanol yield of 80 gallons/dry ton of biomass (and 85 gallons/dry ton by 2030) for GREET 2021. We assumed on-site enzyme production with glucose inputs instead of cellulose. We presumed that the pretreatment is moved from DMR (deacetylation and mechanical refining) to DDA (deacetylation and dilute acid) pretreatment, which has much lower ammonia input, sodium hydroxide (NaOH) input, and power demands than DMR does. In addition, we assumed that a nitrification process is not necessary for the wastewater treatment because of the lower nitrogen loading.

Table 6. Major Parameters for Cellulosic Ethanol Production (Ethanol Yield, Co-Produced Electricity, and Material Inputs) Data from Three Sources and Updated Value for GREET 2021

		NREL 2011 design case	NREL 2012 SOT case	GREET 2020	GREET 2021
Ethanol yield (gal/dry ton)		79.5	70.9	85.0	80.0
Co-produced electricity (kWh/gal)		1.84	2.64	2.41	1.79
Material inputs (g/gal]	glucose	333.4	361.5	107.5 (cellulase)	246.8
	sulfuric acid	273.2	344.0	346.2	304.9
	ammonia	160.8	57.1	41.5	47.2
	corn steep liquor	182.3	156.8	131.6	136.3
	diammonium phosphate	19.6	16.1	13.8	14.7
	calcium oxide (lime)	123.4	74.6	76.2	64.8
	sodium hydroxide (caustic)	310.5	115.2	117.7	102.1
	sulfur dioxide	2.2	2.5	-	21.7
	sorbitol	6.1	5.1	-	4.5
	host nutrients	9.2	10.1	-	6.9
	boiler chemicals	0.1	0.03	-	0.03
	cooling tower chemicals	0.3	0.3	-	0.3
	urea			20.8	
	yeast			28.2	

2.1.13. Steam Methane Reforming for Hydrogen Production

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The process data of steam methane reforming (SMR) with carbon capture and sequestration (CCS) is updated for the two pathways of "Central Plants: North American Natural Gas to Gaseous Hydrogen" and "Central Plants: North American Natural Gas to Liquid Hydrogen." Previously, for the option of industrial data, SMR process without CCS generates surplus steam for export (via heat recovery) as a common industrial practice. When CCS is pursued, additional electricity is consumed, but steam remains exported. This year, the industrial data option of SMR-CCS is updated by removing steam export because the CCS process consumes both electricity and steam. It is assumed that CCS operation will exhaust the internally generated steam, therefore providing no surplus steam for export.

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) are updated in GREET 2021 using the recent simulation results from Argonne's Autonomie vehicle simulation team (Islam et al., 2021). The outputs from that report are extensive and include more than vehicle fuel economy and mass. In this GREET update, the fuel economy of midsize sedans, small sport utility vehicles (SUVs), and pickup trucks are updated in the GREET1 model. This covers multiple fueling pathways and vehicle technologies. Further, the mass of selected vehicle types were updated in the 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 for each of the class types.

The time-series tables for fuel economy for the vehicles extending to 2050 can be found in the "Car_TS," "LDT1_TS," and "LDT2_TS" sheets of GREET1. The GREET2 model now has an updated capability that includes time series of mass information for the vehicle models. Additionally, time-series data are provided for battery power capacity (HEV, FCV), fuel cell stack power capacity (FCV), and battery energy capacity (BEV, PHEV). Using those power and energy data from Autonomie modeling, the GREET2 model sizes battery and fuel cell components internally based on its own data and modeling. Note that for the vehicle mass we do not directly use reported curb weight; rather, we size battery and fuel cell weight as noted and combine that with all other Autonomie-reported weight categories, except for battery, fuel cell system, hydrogen storage, and fuel weight. We use a GREET2 internal weight estimation of hydrogen storage. The Autonomie model provided simulation results for lab years 2015, 2020, 2025, 2030, and 2045, which correspond to model years five years later (2020, 2025, 2030, 2035, and 2050). The Autonomie model has "low" and "high" technology progression profiles. For the GREET 2021 update, we use the "low" progress scenario to be conservative.

2.2.2. Medium/Heavy-Duty Vehicle (MHDV) Fuel Economy

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The fuel economy (FE) values for various classes of MHDVs are updated in GREET 2021 using the most recent simulation results from Autonomie (https://www.autonomie.net/). Autonomie provided fuel economy values for the three standard driving cycles for MHDVs specified by U.S. EPA, for each vehicle and powertrain type (USEPA, 2016). We employed the weighting factors, also specified by U.S. EPA, to estimate the weighted average FE for incorporation in GREET 2021. Detailed calculations on how the weighting is performed are available in Liu et al. (2021).

The time-series tables for fuel economy are expanded to year 2050 in the "HDV_TS" sheet. The Autonomie model provides simulation results for model years 2021, 2027, 2035, and 2050. This update uses the 2021 Autonomie runs to represent the model year 2020 in GREET and interpolates model year 2025 results from the 2021 and 2027 Autonomie runs, and model year 2030 results from the 2027 and 2035 Autonomie runs. The Autonomie model provided FE results for "low" and "high" technology progress scenarios. For incorporation into GREET 2021, we use the average FE values from the "low" and "high" progress scenarios. Since Autonomie provided updated simulation results for certain powertrains, only the following powertrains have been updated in this GREET release: conventional internal combustion engine vehicles, parallel hybrid electric vehicles, battery electric vehicles, and fuel cell electric vehicles. All time-series fuel economy tables and corresponding well-to-wheels results for all other powertrain types (that were not simulated by the most recent Autonomie runs) are greyed out in the "HDV_TS" sheet and "HDV_WTW" sheet, respectively, in the GREET model. Table 7 summarizes MHDV types for the FE updates made in the GREET 2021 release.

Table 7. Update of Fuel Economy Made to MHDV Types in GREET 2021 Release

Vehicle	Class	Application	Vocational	Corresponding table number and updated powertrains in GREET
Pick-up Truck/Van	2	Multi-purpose	Yes	6) Heavy-Duty Pick-Up Trucks and Vans: Baseline Diesel
Pick-up/Delivery	4	Urban	Yes	5) Light Heavy-Duty Vocational Vehicles
Box truck	6	Urban	Yes	4) Medium Heavy-Duty Vocational Vehicles
School bus	7	Urban	Yes	10) School Buses
Refuse truck	8	Urban	Yes	9) Refuse Trucks
Transit bus	8	Urban	Yes	11) Transit Buses
Heavy heavy-duty vocational truck	8	Urban	Yes	3) Heavy Heavy-Duty Vocational Vehicles
Drayage truck	8	Urban	Yes	2) Combination Short-Haul Trucks
Long-haul truck	8	Sleeper cabs	No	1) Combination Long-Haul Trucks

2.2.3. Medium/Heavy-Duty Vehicle (MHDV) Vehicle Cycle

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The GREET 2021 update provides a detailed vehicle-cycle inventory for MHDVs. Three MHDV options are considered in this update: Class 6 pickup-and-delivery (PnD) truck (referred to as "MHD Vocational Vehicle" in GREET1 HDV_TS and HDV_WTW sheets), and Class 8 regional day-cab and long-haul sleeper-cab trucks (referred to as "Combination Short-Haul Truck" and "Combination Long-Haul Truck", respectively, in GREET1 HDV_TS and HDV_WTW sheets).

For all three MHDVs, four powertrains are considered:

1. An internal combustion engine vehicle (ICEV) that employs conventional compression-ignition direct injection (CIDI) diesel engine
2. A grid-independent hybrid electric vehicle (HEV) that employs CIDI diesel engine as primary source
3. A fully battery electric vehicle (EV)
4. A fuel-cell electric vehicle (FCV) with hybrid configuration (same as HEV, with fuel-cell stacks and hydrogen tank as primary energy source).

For the MHDV update, 14 new Excel sheets are created in the Excel version of GREET2 encompassing all three MHDVs. These sheets are analogous to existing vehicle-cycle inventory sheets for light-duty vehicles (LDVs), with all weight and material composition data for MHDVs disaggregated over five vehicle system groups:

1. Vehicle components
2. Fluids (used for operation and maintenance of MHDV, excluding fuel)
3. Trailers (used with Class 8 trucks)
4. Batteries (lead-acid start-up batteries and lithium-ion propulsion batteries)
5. Vehicle assembly, disposal, and recycling (ADR).

These sheets use orange tabs to distinguish them.

Briefly, a hybrid approach was used to determine the vehicle-cycle inventory for the above-mentioned system groups and, thereby, for the entire MHDV. For most system groups, weights were obtained using the most recent simulation results from Autonomie model for model year 2021 (a top-down approach) (Islam et al., 2021), while material composition was obtained via a bottom-up method from literature. For lithium-ion batteries (used in all powertrains barring ICEV for all MHDVs), battery energy/power values (as appropriate) were obtained from Autonomie and inputted in Argonne's BatPaC 4.0 model to obtain the respective battery weight and material composition. Regarding fuel-cell stacks (used in FCV MHDVs), fuel cell stack power values from Autonomie were used to scale-up stack weight and material composition values obtained via personal communication with the Strategic Analysis (SA) Inc. Lastly, ADR processes for light-duty vehicles were extended to MHDVs (in light of the paucity of alternative inventory availability), barring for vehicle disposal (for which process energy use was scaled-up to mass of concerned MHDV).

Individual weights, material composition, replacement schedule for different system groups (like windshield wiper blades and vehicle fluids), and other relevant parameters for the three chosen MHDVs are provided in individual sheets (Class 6 PnD Trucks, Class 8 Day-Cab Trucks, and Class 8 Sleeper-Cab Trucks) of GREET2 Excel for MHDV update. Users can choose their specific MHDV of interest as well as the cathode chemistry for lithium-ion batteries in HEV, EV, and FCV powertrains for different MHDVs among four options (NMC 622 as default, NMC 811, NMC 532, and NMC 111) in MHDV_Inputs sheet. Using these values, weights, material composition, and other relevant parameters are extended as inputs in six sheets (MHDV_Inputs, MHDV_Mat_Parameters, MHDV_Fluids, MHDV_ADR, MHDV_Trailer_Fluids, and MHDV_Trailer_ADR sheets. Using these weights and material composition (along with relevant parameters), energy use and emissions for different MHDV system groups are computed in:

1. MHDV_Comp_Sum (for vehicle components)

2. MHDV_Trailer_Comp_Sum, MHDV_Trailer_ADR, and MHDV_Trailer_Fluids (for trailer components, fluids, and ADR)
3. MHDV_Fluids (for truck tractor fluids)
4. MHDV_ADR (for ADR processes related to truck tractors)
5. MHDV_Battery_Sum (for lithium-ion and lead-acid batteries used in MHDVs).

The final sum of energy use and emissions across these component groups is totaled in MHDV_Sum, while the life-cycle values (inclusive of vehicle-cycle and fuel-cycle) are provided and summed in MHDV_TEC_Results (fuel-cycle results are based on the work described in Section 2.2, imported from GREET1 into GREET1_Import_Export sheet in GREET2 Excel model). More details are provided in the update memo/report for MHDVs mentioned below.

Technical memo:

- Iyer, Rakesh Krishnamoorthy, and Jarod C Kelly. 2021. "Vehicle-Cycle Inventory for Medium- and Heavy-Duty Vehicles." Lemont. https://greet.es.anl.gov/publication-mhdv_vc.

2.3. Materials

2.3.1. Steam Cracking Tab/Chemical Tab

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To improve accessibility for GREET users, we have made various modifications to transform the Chemicals and Bioproducts tabs in GREET. The former Chemicals tab has been renamed "Steam_Cracking" as the analysis framework in this tab is specific to the production of olefins, aromatics, and hydrogen from natural gas liquids (NGL) and petroleum naphtha steam cracking plants. Details regarding calculations for the steam cracking module can be found in Young et al. (2021). In addition, the former Bioproducts tab has been renamed more accurately as "Chemicals" because it contains many pathways for both fossil and bio-derived chemicals.

We have performed several tasks to establish the new Chemicals tab as a comprehensive collection of inventories that can be easily applied in downstream production processes. Information regarding the U.S. shares of production for chemicals with multiple production pathways are moved and included in the new Chemicals tab. The conversion pathway and reference source are now specified as notes in the calculations section for all chemicals for which this information was available. The final results for several commonly used chemicals, such as the olefins from the Steam_Cracking tab and lactic acid from the RNG tab, are also exported to the results section in the new Chemicals tab. Calculations and results are separated by fossil-based and bio-based products.

New production pathways were added for nine fossil-based chemicals that are relevant to downstream processes for plastics production or recycling:

1. Ethylene glycol (EG)
2. Carbon monoxide

3. Mixed xylenes
4. Paraxylene
5. Purified terephthalic acid (PTA)
6. Aluminum sulfate
7. Ferric chloride
8. Defoamant
9. Dimethyl terephthalate (DMT).

The former ethylene glycol inventory, located in the GREET2 Vehi_Fluids tab, has been replaced with this new inventory. The energy and emissions burden of transporting raw material inputs for these chemicals to the production plants in these new pathways was accounted for using a general proxy for transporting chemicals in a heavy-duty truck. More details regarding production of these new chemicals can be found in the forthcoming publication by Gracida-Alvarez et al. (2021).

Publications:

- Young, B., C. Chiquelin, T.R. Hawkins, P. Sun, U.R. Gracida-Alvarez and A. Elgowainy, 2021. "Environmental Life Cycle Assessment of Olefins and By-product Hydrogen from Steam Cracking of Natural Gas Liquids, Naphtha, and Gas Oil." *(in revision at* Journal of Cleaner Production)
- Gracida-Alvarez, U.R., Xu, H., Benavides, P.T. Wang, M., Hawkins, T.R. 2021 "Assessment of environmental metrics and resource utilization of the circular economy of polyethylene terephthalate (PET) bottles and its enabling technologies." *(in preparation)*

2.3.2. Plastics and Bioplastics

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We have constructed a new Plastics tab in GREET1 that contains inventories for several fossil-based and bio-based plastic resins, transformation processes, and final plastic products. New data discussed in the forthcoming publication by Gracida-Alvarez et al. (2021) is used for the inventories of several plastic resins, while other inventories are drawn from those already contained in the GREET2 Plastics tab and the former GREET1 Bioproducts tab. The pathways in the original GREET2 Plastics tab are described by Keoleian et al. (2012). We have renamed the GREET2 Plastics tab "Vehi_Plastics" to distinguish it from the new GREET1 Plastics tab and to emphasize that the "Average Plastic Product" calculations within the Vehi_Plastics tab are specific to vehicles. The construction of this tab allows all plastic resins and transformation processes to be calculated in one location, and it will ease the implementation of an upcoming project involving plastics recycling and the circular economy.

The new Plastics tab includes pathways from the former GREET1 Bioproducts tab and GREET2 Plastics tab. Section 1 describes characteristics of the fossil and bio-based plastic resins, including their heating value, carbon content, biodegradability, and the percent of carbon that is biogenic (0% for fossil-based and 100% for bio-based products). Section 1.2 details the U.S. shares of production for plastics that have multiple production pathways. Section 2 contains the combustion shares for the plastic resins and transformation technologies. Section 3 describes the amount of resin needed per ton of final transformed plastic product if a transformation were to be applied. Section 4 contains the calculations for the energy and emissions of production, with subsection 4.1 corresponding to virgin plastic resin production and subsection 4.2 corresponding to transformation technologies. Section 5 contains the cradle-to-gate results, with subsection 5.1 detailing results for plastic resins production and subsection 5.2 describing the results for plastic products following one or more transformation processes. Section 6 examines the end-of-life emissions CH_4 and CO_2 emissions associated with disposal of the fossil-based and bio-based plastic resins in a landfill. Finally, Section 7 contains the inventory results of all products used as material inputs in the calculations for resin production in Section 4.1.

Five new fossil-based resin production pathways are added in the new Plastics tab:

1. High-Density Polyethylene (HDPE)
2. Low-Density Polyethylene (LDPE)
3. Polypropylene (PP)
4. Polyethylene Terephthalate (PET) from PTA and EG
5. Polyethylene Terephthalate (PET) from DMT and EG.

The U.S. shares of production for PET are applied to determine a combined PET inventory that is the weighted average of its two production routes. Inventories for HDPE, LDPE, PP, and PET were previously located in the GREET2 Plastics tab and are thus removed from that tab. The results for the production of these resins are exported from the GREET1 Plastics tab to GREET2 for use in vehicle plastic calculations, using the combined PET inventory as the default PET production pathway. Three new transformation processes were also added to the GREET1 Plastics tab: 1) Injection Stretch Blow Molding (PET), 2) Extrusion (PET), and 3) Yarn Spinning (PET) for future application in PET bottle production and recycling case studies. More information about these new resin production and transformation processes can be found in the forthcoming publication by Gracida-Alvarez et al. (2021).

Eleven fossil-based plastic resin production pathways were moved from the GREET2 Vehi_Plastics tab to the GREET1 Plastics tab:

1. Acrylonitrile-Butadiene-Styrene (ABS)
2. Ethylene Propylene Diene Monomer (EPDM)
3. General Purpose Polystyrene (GPPS)
4. High-Impact Polystyrene (HIPS)
5. Linear Low-Density Polyethylene (LLDPE)
6. Nylon 6
7. Nylon 66
8. Polycarbonate (PC)
9. Polyurethane (PUR) Flexible Foam
10. Polyurethane (PUR) Rigid Foam
11. Polyvinyl Chloride (PVC).

Nine transformation processes were moved from the GREET2 Vehi_Plastics tab to the GREET1 Plastics tab:

1. Compression Molding
2. Calendaring (PVC)

3. Extrusion (PVC)
4. Injection Molding (PVC)
5. Blow Molding (HDPE)
6. Extrusion (HDPE)
7. Injection Molding (HDPE)
8. Extrusion (PP)
9. Injection Molding (PP).

The calculations for these resin production and transformation processes were removed from the GREET2 Vehi_Plastics tab. Their results are in turn exported from the GREET1 Plastics tab to GREET2 for use in vehicle plastic calculations. Three bio-based plastic resin production pathways were also moved from the former GREET1 Bioproducts tab to the GREET1 Plastics tab: 1) Bio Polyethylene (PE), 2) Bio Polylactic Acid (PLA), and 3) Bio Polyethylene Terephthalate.

Finally, for the 2021 GREET release we added a new biobased plastic known as polyethylene furanoate (PEF) that can be produced via three pathways: 1) Polyethylene Furanoate via ethanol (EtOH) pretreatment and enzymatic hydrolysis, 2) Polyethylene Furanoate via methanol (MeOH) pretreatment and methanolysis, and 3) Polyethylene furanoate via pretreatment and hydrolyzation consolidated into one step process called Furanosolv. These pathways are implemented in the GREET1 Plastics tab. The PEF is a bio-based polymer that can potentially replace fossil-based PET for different applications. We assess three production pathways of PEF from a lignocellulosic feedstock (i.e., wheat straw) via furanics conversion and implement the results in the current working version of GREET1. The feedstock production (i.e., wheat straw production) process is implemented in the ethanol (EtOH) tab with the title "Wheat straw (WS) production." Three co-product allocation methods are implemented for this process and users can choose different options using the drop-down menu with the mass allocation method set as default. The GHG emissions from wheat straw baling is compared to four different status-quo wheat straw management assumptions (100% baling, 100% soil incorporation, 100% open-field burning, and Italian benchmark), and the difference is implemented as wheat straw management GHG emissions. A status-quo scenario can be chosen from the dropdown menu, with 100% baling set as the default. All three PEF production pathways use the wheat straw feedstock with some different conversion processes (pretreatment and hydrolysis), which results in different ratios of final products in the product basket. The co-products of the three pathways include furfuryl ethyl ether (FEE), methyl levulinate (ML), and dimethyl ether (DME). Two co-product allocation methods (mass and market value allocation) are implemented for each pathway, and users can choose from the drop-down menu. More information will be available in the forthcoming publication by Kim et al. (2021).

Publications:

- Gracida-Alvarez, U.R., Xu, H., Benavides, P.T. Wang, M., Hawkins, T.R. 2021 "Assessment of environmental metrics and resource utilization of the circular economy of polyethylene terephthalate (PET) bottles and its enabling technologies." *(in preparation)*
- Kim T, Benavides PT, Gracida-Alvarez UR, Bamford J. 2021 'Life Cycle Greenhouse Gas Emissions, Water and Fossil-Fuel Consumption for Polyethylene Furanoate and Its Co-Products from Lignocellulosic Biomass.' 2021. *(in preparation)*

2.3.3. Platinum-Group Metals (PGM)

Pahola Thathiana Benavides (pbenavides@anl.gov) and Kathryn Kingsbury (kkingsbury@anl.gov)

We evaluated the production of platinum-group metals (PGMs) including platinum, palladium, ruthenium, and gold. We compiled life cycle inventories for these metals using data reported by Anglo American Platinum from 2015 to 2019, and we applied both mass and market allocation methods to determine the consumed energy per ton of PGM product. These pathways were added to GREET2 in the Platinum tab, which we have renamed the "PGMs" tab. The GREET2 model includes options for selecting mass or market allocation in the Mat_Inputs tab. Data for platinum production was already included in GREET, so we updated these values to account for our new inventories, while palladium, ruthenium, and gold were implemented as new pathways. Anglo American Platinum is a South African mining company, so we also added a new electricity generation mix for South Africa in the GREET1 Electric tab using data reported by the International Energy Agency (IEA) in 2019. These updates are summarized in the technical memo below.

Technical memo:

- Kingsbury, K., and P. T. Benavides. "Update of Platinum Production and Addition of Platinum-Group Metals (PGMs) to GREET® 2021." https://greet.es.anl.gov/publication-pgm_2021

2.3.4. Catalyst and Associated Materials

Pahola Thathiana Benavides (pbenavides@anl.gov) and Kathryn Kingsbury (kkingsbury@anl.gov)

The Catalyst tab in GREET1 contains material and energy inventories for catalysts that can be applied in LCAs of biofuels or other products. We have added two new catalysts ($Pd/NbOPO_4$ and ZrO_2) to this tab, as well as four additional materials associated with the catalysts' production (Nb_2O_5, $KNbO_3$, $NbOPO_4$, and zircon). Both catalysts have been used successfully in biofuel production, so the material and energy flows for the new catalysts and associated materials will be relevant to future biofuel LCAs. We describe the supply chain, life cycle inventory collection, and cradle-to-gate life cycle analysis results for the two catalysts and their associated materials in the following technical report. Material and energy inputs were collected from a variety of sources, including scientific literature, technical reports from Argonne and other national laboratories, sustainability reports from mining and chemical companies, information already in the GREET model, and direct correspondence with experts in the field. In the report, we also identify and discuss the primary contributors to each catalyst's environmental burden, and we provide suggestions for improvements in the catalysts' supply chains.

Technical report:

- Kingsbury, K., and P. T. Benavides. “Life Cycle Inventories for Palladium on Niobium Phosphate (Pd/$NbOPO_4$) and Zirconium Oxide (ZrO_2) Catalysts” ANL/ESD-21/6. https://greet.es.anl.gov/publication-pdnbopo4_zro2

2.3.5. Manganese

Jarod C. Kelly (jckelly@anl.gov) and Olumide Winjobi (owinjobi@anl.gov)

To improve our modeling of manganese, we evaluated the literature to identify data within GREET that may be out of date, and updated the Manganese tab to reflect these findings. The quality of the manganese ore being processed for the production of manganese through the direct ore processing route was updated from 55% to 35% in GREET 2021. Recent literature has shown that some manganese ores in countries like Brazil, India, and Gabon may have manganese content higher than 40%. However, South Africa, which has the highest identified manganese resources, typically has ores with average ore grade of about 35%. The update to the manganese content of the ore for the direct ore processing was therefore updated to reflect this. Additionally, a High Purity Electrolytic Manganese Metal pathway added to GREET 2021 is based on data from literature.

Technical memo:

- Winjobi, O., and J.C. Kelly. (2021). *Update of the Manganese pathway in GREET® 2021*. https://greet.es.anl.gov/publication-mn_update_2021

2.3.6. Carbon Fiber

Rakesh Krishnamoorthy Iyer (riyer@anl.gov) and Jarod C. Kelly (jckelly@anl.gov)

We have disaggregated the carbon fiber inventory into each of its individual steps, outlined in a previous Argonne report (Johnson & Sullivan, 2014), both to update this inventory in line with more recent literature and to provide greater clarity to GREET users. Briefly, carbon fiber production involves production of propylene and ammonia precursors, which are then reacted to produce acrylonitrile. Separately, methyl methacrylate is produced and then used to polymerize acrylonitrile into polyacrylonitrile, whose fiber form (via spinning) is used in conjunction with other processes to obtain the final carbon fiber. All these steps are provided in detail in the Vehi_Plastics sheet of the GREET2 Excel model. Energy use and emissions for propylene and ammonia production are considered from the most recent update in GREET1, while the latest inventory for polyacrylonitrile and carbon fiber production are incorporated from literature (Ghosh et al., 2021). With no recent inventory available for acrylonitrile and methyl methacrylate production, we assume the values for their process-related material and energy use are the same as those in the previous GREET 2020 model — in line with the previous Argonne report (Johnson & Sullivan, 2014). More details are available in the update memo on carbon fiber mentioned below.

Technical memo:

- Iyer, R. K., & Kelly, J. C. (2021). *Update of the Carbon Fiber pathway in GREET 2021*. https://greet.es.anl.gov/publication-carbon_fiber_2021_update

2.3.7. Lithium

Jarod C. Kelly (jckelly@anl.gov) and Michael Wang (mwang@anl.gov)

We updated lithium pathways within GREET to reflect a recent publication from the Argonne research team. The effort details the production of lithium from brine-based resources in Chile and from ore-based resources in Australia. The processes considered extend to the production of Li_2CO_3 and LiOH, thereby capturing the processes that precede the use of lithium with battery cathode materials. The numerical data within GREET are consistent with that in the publication by Kelly, et al. (2021).

Publication:

- Kelly, Jarod C., Michael Wang, Qiang Dai, Olumide Winjobi. "Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries." *Resources, Conservation and Recycling* 174 (2021): 105762. https://doi.org/10.1016/j.resconrec.2021.105762

2.3.8. Steel

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We updated the Steel tab within GREET2 to reflect energy consumption for U.S. baseline steel production processes and expanded with several steel production pathways with lower CO_2 emissions.

In 2019, the United States produced 87.8 MMT of steel, 30% of which is virgin production from blast furnace–basic oxygen furnace (BF–BOF) and 70% is secondary production from electric arc furnace (EAF) using recycled steel. The BF-BOF technology pathway includes the stages of iron ore extraction and processing, coke production, sintering, blast furnace, and basic oxygen furnace to produce crude steel from iron ore (scrap ratio can be up to 30%). The EAF has only a one-step process in an electric arc furnace to produce crude steel from scrap. The energy consumption and emissions related to all the stages of BF-BOF and EAF have been updated using Jamison et al. (2015), while the mass consumption data are sourced from Athena Sustainable Materials Institute (2002).

Direct reduced iron (DRI) is a reduction process that removes oxygen from iron ore in its solid state without melting. This GREET update includes three technology pathways for steel production via DRI:

1) 100% natural gas energy use
2) 83% H_2 and 17% natural gas by energy (based on lower heating value)
3) 100% H_2 energy use.

The first technology pathways use natural gas as the primary fuel to produce DRI iron, with the mass and energy balance sourced from a DOE report (Greene, 2005). The second pathway uses 83% H_2 and 17% natural gas to produce DRI iron, with the energy consumption data sourced from Rechberger et al. (2020). The third pathway uses 100% H_2 to produce DRI iron using Flash Ironmaking Technology (FIT) developed by a research group from the University of Utah. The DRI pathways are evaluated for two ratios of iron supply to EAF: 1) 100% DRI supplied to EAF for steel production, and 2) 75% DRI and 25% scrap supplied to EAF for steel production. The second DRI case is meant to match the iron supply ratio to the BOF in the BF-BOF process.

We also considered two energy switching options: 1) switch from fossil natural gas to renewable natural gas (using organic waste as the feedstock), and 2) switch from U.S. grid electricity to wind electricity. GREET users can define the energy switching ratio to evaluate the impact of energy sources on the C2G emissions. More information will be available in the following forthcoming publications.

Publications:

- Guiyan Zang, Pingping Sun, Amgad Elgowainy, Pallavi Bobba, Colin McMillan, Ookie Ma, Kara Podkaminer, Neha Rustagi, Marc Melaina, Mariya Koleva "CO_2 Emissions Reduction Potential in U.S. Steelmaking Industry via Efficiency Improvement, Energy Switching, and Carbon Capture: Economic and CO_2 Emissions Analysis" *(submitted for peer-reviewed publication)*
- Guiyan Zang, Pallavi Bobba, Pingping Sun, Amgad Elgowainy, Colin McMillan, Ookie Ma, Kara Podkaminer, Neha Rustagi, Marc Melaina, Mariya Koleva "Deep CO_2 emissions reduction potentials for steelmaking via DRI technology: cost and life cycle CO_2 emissions analysis" *(in preparation)*

2.4. GREET Building Module

Hao Cai (hcai@anl.gov), Michael Wang (mwang@anl.gov)

As the building sector moves to holistically address sustainability, the embodied energy and environmental footprints of buildings and building components (as well as buildings operations) need to be quantified for improvements. Analyzing the energy and emissions produced during the life cycle of buildings helps improve our understanding of the sustainability of different building materials and building design decisions. The building LCA module of the GREET model developed at Argonne is a transparent, consistent tool for the bottom-up assessment of embodied GHGs, energy use, and criteria air pollutant emissions across the supply chain of building materials, building technologies, and whole buildings.

With an interactive, streamlined graphical user interface, the GREET Building Module allows users to easily conduct detailed, bottom-up LCA. For example, the module includes Cradle-to-Gate supply chains of a variety of building materials and with detailed information about building component material composition, logistics, and manufacturing processes. The GREET module includes conventional and new building materials and can inform early-stage research and development efforts of new building materials and components, as well as whole building designs and material choices.

Supported by the Building Technology Office of the DOE Energy Efficiency and Renewable Energy Office, the development of the GREET Building Module has leveraged the long history of GREET development. The GREET Building Module empowers technology developers, researchers, manufacturers, building designers, architects, and policy makers to holistically address embodied carbon and sustainability performance of novel and conventional building materials with a publicly accessible LCA tool and extensive background data.

The GREET Building Module is fully synchronized with the Fuel Cycle and Vehicle Cycle models (GREET1_2021 and GREET2_2021), sharing such data as process energy types and common materials. The module is included in the GREET release package and is also available for download free of charge at the GREET website under the GREET Excel category (https://greet.es.anl.gov). Users can refer to a technical report for details about the methodology, data, and sample modeling results (Cai et al., 2021a). The module's user guide offers modeling techniques and best practices (Cai et al., 2021b).

Technical reports:

- Cai, H., Wang, X., Kelly, J., & Wang, M. (2021a). GREET Building Life-Cycle Analysis: Methodologies, Data, and Case Studies. Argonne National Laboratory. Technical Report: ANL/ESD-21/13. https://greet.es.anl.gov/files/greet_building_method_2021
- Cai, H., Sykora, T., & Wang, M. (2021b). Building Life-Cycle Analysis with the GREET Building Module: A User Guide. Argonne National Laboratory. Technical Report: ANL/ESD-21/14. https://greet.es.anl.gov/files/greet_building_guide_2021

3. OTHER UPDATES AND ADDITIONS

3.1. GREET Modeling Features

3.1.1. Expanded Time-Series Tables; Selection of Vehicle Model Year

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The GREET model can simulate changing conditions that are mainly driven by technology improvements and market shares (e.g., vehicles' fuel economy and emission factors, electricity generation mix, and conversion efficiencies of key LCA stages). We have expanded all the time-series tables in GREET Excel through 2050 to facilitate users to simulate different conditions in future years. Note that GREET.net already permits adding and deleting values for specific simulation years.

In addition, GREET had a five-year lag between the simulation year and the model year (e.g., the simulation year of 2020 uses the model year of 2015) for light-duty vehicles. This lag is to adjust the changing vehicle operation emission rates that deteriorate over time by considering that the half lifetime of light-duty vehicles is around five years (Wang et al., 2007). Although we maintained this rationale in GREET 2021, we made the lag year to be variable so that users could select a specific lag year for each LDV type (car, SUV, or PUT). Note that medium/heavy-duty vehicles (MHDVs) in previous GREET versions use "fleet year" data, not "model year," which so far do not have lag years. Similar to LDVs, however, we enabled the lag year option for each MHDV type so that users can select a specific lag year, if needed.

3.1.2. Aviation Module

Michael Wang (mwang@anl.gov), Amgad Elgowainy (aelgowainy@anl.gov), Uisung Lee (ulee@anl.gov), Zifeng Lu (zlu@anl.gov)

Argonne has been participating in the effort of the ICAO Fuels Working Group for the ICAO CORSIA program to develop CIs of different SAF pathways together with the Massachusetts Institute of Technology, the Joint Research Centre of European Commission, and others. Through this effort, we have developed ICAO-GREET, a version of GREET that includes various SAF production pathways in the CORSIA program. ICAO-GREET was designed with the various datasets developed by these several organizations and has adopted ICAO LCA methods (such as the energy-based allocation method for co-products). We have incorporated CORSIA-approved SAF production pathways in the ICAO-GREET by building options to select different datasets.

The most recent ICAO-GREET is based on the GREET 2019 Excel version; we plan to develop a more user-friendly ICAO-GREET that is dynamically linked to GREET 2021. The new ICAO-GREET, to be released after the GREET 2021 release, will interact with the latest version of the GREET model to use the most up-to-date datasets to simulate CORSIA SAF pathways.

Meanwhile, since 2011 the GREET Excel model has maintained and expanded an aviation module (Jet_WTP, Jet_PTWa, and Jet_WTWa). The module includes various jet fuel production pathways including both petroleum jet fuels and SAFs based on our studies (Elgowainy et al., 2012; Han et al., 2013, 2017; Prussi et al., 2021). The GREET aviation module adopts GREET LCA methods, which may be different from those in ICAO-GREET. Further, the module has six passenger aircraft classes and four freight aircraft classes, which presents the differences in fuel consumption and emissions per passenger-mile for passenger air transportation and per ton-mile for freight air transportation.

In 2013 Argonne released an aviation module (called Jet Fuels Module) in GREET.net that corresponded to the GREET Excel aviation module. This .net aviation module uses fuel production (upstream) pathways developed in GREET.net and can add/edit parameters for different types of aircraft, which are used to calculate full life-cycle results. The .net aviation module was disabled in 2018. We restored the aviation module in GREET.net 2021 after resolving technical issues.

3.2. Other Updates

3.2.1. Annual Electricity Generation Mix and Crude Oil Mix Updates

Uisung Lee (ulee@anl.gov)

We have updated the U.S. regional electricity generation mixes by 2050 using EIA's Annual Energy Outlook (AEO) (EIA, 2021a). The updated electricity generation mixes for eight NERC regions and three states (Alaska [AK], California [CA], and Hawaii [HI]) are presented in Table A-1 of the Appendix.

We have also updated the regional shares of U.S. crude oil supply to petroleum refineries based on EIA's AEO and company-level crude import data. As the Canadian Association of Petroleum Producers no longer publishes projections of Canadian oil production and exports, we assumed current crude oil import splits between conventional crude and oil sands from Canada remain the same through 2050, while we used the projection of the U.S. domestic crude oil share available in AEO. Projected U.S. regional crude oil shares from 2020 to 2050 are presented in Table B-1 in the Appendix. For shale oil production, the shares (out of total U.S. domestic crude oil production) between Eagle Ford and Bakken in 2020 were estimated at 9.3% and 10.5%, respectively, based on EIA (EIA, 2021c, 2021d). We have simulations of shale oil production specific to these two plays in GREET. We updated the crude oil transportation distance based on company-level import data from EIA (EIA, 2021b). Weighted average distances are estimated at 8,727 miles by ocean tankers for offshore countries and 1,684 miles for Canada and Mexico by pipeline.

3.2.2. Methane Leakage of Natural Gas Supply Chain

Andrew Burnham (aburnham@anl.gov)

Methane (CH_4) emissions from the natural gas supply chain are updated based on newly published data. In GREET 2021, we changed the default CH_4 emissions to be based on a hybrid top-down and bottom-up approach using two studies that discovered the bottom-up EPA greenhouse gas emission inventory (GHGI) may have consistently underestimated natural gas CH_4 emissions (EPA, 2021). Scaling factors based on Alvarez et al. (2018) modifying the most recent EPA GHGI production, processing, and transmission CH_4 emissions have served as a hybrid option since GREET 2018 (Burnham, 2018). We now use the processing and transmission scaling factors in GREET 2021 by default. In addition, we use production scaling factors from Rutherford et al. (2021), who found that equipment leakage and liquid hydrocarbon storage tanks resulted in significantly higher emissions than documented in the GHGI. In GREET 2021, the EPA (2021) GHGI bottom-up data becomes the optional case for users to select.

Technical memo:

- Burnham, A. (2021). "Updated Natural Gas Pathways in GREET 2021." https://greet.es.anl.gov/publication-update_ng_2021

3.2.3. Updated the E-Fuels Tab

Eunji Yoo (eyoo@anl.gov), Guiyan Zang (gzang@anl.gov), Uisung Lee (ulee@anl.gov)

We have made several updates in the E-fuel tab. First, we have added new CO_2-derived methanol production pathways (indirect and direct) through a collaborative US DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) project with other national laboratories. Indirect methanol production generates syngas from CO_2, which is converted into methanol. For direct methanol production, CO_2 and H_2 react to produce methanol in a single step. For the direct case, we considered two cases (the SOT and the future) for the technology levels in 2018 and 2030. The details will be presented in a forthcoming US DRIVE report. We also have added a CO_2 feedstock option from direct air capture (DAC), in addition to existing CO_2 from corn ethanol plants. Details for DAC are provided in Section 3.2.4.

We also made the following updates in the E-fuels tab:

- Created an option for H_2 recycling for FT-fuel and methanol production pathways
- Enabled various CO_2, hydrogen, electricity, and natural gas source options for each fuel production pathway
- Added an option for a heat source for CO_2-to-ethanol production: waste heat or fossil natural gas
- Updated the amount of CO_2 from ethanol plants using the stoichiometric ratio of 1:1 between ethanol and CO_2 (Explained in Section 2.1.1)
- Updated the electricity/natural gas inputs for corn ethanol plant CO_2 capture and transportation based on the assumptions for each pathway.

Publication:

- U.S. DRIVE – Net-zero carbon Tech-Team Analysis Summary Report 2020 *(forthcoming)*

3.2.4. Direct Air Capture (DAC)

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We have incorporated a direct air capture (DAC) option as CO_2 feedstock for CO_2 utilization technologies in the E-Fuels tab. Two DAC technologies have been incorporated: low-temperature (LT) DAC using solid sorbent and cryogenic carbon capture.

For LT-DAC, we have used the future case of Deutz and Bardow (2021), which considers potential heat recovery and optimization of systems. The heat and electricity requirements are estimated at 5.4 GJ/t-CO_2 and 500 kWh/t-CO_2, respectively (see Supplementary Table 1 in Deutz and Bardow [2021]). Because this includes electricity required for CO_2 compression from 1 to 150 bar, this portion (101 kWh/t-CO_2 in Supplementary Table 28 in Deutz and Bardow [2021]) has been subtracted. In addition, Deutz and Bardow (2021) listed "heat" requirements, so we consider a boiler efficiency of 80% to estimate external natural gas inputs. Note that LT-DAC only requires low-quality heat (less than 100°C), which means it may use waste heat rather than heat from boilers with external natural gas. Thus, GREET uses waste heat, not fossil natural gas, by default. Additionally, LT-DAC requires 3 grams of amine or silica per kg CO_2 captured, which we included in DAC LCA.

A recent study shows that cryogenic carbon capture (CCC) technologies can efficiently capture atmospheric CO_2 (Baxter et al., 2021). With the capture rate of ~100%, the electricity requirement for CCC is estimated at 1.0-1.1 GJ per metric ton of CO_2 (Baxter et al., 2021). Table 8 summarizes the energy and material requirements for the two DAC technologies, which have been implemented in GREET 2021.

Table 8. Energy and Material Requirements for LT-DAC and Cryogenic DAC Technologies

	LT-DAC	**Cryogenic**
Natural gas (Btu/kg CO_2)	6,398†	
Electricity (Btu/kg CO_2)	1,361 (0.4 kWh)	962 – 1,020
Sorbent (amine or silica) (g/kg CO_2)	3	
Reference	Deutz and Bardow (2021)	(Baxter et al., 2021)

† When waste heat is used, the natural gas requirement becomes zero.

3.2.4. New Marine Fuel Pathways

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As part of GREET 2021, we added five novel marine fuel pathways to the GREET Marine Fuels module (Marine_WTH tab). These pathways include eMethanol, eFT Fuel, Ammonia, and HFO (2.7% sulfur content) using a wet sulfur scrubber. Cradle-to-gate LCI for newly added pathways were derived from existing fuel pathways developed in GREET. In addition, as part of the GREET 2021 release, several updates were made to the biomass to methanol pathway (see Section 2.1.5 for addition details), which were propagated into the Marine module's Methanol (Biomass) pathway. A complete description of the changes and additions to the Marine Fuels module in GREET 2021 are provided in Table 9.

Table 9. Summary of Marine Fuel Pathways Implemented in GREET 2021

	Pathway		**Cradle-to-Gate LCI**	
New (N) or Revision (R)	**Marine pathway**	**Feedstock**	**GREET module**	**GREET pathway**
N	eMethanol	CO_2	E_fuel	Multiple[1]
N	eFT fuel	CO_2	E_fuel	FT fuel production with RWGS[2]
N	ammonia (conventional)	Natural gas	Ag_Inputs	Conventional ammonia
N	ammonia (low carbon)	Multiple[3]	Ag_Inputs	Green ammonia
N	HFO (2.7% S), wet sulfur scrubber (open-loop)	Crude oil	Marine_WTH	HFO (2.7% S)
R	methanol (biomass)	Ligno-cellulosic biomass	MeOH_FTD	Biomass to methanol

[1]Based on user selection, including MeOH production with RWGS with H2 recycle, MeOH production with RWGS without H2 recycle, CO2-to-CO-to-MeOH, Direct CO2-to-MeOH (SOT), or Direct CO2-to-MeOH (Future).
[2]Based on user selection, including FT fuel production with RWGS with H2 recycle, or FT fuel production with RWGS without H2 recycle.
[3]Based on user selection of H_2 and N_2 production as well as the electricity source for Haber Bosch process and N_2 production.

We developed well-to-hull life cycle analysis for new marine pathways by coupling cradle-to-gate LCI for the upstream fuel supply chain, including feedstock acquisition, processing, fuel conversion, and transportation, with downstream marine vessel operations and marine fuel combustion. This approach uses the existing analytical structure of the GREET Marine Fuels Module to estimate the life-cycle energy and environmental impacts of novel marine fuel for maritime applications, considering specific fuel properties (e.g., heating value, carbon content, sulfur content, etc.) as well as user-defined vessel engine, emissions regulations, and trip characteristics. Additional details and assumptions for ammonia-based fuels and HFO (2.7% S) using a wet (open loop) sulfur scrubber are provided in the following subsections.

Ammonia as a fuel

Life cycle analysis of ammonia as a fertilizer has been part of the GREET model since its inception. Recently, ammonia has gained traction as a promising next-generation fuel for the maritime sector (Bicer & Dincer, 2018a, 2018b). This work considers the use of conventional (natural gas based, Haber-Bosch process) or low-carbon ammonia (derived from renewables or industrial by-products) for use in marine internal combustion engines (ICE). Due to limited data on the combustion profiles of ammonia in marine vessels, emissions from ammonia combustion are estimated by scaling emissions from hydrogen ICE, based on the hydrogen content of ammonia (% w/w), and assume complete combustion of ammonia.

Wet sulfur scrubber (open-loop) for marine vessel emission reductions

Marine scrubbers are a form of an Exhaust Gas Cleaning System (EGCS) that can be used to reduce sulfur oxides and other particulate emissions from the combustion gases generated in marine engines. Several forms of scrubbing technologies exist, noted below:

- Wet scrubbers: use seawater or freshwater as the scrubbing medium
    - Open loop: uses seawater as the scrubbing medium and discharges scrubber wash water into the marine environment.
    - Closed loop: uses fresh water with the addition of an alkaline chemical as the scrubbing medium. Scrubber wash water is retained onboard the vessel and eventually disposed of on land.
    - Hybrid systems: can operate in either open loop or closed loop configurations.
- Dry scrubbers: use a dry chemical reagent to remove sulfur oxides from exhaust gases.

This work develops a new marine fuel pathway that considers using HFO (2.7% sulfur) and a wet (open-loop) scrubber. This scrubber technology was selected due to its widespread use in the marine sector, with prior estimates suggesting that about 80% of installed scrubbers are wet (open loop) systems because of their comparatively lower cost for installation and use relative to other scrubber technologies (Georgeff et al., 2019). It is assumed that the marine scrubber system reduces direct combustion sulfur oxides emissions by 93% (Caiazzo et al., 2013), consistent with published literature that reports sulfur oxides reductions ranging from 64% to 94% (Brynolf et al., 2014). Moreover, parasitic energy use from the scrubber system are modeled assuming 1.5% of engine power output, in line with technical documentation that reports a parasitic energy loss ranging from 1% to 2% (Register, 2012).

3.2.5. LDV and MHDV Vehicle Operation Emission Factors

Andrew Burnham (aburnham@anl.gov)

We used MOVES3.01, the latest version of the EPA's vehicle emissions model, to develop vehicle operation emission factors for gasoline and diesel LDVs and MHDVs in GREET 2021. The air pollutant emission factors generated include carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SOx), volatile organic compounds (VOCs), particulate matter with diameters of 10 micrometers or less (PM_{10}), and particulate matter with diameters of 2.5 micrometers or less ($PM_{2.5}$) as well as the two major components of particulate matter, black carbon (BC) and organic carbon (OC). We also estimated the greenhouse gas emissions of methane (CH_4) and nitrous oxide (N_2O). The development of MOVES has been based on the analysis of millions of emission test results and considerable advances in the EPA's understanding of vehicle emissions (EPA, 2020).

Technical memo:

- Burnham, A. (2021). "MOVES3 Vehicle Operation Emission Factors" https://greet.es.anl.gov/publication-update_moves3

3.2.6. Sulfuric Acid Production

Hui Xu (hui.xu@anl.gov)

Sulfuric acid is an important chemical product used in multiple pathways. Production of sulfuric acid would generate SOx emissions, and the emission factor depends on conversion efficiency from SO_2 to SO_3. The SOx emission factor (40 lb/ton product, assuming a 97% conversion factor) was based on a DOE 2000 report. However, EPA regulations require producers to limit SO_2 emissions to be 4 lb/ton of product or lower (National Archives and Records Administration, 2021). For this reason, we revised the SOx emission factor from 40 lb/ton to 4 lb/ton in the GREET 2021 release.

3.2.7. Change of E-Diesel and EtOH-Diesel Terminology

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In previous GREET versions, we provided the "E-D additives" sheet to represent the blending of ethanol and diesel fuels (with additives) to improve diesel engine emission performance (Wang et al., 2003, 2007), which was also called "E-diesel." This terminology became confusing when we added "Electro-Fuels (e-fuels)" in GREET 2020 (Wang et al., 2020), which also includes an "E-diesel" option. "E-fuels" now refers to fuels produced from CO_2 and hydrogen via electrolysis using renewable and low-carbon electricity. To avoid confusion, all previously used E-diesel terms have been changed to "EtOH-diesel" in GREET 2021.

3.2.8. The Rail Module

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The GREET model includes alternative pathways of transportation fuels and powertrain technologies across major transportation sectors (road, air, marine, and rail) for well-to-wheels (WTW) analysis. Within this framework, GREET's Rail Module provides a pump-to-wheels (PTW) analysis for freight rail and four classes of passenger rail. Recently the baseline rail module of GREET was updated with the most current data available and is expanded to include hydrogen fuel cell pathways. This memo documents the updated data sources and calculation of energy intensity for each rail class, and summarizes the GREET update for the rail module.

Energy intensity of diesel locomotives by rail type

- **Freight rail**

For each Class 1 railroad company, the data for total revenue ton-miles and diesel fuel consumption by year are obtained from Surface Transportation Board (2018). Total diesel consumption and revenue ton-miles were calculated by summing all six Class 1 railroad company's data. The energy intensity per ton-mile for freight railroad is then calculated as follows:

$$Energy\ Intensity\ for\ Freight\ Railroad = \frac{Total\ Diesel\ use\ \times Lower\ Heating\ Value\ of\ Diesel}{Total\ Revenue\ Ton\ Miles} \quad (1)$$

- **Passenger intercity rail (Amtrak)**

Amtrak's Northeast Corridor (NEC) uses electricity as fuel, whereas the rest of its operation use diesel. The total passenger-miles for NEC and diesel operation were separately obtained from Amtrak (2020) along with respective electricity and diesel use. The energy intensity in Btus per passenger-mile for electric operation in NEC is calculated as follows.

$$Energy\ Intensity\ for\ Electric\ Operation = \frac{Total\ Electricity\ use\ (kWh)}{Total\ Passenger\ Miles} \times Btu\ per\ kWh \quad (2)$$

Similarly, the energy intensity per passenger-mile for diesel operation is calculated using the following equation:

$$Energy\ Intensity\ for\ Diesel\ Operation = \frac{Total\ Diesel\ use\ \times Lower\ Heating\ Value\ of\ Diesel}{Total\ Passenger\ Miles} \quad (3)$$

- **Light and heavy transit rail**

Both light and heavy transit rails run exclusively on electricity. The National Transit Database (NTD) reports total electricity use and passenger-miles for each transit agency (Federal Transit Administration, 2019). The energy intensities for light transit rail and heavy transit rail are calculated separately using Equation 2. For light transit rail, total electricity consumption and passenger miles are calculated by summing the data from 23 individual transit agencies. On the other hand, data from 15 heavy transit rail agencies are used to calculate the average energy intensity per passenger mile.

- **Commuter rail**

For commuter rails, the National Transit Database (Federal Transit Administration, 2019) show that five among 26 agencies, including the four largest agencies (MTA Metro-North Railroad, MTA Long Island Railroad, New Jersey Transit Corporation, and Illinois' Metra Rail) report the consumptions of both diesel and electricity combined without separating diesel and electric passenger miles (PM). For four of these five agencies, we estimated diesel passenger-miles and electric passenger-miles by using weighted average (weighted by average passenger on board) gal/PM and kwh/PM, respectively. We exclude the MTA's Long Island Railroad from this calculation as the value of total estimated passenger-miles for this agency appeared to be an outlier (the figures were much smaller compared to total actual passenger-miles reported in NTD). Our attempts to communicate with MTA Long Island Railroad to confirm operation data were not successful.

Energy consumption ratios for hydrogen fuel cell

The reductions from baseline diesel for hydrogen fuel cell locomotives are estimated based on Isaac (2020). The study simulated freight, switcher, and passenger rails to analyze the fuel consumption and environmental impacts for different combinations of diesel and hydrogen hybrid powertrains with batteries.

U.S. railroad operational characteristics

Truck Miles Traveled (TMT) for different commodity types using railway are updated based on Freight Analysis Framework (FAF) version 4.5.1 (Bureau of Transportation Statistics, 2021). Two new commodity types (Crude Petroleum and Apparels & Finished Textiles) are added. The remaining commodities are aggregated, as in GREET's previous versions. Total million ton-miles, average tons/car, and total diesel use are updated based on data from the Association of American Railroads (AAR) (2019).

Emission factors of fuel combustion

For line-haul and switcher locomotives, emission factors were calculated based on the 2018 AAR report (Smith, 2018). We used a stock-weighted average to aggregate the locomotives from different tiers. The shares of diesel use for line-haul and switcher locomotives are updated based on data from the Surface Transportation Board (2018).

4. HELPS, TUTORIALS, AND PRESENATION MATERIALSS

The GREET website (https://greet.es.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 represent technical documentation of 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 as your email subject line. Please indicate whether you use GREET Excel version or .net version.

- GREET1: Oil/gas fuel pathways LCA
- GREET1: Biofuel/waste fuel pathways LCA
- GREET1: Electricity modeling LCA
- GREET1: Hydrogen modeling LCA
- GREET1: Electro-fuel modeling LCA
- GREET1: Plastics/chemicals LCA
- GREET1: Vehicle operations LCA
- GREET marine LCA
- GREET aviation LCA
- GREET rail LCA
- GREET2, vehicle cycle LCA
- GREET Building LCA related to the buildings LCA module
- GREET farm-level biofuel feedstock LCA related to the FD-CIC.

To help users navigate inside the model, 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 GREET models, technical approaches, and general coverage.

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APPENDIX A: U.S. ELECTRICITY GENERATION MIX

Table A-1. Electric Generation Mix 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										
2020	0.38%	39.57%	19.95%	20.42%	0.32%	7.37%	0.41%	8.90%	2.22%	0.48%
2025	0.24%	34.93%	17.15%	18.26%	0.31%	7.22%	0.45%	15.34%	5.43%	0.68%
2030	0.20%	34.12%	16.47%	15.07%	0.28%	7.03%	0.60%	15.24%	9.41%	1.58%
2035	0.18%	33.29%	14.98%	14.10%	0.28%	6.78%	0.74%	14.97%	11.84%	2.84%
2040	0.15%	34.39%	13.63%	13.22%	0.27%	6.50%	0.88%	14.51%	13.30%	3.13%
2045	0.11%	35.24%	12.42%	12.70%	0.25%	6.17%	0.95%	14.14%	14.86%	3.16%
2050	0.11%	35.20%	11.79%	11.92%	0.24%	5.82%	1.00%	13.97%	16.78%	3.16%
Texas Reliability Entity (TRE) Mix										
2020	0.05%	50.78%	12.52%	11.04%	0.03%	0.25%	0.00%	23.20%	2.03%	0.09%
2025	0.06%	41.44%	15.04%	10.26%	0.03%	0.21%	0.00%	26.29%	6.44%	0.24%
2030	0.07%	38.56%	15.59%	9.88%	0.02%	0.20%	0.00%	25.25%	10.02%	0.41%
2035	0.06%	33.83%	14.26%	9.48%	0.02%	0.19%	0.00%	24.21%	17.37%	0.58%
2040	0.06%	32.46%	13.47%	9.10%	0.02%	0.17%	0.00%	23.07%	20.91%	0.75%
2045	0.04%	37.55%	9.14%	8.71%	0.02%	0.16%	0.00%	21.88%	21.60%	0.90%
2050	0.04%	36.88%	9.25%	8.33%	0.02%	0.15%	0.00%	20.69%	23.61%	1.02%
Florida Reliability Coordinating Council (FRCC) Mix										
2020	0.15%	71.96%	10.12%	13.35%	0.21%	0.79%	0.00%	0.00%	2.36%	1.06%
2025	0.16%	64.48%	13.29%	12.69%	0.20%	0.74%	0.00%	0.00%	7.29%	1.16%
2030	0.10%	53.72%	13.87%	12.35%	0.19%	0.71%	0.00%	0.00%	17.72%	1.34%
2035	0.09%	47.50%	12.72%	11.54%	0.18%	0.64%	0.00%	0.00%	25.78%	1.55%
2040	0.06%	49.47%	12.11%	11.01%	0.17%	0.61%	0.00%	0.00%	24.93%	1.64%
2045	0.05%	50.60%	11.59%	10.87%	0.16%	0.58%	0.00%	0.00%	24.43%	1.71%
2050	0.04%	52.40%	10.91%	10.23%	0.15%	0.55%	0.00%	0.00%	23.99%	1.72%

Table A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Midcontinent ISO (MISO) Mix										
2020	0.82%	29.56%	39.22%	15.85%	0.14%	1.49%	0.00%	12.16%	0.38%	0.38%
2025	0.14%	28.29%	30.54%	13.04%	0.12%	1.43%	0.00%	20.77%	5.17%	0.50%
2030	0.14%	36.26%	28.83%	5.09%	0.11%	1.38%	0.00%	20.45%	7.13%	0.61%
2035	0.13%	35.98%	27.77%	3.82%	0.12%	1.35%	0.00%	20.09%	9.95%	0.78%
2040	0.12%	36.85%	26.12%	3.79%	0.12%	1.31%	0.00%	19.45%	11.31%	0.93%
2045	0.12%	37.40%	25.12%	3.64%	0.12%	1.25%	0.00%	18.78%	12.52%	1.05%
2050	0.11%	36.44%	23.69%	3.49%	0.12%	1.20%	0.00%	18.55%	15.25%	1.16%
Northeast Power Coordinating Council (NPCC) Mix										
2020	0.16%	45.69%	0.07%	29.72%	1.29%	16.48%	0.00%	3.73%	1.06%	1.80%
2025	0.14%	34.73%	0.00%	24.53%	1.44%	17.34%	0.00%	15.60%	2.92%	3.30%
2030	0.12%	28.99%	0.00%	22.64%	1.33%	15.97%	0.00%	14.51%	8.42%	8.02%
2035	0.04%	21.84%	0.00%	22.29%	1.31%	15.66%	0.00%	14.28%	8.40%	16.18%
2040	0.02%	21.26%	0.00%	21.35%	1.26%	15.01%	0.00%	13.72%	8.20%	19.18%
2045	0.01%	22.60%	0.00%	21.01%	1.23%	14.61%	0.00%	13.42%	8.35%	18.76%
2050	0.01%	22.88%	0.00%	20.47%	1.18%	14.09%	0.00%	13.07%	10.02%	18.27%
Pennsylvania, New Jersey, and Maryland (PJM) Mix										
2020	0.12%	42.34%	18.22%	33.25%	0.16%	1.39%	0.00%	3.23%	0.71%	0.58%
2025	0.09%	43.86%	14.92%	27.81%	0.14%	1.37%	0.00%	7.70%	3.44%	0.66%
2030	0.06%	42.14%	13.82%	25.53%	0.04%	1.33%	0.00%	7.60%	6.38%	3.09%
2035	0.05%	43.34%	12.49%	22.88%	0.04%	1.27%	0.00%	7.32%	6.32%	6.28%
2040	0.05%	46.85%	11.75%	20.33%	0.03%	1.22%	0.00%	7.06%	6.40%	6.32%
2045	0.05%	48.42%	11.06%	19.82%	0.03%	1.16%	0.00%	6.78%	6.50%	6.18%
2050	0.04%	48.87%	10.44%	18.65%	0.03%	1.07%	0.00%	6.47%	8.45%	5.98%

Table A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
SERC Reliability Corporation (SERC) Mix										
2020	0.19%	41.50%	16.95%	33.92%	0.58%	4.70%	0.00%	0.01%	1.93%	0.21%
2025	0.18%	36.95%	18.10%	35.29%	0.55%	4.63%	0.00%	0.51%	3.48%	0.31%
2030	0.10%	35.16%	17.89%	31.76%	0.55%	4.60%	0.00%	0.79%	8.74%	0.43%
2035	0.09%	33.89%	16.65%	31.08%	0.53%	4.46%	0.00%	1.00%	11.74%	0.55%
2040	0.07%	33.82%	14.66%	29.84%	0.51%	4.28%	0.00%	1.01%	15.16%	0.66%
2045	0.06%	31.86%	13.11%	27.87%	0.48%	3.98%	0.00%	1.05%	20.85%	0.75%
2050	0.05%	30.56%	12.37%	25.69%	0.45%	3.76%	0.00%	1.29%	25.01%	0.81%
Southwest Power Pool (SPP) Mix										
2020	0.13%	25.51%	32.54%	5.81%	0.00%	5.61%	0.00%	30.05%	0.29%	0.06%
2025	0.10%	18.34%	24.93%	5.44%	0.00%	5.39%	0.00%	41.58%	4.01%	0.20%
2030	0.11%	13.84%	26.21%	0.00%	0.00%	5.29%	0.00%	41.83%	12.37%	0.36%
2035	0.10%	13.07%	25.43%	0.00%	0.00%	5.10%	0.00%	40.78%	15.00%	0.52%
2040	0.09%	13.31%	21.76%	0.00%	0.00%	4.90%	0.00%	39.56%	19.69%	0.68%
2045	0.08%	13.14%	20.28%	0.00%	0.00%	4.65%	0.00%	38.25%	22.80%	0.81%
2050	0.08%	13.13%	19.72%	0.00%	0.00%	4.43%	0.00%	37.48%	24.26%	0.91%
Western Electricity Coordinating Council (WECC) Mix										
2020	0.14%	31.94%	15.84%	8.27%	0.45%	25.12%	2.21%	8.78%	6.87%	0.39%
2025	0.11%	23.36%	10.88%	6.81%	0.44%	25.12%	2.53%	20.34%	9.81%	0.61%
2030	0.11%	23.43%	9.42%	5.50%	0.45%	24.57%	3.37%	20.47%	11.81%	0.88%
2035	0.09%	25.71%	6.26%	5.48%	0.46%	23.74%	4.13%	20.70%	12.31%	1.12%
2040	0.08%	27.13%	5.21%	5.24%	0.43%	22.62%	4.88%	20.48%	12.58%	1.36%
2045	0.08%	27.80%	4.86%	4.93%	0.40%	21.23%	5.23%	20.61%	13.31%	1.56%
2050	0.07%	28.51%	4.55%	4.63%	0.38%	19.84%	5.44%	21.20%	13.64%	1.73%

Table A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
California Mix										
2020	0.02%	41.73%	3.82%	9.31%	1.09%	14.04%	4.19%	7.58%	17.28%	0.95%
2025	0.00%	36.14%	0.00%	5.13%	1.22%	15.79%	5.47%	8.11%	26.90%	1.24%
2030	0.00%	25.63%	0.00%	0.00%	1.38%	16.39%	8.40%	8.82%	37.83%	1.55%
2035	0.00%	20.30%	0.00%	0.00%	1.48%	16.16%	11.14%	8.41%	40.71%	1.79%
2040	0.00%	18.24%	0.00%	0.00%	1.37%	15.35%	12.86%	8.00%	42.25%	1.92%
2045	0.00%	16.89%	0.00%	0.00%	1.26%	13.97%	13.46%	6.94%	45.50%	1.97%
2050	0.00%	16.94%	0.00%	0.00%	1.18%	12.41%	13.51%	7.53%	46.46%	1.97%
Alaska Mix										
2020	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
2025	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
2030	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
2035	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
2040	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
2045	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
2050	14.84%	44.26%	11.25%	0.00%	0.62%	26.74%	0.00%	2.35%	0.00%	0.00%
Hawaii Mix										
2020	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%
2025	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%
2030	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%
2035	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%
2040	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%
2045	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%
2050	70.40%	0.00%	13.35%	0.00%	2.99%	0.97%	0.00%	5.43%	2.75%	4.11%

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
2020	80.2%	7.2%	4.9%	2.2%	2.4%	2.0%	0.5%	0.6%
2025	75.9%	6.7%	8.0%	2.7%	2.9%	2.4%	0.7%	0.8%
2030	78.3%	6.1%	7.2%	2.4%	2.6%	2.1%	0.6%	0.7%
2035	78.8%	5.9%	7.0%	2.4%	2.5%	2.1%	0.6%	0.7%
2050	74.1%	7.2%	8.6%	2.9%	3.1%	2.6%	0.7%	0.8%

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