ANL/ESD-19/6

Summary of Expansions and Updates in GREET® 2019

Energy Systems Division

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Summary of Expansions and Updates in GREET® 2019

prepared by
Michael Wang, Amgad Elgowainy, Uisung Lee,
Pahola Thathiana Benavides, Andrew Burnham, Hao Cai, Qiang Dai, Troy R. Hawkins,
Jarod Cory Kelly, Hoyoung Kwon, Xinyu Liu, Zifeng Lu, Longwen Ou, Pingping Sun, Olumide Winjobi, Hui Xu

Systems Assessment Center, Energy Systems Division, Argonne National Laboratory

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CONTENTS

TABLES

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1. INTRODUCTION

The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) 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). Argonne has expanded and updated the model in various sectors in GREET 2019, and this report provides a summary of the release.

2. MAJOR EXPANSIONS AND UPDATES IN GREET 2019

2.1. Biofuels and Bioproducts

2.1.1. Bioplastics

Pahola Thathiana Benavides (pbenavides@anl.gov) and Uisung Lee (ulee@anl.gov)

GREET 2019 expanded the GREET bioproduct module by adding two new bio-derived plastic pathways for polylactic acid (PLA) and polyethylene terephthalate (PET) production. PLA is a linear aliphatic thermoplastic polyester derived from biomass. It currently accounts for about 10% of global bioplastic production (233,749 tons); its production capacity is expected to increase significantly in the near future. PLA is a potential replacement for conventional plastics used in applications such as cups, bottles, to-go containers, packaging, films, and textiles. These are commonly produced using plastics such as conventional PET, polypropylene (PP), high-density polyethylene (HDPE), and acrylonitrile butadiene styrene (ABS), which are also available in GREET 2019. PET is a common plastic resin used to produce packaging, notably plastic bottles, because of its excellent properties, such as its impermeability to oxygen, water, and carbon dioxide. Most PET bottles are now produced from fossil fuel-derived feedstocks. Bio-derived pathways to PET bottles, however, offer lower greenhouse gas (GHG) emissions than the conventional route.

More details of PLA production can be found at Benavides et al. (2019), which presents life-cycle inventory (LCI) for PLA production that can be used to evaluate the energy and environmental effects of PLA production.

Details of PET production from different bio-based pathways can be found at Benavides et al. (2018).

Technical Memo: P.T. Benavides, O. Zare`-Mehrjerdi, and U. Lee, 2019, "Life Cycle Inventory for Polylactic Acid (PLA) Productionin GREET 2019," Argonne National Laboratory, Lemont, IL.
(https://greet.es.anl.gov/publication-pla_lca)

2.1.2. Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) and Direct Nitrous Oxide Emission Factors

Hao Cai (hcai@anl.gov), Hoyoung Kwon (hkwon@anl.gov), Xinyu Liu (xinyu.liu@anl.gov), and Hui Xu (hui.xu@anl.gov)

In the previous version of CCLUB, GHG emissions related to land management changes were calculated and incorporated into GREET as a unit of g CO_2e/Mg dry biomass, which was inconsistent with a unit of g CO_2e/Mg dry short ton biomass used in GREET. We corrected this unit inconsistency by applying the unit conversion factor of Mg to short ton (1.102) in CCLUB.

In GREET, the direct nitrogen fertilizer-induced nitrous oxide (N_2O) emission factor (N_2O EF) was updated from 1.2% to 1%; this reduction is based on our recent analysis of available data and is consistent with the default direct N_2O EF for mineral fertilizers (Tier 1) reported in the Intergovernmental Panel on Climate Change guideline (IPCC 2006). Corn farming requires intensive nitrogen fertilizer use, and N_2O emissions from corn farming contribute significantly to corn ethanol carbon intensity. In 2012, we estimated an N_2O EF of 1.2% (Wang et al. 2012). Since then, more than 260 studies on this topic have been published, according to the Web of Science. This update is the outcome of literature review of these new studies to reflect recent empirical evidences of nitrogen fertilizer-induced N_2O emissions for major cornfields in the United States.

In addition, we amended the current N_2O EF for animal manure application, which is 0.02 kg-N_2O-N/kg-N, adopted from IPCC EF_{3PRP} (IPCC 2006). Because that EF accounts for the annual amount of urine and dung nitrogen deposited by grazing animals on pasture, range, and paddock rather than cropland, we adapted EF_1 (0.01 kg-N_2O-N/kg-N) for manure application in cropland. The details of this update are provided in the following technical memo.

Technical memo: H. Xu, H. Cai, and H. Kwon, 2019, "Update of Direct N_2O Emission Factors from Nitrogen Fertilizers in Cornfields in GREET® 2019." (https://greet.es.anl.gov/publication-n2o_update_2019).

2.1.3. GREET Open-Source Database of Soil Organic Carbon

Hoyoung Kwon (hkwon@anl.gov), Xinyu Liu (xinyu.liu@anl.gov), and Hui Xu (hui.xu@anl.gov)

A new database, the Regional Soil Carbon Observations for Renewable Energy and Agriculture (ReSCORE-A), was developed to refine soil organic carbon (SOC) changes estimated in CCLUB. This database includes data points from field experiments. It aims to reflect regional variations in land use and management changes, and calculate their impacts on SOC changes and associated GHG emissions for corn-based feedstock and cellulosic feedstocks, such as corn stover, dedicated energy crops, and forest residues. ReSCORE-A is publicly available at https://greet.es.anl.gov/rescorea.

Publication: H. Hui, H. Sieverding, H. Kwon, D. Clay, C. Stewart, J.M.F. Johnson, Z. Qin, D.L. Karlen, and M. Wang. 2019, "A Global Meta-analysis of Soil Organic Carbon Response to Corn Stover Removal." Global Change Biology Bioenergy 11: 1215–1233. (https://greet.es.anl.gov/publication-soc_corn_stover)

2.2. Petroleum Production Pathways

Pingping Sun (psun@anl.gov), Zifeng Lu (zlu@anl.gov), and Amgad Elgowainy (aelgowainy@anl.gov)

The following updates were made in the GREET petroleum pathways in 2019.

2.2.1 Updated Non-combustion Emissions

For petroleum products, the noncombustion emissions associated with refinery products were updated based on a recent study by Sun et al (2019). The criteria air pollutant (CAP) emissions and greenhouse gas (GHG) emissions were evaluated for U.S. refineries using the emission data from U.S. Environmental Protection Agency (EPA) databases. The CAP emission data were obtained from the EPA National Emissions Inventory (NEI) and the GHG emission data from the EPA Greenhouse Gas Reporting Program (GHGRP) database, for the year 2014. The refinery facility emissions were allocated to refinery products at the unit process level.

2.2.2 Added Four Refinery Products Pathways

Pathways were added/updated for four refinery products, namely, propane, butane, asphalt, and propylene, based on U.S. refinery Linear Programming (LP) modeling results by Elgowainy et al. (2014). In earlier GREET versions, a butane pathway existed, but it relied on surrogate data using a portion of gasoline production data, whereas in GREET 2019, butane-specific production data were incorporated to displace the surrogate data. For propane, butane, asphalt, and propylene, the specific product efficiency for each product was added in the Inputs and the Fuel_Prod_TS tabs.

2.2.3 Updated Combustion Emission Factors of Refinery Still Gas and Refinery Catalyst Coke

The combustion EFs for refinery still gas and refinery catalyst coke were updated based on Sun et al. (2019). The CO_2 EF was calculated based on the fuel carbon content. The CAP emissions in Sun et al. (2019) were based on the average of reported U.S. refinery CAP emissions in the year 2014, as a result of historical fuel uses, operating conditions, control technologies.

2.2.4 Updated Properties of Refinery Still Gas

The properties of refinery still gas were updated based on Sun et al. (2019), who provided the CO_2 emission per mm Btu of refinery still gas. Based on the assumption that refinery still gas consists of only methane and ethane, the shares of methane and ethane in still gas were estimated, and the lower and higher heating values of still gas were subsequently calculated.

Publication: P. Sun, B. Young, A. Elgowainy, Z. Lu, M. Wang, B. Morelli, T. Hawkins, Criteria Air Pollutant and Greenhouse Gases Emissions from U.S. Refineries Allocated to Refinery Products, Environ. Sci. Technol., 2019, 53, 11, 6556-6569. (https://greet.es.anl.gov/publication-cap_ghg_refinery)

Technical memo: P. Sun and Z. Lu, "2019 GREET Update for Petroleum Products Pathways." (https://greet.es.anl.gov/publication-petro_2019)

2.3. Hydrogen and Fuel Cell Vehicles

Pingping Sun (psun@anl.gov), Zifeng Lu (zlu@anl.gov), and Amgad Elgowainy (aelgowainy@anl.gov)

The hydrogen production pathways using steam methane reforming (SMR) of natural gas (NG) were updated in GREET 2019, based on a recent study by Sun et al. (2019). This study investigated U.S. stand-alone SMR facilities and reported CAP and GHG emissions per unit of hydrogen production, using SMR facility emission data reported in the NEI and GHGRP databases, respectively. The study summarized the CO_2 emissions associated with hydrogen production by accounting for emissions from both combustion and chemical conversion processes. The median CO_2 emissions normalized for SMR hydrogen production was 9 kg CO_2/kg H_2 production, or 75 g CO_2/MJ H_2 (using H_2 low heating value [LHV]). The median emissions are similar to the value of 9.26 kg CO_2/kg H_2 in GREET 2018, which was based on the H2A modeling by Rutkowski et al. (2012). Other emissions, the combustion and non-combustion CAP emissions, based on NEI data from Sun et al. (2019), were updated with values lower than those in GREET 2018.

Publication: Sun, P., B. Young, A. Elgowainy, Z. Lu, M. Wang, B. Morelli, and T. Hawkins, 2019, "Criteria Air Pollutants and Greenhouse Gas Emissions from Hydrogen Production in U.S. Steam Methane Reforming Facilities," Environmental Science & Technology 3(12): 7103–7113. (https://greet.es.anl.gov/publication-cap_ghg_h2_smr)

Technical Memo: P. Sun and A Elgowainy, "2019 GREET Update for Hydrogen Production from SMR Process." (https://greet.es.anl.gov/publication-smr_h2_2019)

2.4. Electricity and Electric Vehicles

2.4.1. Electricity Mix

Uisung Lee (ulee@anl.gov)

We updated the projection of U.S. regional electricity grid mixes through 2050 based on the Annual Energy Outlook (AEO) by the U.S. Energy Information Administration (EIA 2019a). The projection include eight North American Electric Reliability Corporation (NERC) regions: Florida Reliability Coordinating Council (FRCC), Midwest Reliability Organization (MRO), Northeast Power Coordinating Council (NPCC), Reliability First Corporation (RFC), SERC Reliability Corporation (SERC), Southwest Power Pool (SPP), Texas Reliability Entity (TRE), and Western Electricity Coordinating Council (WECC). For California, sub-NERC region data were used to update the California electricity grid mix. Since Alaska and Hawaii are not covered by NERC, we used EIA's 2017 state-level electricity generation data, which do not have projections. All the updated regional electricity grid mixes in GREET 2019 are presented in Table A-1 of the Appendix.

2.4.2. Fuel Economy Expansion and Updates for Medium- and Heavy-Duty Vehicles

Xinyu Liu (xinyu.liu@anl.gov) and Amgad Elgowainy (aelgowainy@anl.gov)

The fuel economy values for various classes of medium- and heavy-duty vehicles were updated in GREET 2019 using the most recent simulation results from Autonomie.[a] The baseline diesel internal combustion engine vehicle (ICEV) fuel economy values were updated. GREET 2019 was expanded to include the fuel economy ratios between battery electric vehicles (BEVs) and corresponding baseline diesel trucks. These ratios were also updated for fuel cell electric vehicles (FCEVs). Tables 1 and 2 list the classes of vehicles that were updated in GREET 2019 for model years 2017 and 2020.

Table 1. Updated Fuel Economy for Battery Electric Vehicles

Class	Type	Weighting Factors of Different Cycles (%)			Diesel Truck (MPDGE)		BEV/ICEV Ratio	
		ARB cycle	55 MPH cycle	65 MPH cycle	MY 2017	MY 2020	MY 2017	MY 2020
8	Long-haul combination truck	5	9	86	6.2	6.8	1.72	1.73
8	Short-haul combination truck	19	17	64	5.8	6.2	1.93	1.92
8	Heavy heavy-duty vocational truck	90	10	0	5.4	5.5	3.50	3.64
8	Refuse truck	90	10	0	4.6	4.6	3.79	3.79
6	Medium heavy-duty vocational truck	92	8	0	7.0	7.2	4.13	4.29
4	Light heavy-duty vocational truck	92	8	0	8.6	9.1	4.88	5.06
2	Pick-up trucks and vans	54	29	17	14.3	14.3	3.85	3.85

MPDGE: mile per diesel gallon equivalent
ARB: Air Resources Board
MY: Model Year
MPH: mile per hour

[a] https://www.autonomie.net/

Table 2. Updated Fuel Economy for Fuel Cell Electric Vehicles

Class	Type	Weighting Factors of Different Cycles (%)			Diesel Truck (MPDGE)		FCEV/ICEV Ratio	
		ARB cycle	55 MPH cycle	65 MPH cycle	MY 2017	MY 2020	MY 2017	MY 2020
8	Heavy heavy-duty vocational truck	90	10	0	5.4	5.5	1.97	2.06
8	Refuse truck	90	10	0	4.6	4.6	1.84	1.84
6	Medium heavy-duty vocational truck	92	8	0	7.0	7.2	2.19	2.36
4	Light heavy-duty vocational truck	92	8	0	8.6	9.1	2.61	2.73
2	Pick-up trucks and vans	54	29	17	14.3	14.3	2.09	2.09

2.4.3. Regionalization of Battery LCA

Jarod Kelly (jckelly@anl.gov), Qiang Dai (qdai@anl.gov), and Michael Wang (mqwang@anl.gov)

We examined the globally regional production of lithium-ion batteries (LIB) with lithium nickel manganese cobalt oxide (NMC) cathodes focused on $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$ (NMC111) to understand the impact of different production and sourcing locations on energy demands and pollutant emissions. We found that 27-kWh automotive NMC111 LIBs produced via a European-dominant supply chain would generate 65 kg CO_2e/kWh, while those from a Chinese-dominant supply chain would generate 100 kg CO_2e/kWh. We also noted significant regional differences for LIB-associated local pollutants. We updated GREET's material and battery production pathways with a focus on a number of specific battery constituents and processes, including the electrical grid compositions for aluminum smelting, nickel mining and refining, cobalt sulfate production, NMC111 cathode powder production, battery management system production, and battery assembly. These modifications were made to achieve consistency with the research conducted in these areas, and to allow users to easily modify NMC111 parameters to determine LIB production impacts.

Publication: Kelly, J.C., Q. Dai, and M. Wang, 2019, "Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries," Mitigation and Adaptation Strategies for Global Change, pp. 1–26. (https://doi.org/10.1007/s11027-019-09869-2)

2.4.4. Battery Recycling

Qiang Dai (qdai@anl.gov) and Olumide Winjobi (owinjobi@anl.gov)

In GREET 2019, we replaced the intermediate physical pathway for battery recycling with a hydrometallurgical pathway based on inorganic acid leaching, and updated the materials and energy flows for all battery recycling pathways based on industry and literature reports. GREET 2019 includes four pathways for recycling batteries at the cell level: (1) a pyrometallurgical pathway; (2) a hydrometallurgical pathway based on inorganic acid leaching, both of which represent commercial-scale operation; (3) a hydrometallurgical pathway based on organic acid leaching; and (4) a direct recycling pathway, both of which represent bench-scale operation. Other updates were also made in GREET 2019 to enable the use of recycled nickel and cobalt salts for cathode material production.

Technical Memo: Q. Dai and O. Winjobi, 2019, "Updates for Battery Recycling and Materials in GREET 2019."
(https://greet.es.anl.gov/publication-battery_recycling_materials_2019)

2.4.5. Materials Requirements for Lithium-Ion Batteries

Qiang Dai (qdai@anl.gov) and Olumide Winjobi (owinjobi@anl.gov)

In GREET 2019, we (1) corrected the material requirements for nickel sulfate production, (2) updated the life cycle inventory for lithium hydroxide production to better represent the industrial practice, and (3) updated the water consumption for limestone mining based on recent industry data.

Technical Memo: Q. Dai and O. Winjobi, 2019, "Updates for Battery Recycling and Materials in GREET 2019."
(https://greet.es.anl.gov/publication-battery_recycling_materials_2019)

3. OTHER UPDATES AND ADDITIONS

3.1. Marine Fuels

Troy R. Hawkins (thawkins@anl.gov) and Uisung Lee (ulee@anl.gov)

In GREET 2019, the marine module underwent significant revisions to improve usability and to expand marine fuel pathways by adding low-sulfur versions of conventional fuels, liquefied natural gas, and marine biofuels. The production of low-sulfur conventional fuels was approximated assuming sulfur removal at the refinery through an additional hydrotreating process. The liquefied natural gas (LNG) pathway draws on the updated natural gas supply chain described in another section of this report, and a study by Thomson and colleagues (2015) on the use of natural gas as a ship fuel. The new marine biofuel pathways were developed through collaboration with the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory (PNNL), which modeled the conversion process and performed techno-economic assessment. The new marine fuel pathways will be described in a forthcoming journal article.

Publication: in preparation.
(https://greet.es.anl.gov/publication-marine_2019)

3.2. Cement and Concrete

Troy R. Hawkins (thawkins@anl.gov) and Pingping Sun (psun@anl.gov)

In GREET 2019, the inventories for cement and concrete were replaced with inventories based on new process unit datasets for cement production, gypsum quarrying, clay quarrying, sand and gravel quarrying, and ready-mix facility operations. These new inventories replace those in GREET 2018 using data from the U.S. Life Cycle Inventory and mix ratios reported in the literature. The new inventories were created using facility-level data from the EPA NEI and GHGRP databases, together with production capacities, utilization rates, and other facility-specific technology details from the Portland Cement Association and the USGS *Minerals Yearbook*. Point-source emissions from upstream quarries and wet-mix concrete batch plants were aggregated and evaluated on a national level, along with additional impacts associated with off-road fuel consumption and other non-point source emissions. The new developments will be published in a forthcoming journal article (Hottle et al. 2019).

Publication: Troy Hottle, Troy R. Hawkins, Caitlin Chiquelin, Bryan Lange, Ben Young, Pingping Sun, Michael Wang. Environmental Life Cycle Assessment of U.S. Concrete. 2019 (in preparation)

(https://greet.es.anl.gov/publication-cement_concrete_2019)

3.3. Methane Leakage of Natural Gas Supply Chain

Andrew Burnham (aburnham@anl.gov) and Yu Gan (ygan@anl.gov)

We updated methane (CH_4) emissions from the natural gas supply chain in GREET 2019 based on new published data. Default CH_4 emissions were updated based on the 2019 EPA Greenhouse Gas Emission Inventory (EPA 2019). In addition, we updated the optional CH_4 emissions data from Alvarez et al. (2018) for GREET 2019, which is referred to as EDF 2019 (Environmental Defense Fund).

Technical memo: A. Burnham, 2019, "Updated Natural Gas Pathways in the GREET1_2019 Model."
(https://greet.es.anl.gov/publication-update_ng_2019)

3.4. Crude Oil Mix

Uisung Lee (ulee@anl.gov) and Hao Cai (hcai@anl.gov)

The properties and carbon intensities of crude oil vary by region and influence the life-cycle energy use and emissions of various energy products. We updated the regional share of U.S. crude oil supply in GREET 2019, based on EIA's Annual Energy Outlook (AEO) projection (EIA 2019a). In GREET, there are six regions for conventional crude oil sources: the United States, Canada, Mexico, the Middle East, Latin America, and Africa. Canadian crude is differentiated as Canadian oil sands.

The projection of domestic U.S. crude oil production share through 2050 was adopted from the EIA's AEO. The projection shows a high domestic production share, up to 82–84% for 2025–2035. For the crude import shares, we assumed that the split among regional crude oil imports remain the same through 2050. Crude oil import shares are allocated based on EIA's company-level import data in 2018 (EIA 2019b). Table B-1 in the Appendix shows the projected regional crude oil shares in the United States through 2050. The shares of shale oil production in Eagle Ford and Bakken out of total U.S. domestic crude oil production in 2018 were estimated at 11.0% and 11.7%, respectively, according to EIA statistics (EIA 2019c, d).

To estimate the weighted average transportation distance of imported crude oil, company-level import data were used (EIA 2018c). We used the distance between the importing state and the origin country for each imported crude oil product, and calculated the weighted average distances for each mode of transportation, as described in Lee et al. (2016). The weighted average distances for importing crude oil are estimated at 8,707 miles for offshore countries by ocean tanker, and 1,672 miles for Canada and Mexico by pipeline.

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EPA (U.S. Environmental Protection Agency), 2019, "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2017," EPA 430-R-19-001, EPA, Washington, D.C.

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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										
2017	0.51%	30.60%	31.04%	20.85%	0.36%	7.83%	0.41%	6.57%	1.37%	0.46%
2018	0.41%	33.44%	28.96%	20.31%	0.34%	7.11%	0.41%	6.85%	1.67%	0.49%
2020	0.39%	35.37%	25.89%	19.56%	0.36%	7.32%	0.43%	8.00%	2.18%	0.50%
2025	0.26%	37.31%	24.21%	16.21%	0.35%	7.47%	0.60%	8.78%	4.29%	0.51%
2030	0.22%	37.73%	23.57%	15.60%	0.35%	7.24%	0.85%	8.67%	5.23%	0.52%
2035	0.20%	39.40%	21.55%	15.04%	0.34%	7.02%	1.11%	8.52%	6.28%	0.55%
2040	0.18%	38.95%	20.63%	14.65%	0.34%	6.77%	1.24%	8.41%	8.26%	0.58%
2045	0.14%	39.17%	19.80%	14.25%	0.33%	6.54%	1.29%	8.44%	9.41%	0.65%
2050	0.14%	38.33%	19.10%	13.80%	0.34%	6.26%	1.35%	8.74%	11.23%	0.71%
Texas Reliability Entity (TRE) Mix										
2017	0.02%	40.56%	33.10%	11.10%	0.02%	0.55%	0.00%	13.97%	0.54%	0.14%
2018	0.10%	49.42%	24.28%	10.72%	0.03%	0.24%	0.00%	14.31%	0.77%	0.14%
2020	0.09%	49.66%	19.54%	10.37%	0.03%	0.24%	0.00%	15.96%	3.92%	0.21%
2025	0.08%	51.56%	18.13%	9.88%	0.03%	0.24%	0.00%	15.64%	4.23%	0.22%
2030	0.07%	55.21%	15.57%	9.54%	0.02%	0.23%	0.00%	15.02%	4.10%	0.24%
2035	0.06%	59.22%	12.42%	9.25%	0.02%	0.22%	0.00%	14.42%	4.09%	0.30%
2040	0.06%	59.70%	12.83%	8.97%	0.02%	0.21%	0.00%	13.83%	4.00%	0.37%
2045	0.06%	61.00%	12.35%	8.68%	0.02%	0.20%	0.00%	13.24%	3.99%	0.46%
2050	0.05%	56.16%	11.79%	8.39%	0.02%	0.19%	0.00%	12.66%	10.18%	0.55%
Florida Reliability Coordinating Council (FRCC) Mix										
2017	0.65%	68.67%	15.39%	13.04%	0.28%	0.65%	0.00%	0.00%	0.35%	0.96%
2018	0.18%	67.32%	16.56%	13.00%	0.35%	0.67%	0.00%	0.00%	0.84%	1.08%
2020	0.16%	71.72%	12.01%	12.69%	0.26%	0.66%	0.00%	0.00%	1.40%	1.09%
2025	0.18%	59.32%	17.20%	12.52%	0.26%	0.65%	0.00%	0.00%	8.79%	1.08%
2030	0.10%	59.88%	17.12%	12.09%	0.25%	0.63%	0.00%	0.00%	8.88%	1.05%
2035	0.09%	60.12%	15.84%	11.48%	0.24%	0.60%	0.00%	0.00%	10.62%	1.02%
2040	0.09%	52.08%	14.74%	10.72%	0.22%	0.56%	0.00%	0.00%	20.61%	0.98%
2045	0.09%	52.73%	14.22%	10.36%	0.21%	0.54%	0.00%	0.00%	20.88%	0.97%
2050	0.10%	54.04%	13.51%	9.85%	0.20%	0.51%	0.00%	0.00%	20.79%	1.00%

TABLE A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Midwest Reliability Organization (MRO) Mix										
2017	0.14%	6.72%	50.56%	11.53%	0.45%	6.39%	0.00%	23.33%	0.42%	0.45%
2018	0.26%	10.30%	47.71%	10.60%	0.42%	4.93%	0.00%	24.86%	0.57%	0.34%
2020	0.25%	8.82%	44.14%	10.21%	0.38%	5.01%	0.00%	30.28%	0.58%	0.34%
2025	0.25%	9.33%	46.57%	3.31%	0.37%	5.03%	0.00%	34.25%	0.52%	0.35%
2030	0.25%	9.37%	47.10%	3.27%	0.37%	4.96%	0.00%	33.77%	0.52%	0.39%
2035	0.26%	9.23%	47.44%	3.32%	0.36%	4.92%	0.00%	33.53%	0.51%	0.42%
2040	0.25%	9.45%	47.15%	3.36%	0.37%	4.86%	0.00%	33.15%	0.95%	0.46%
2045	0.25%	9.58%	46.18%	3.35%	0.38%	4.74%	0.00%	33.19%	1.81%	0.51%
2050	0.23%	9.72%	43.05%	3.22%	0.36%	4.45%	0.00%	36.67%	1.75%	0.55%
Northeast Power Coordinating Council (NPCC) Mix										
2017	0.55%	43.09%	0.97%	31.75%	1.86%	16.56%	0.00%	3.26%	0.53%	1.45%
2018	0.27%	41.96%	2.68%	32.59%	1.56%	15.05%	0.00%	3.31%	0.83%	1.77%
2020	0.28%	43.73%	2.42%	29.52%	1.65%	15.80%	0.00%	3.93%	0.86%	1.81%
2025	0.19%	48.16%	2.06%	23.47%	1.68%	16.45%	0.00%	4.03%	2.17%	1.79%
2030	0.15%	46.06%	1.04%	23.86%	1.72%	16.70%	0.00%	5.02%	3.61%	1.84%
2035	0.06%	49.81%	1.75%	19.17%	1.74%	16.84%	0.00%	5.06%	3.67%	1.90%
2040	0.04%	50.46%	1.57%	19.01%	1.71%	16.55%	0.00%	5.13%	3.61%	1.92%
2045	0.04%	50.88%	1.69%	18.81%	1.68%	16.22%	0.00%	5.13%	3.53%	2.02%
2050	0.04%	51.64%	1.50%	18.29%	1.65%	15.76%	0.00%	5.60%	3.41%	2.11%
Reliability First Corporation (RFC) Mix										
2017	0.28%	23.10%	38.89%	32.34%	0.13%	1.33%	0.00%	3.06%	0.25%	0.62%
2018	0.16%	26.11%	38.61%	30.04%	0.06%	1.22%	0.00%	2.88%	0.29%	0.63%
2020	0.14%	31.49%	34.30%	28.30%	0.06%	1.26%	0.00%	3.51%	0.30%	0.64%
2025	0.12%	41.51%	28.91%	23.63%	0.06%	1.28%	0.00%	3.62%	0.26%	0.62%
2030	0.12%	41.19%	29.47%	23.42%	0.06%	1.27%	0.00%	3.59%	0.25%	0.62%
2035	0.12%	43.49%	27.71%	23.01%	0.05%	1.24%	0.00%	3.51%	0.25%	0.63%
2040	0.11%	44.36%	27.07%	22.75%	0.08%	1.22%	0.00%	3.51%	0.25%	0.65%
2045	0.11%	45.41%	26.43%	22.34%	0.07%	1.19%	0.00%	3.52%	0.26%	0.68%
2050	0.11%	45.87%	26.04%	22.16%	0.11%	1.17%	0.00%	3.55%	0.26%	0.73%

TABLE A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
SERC Reliability Corporation (SERC) Mix										
2017	0.31%	32.47%	33.80%	28.51%	0.35%	3.01%	0.00%	0.57%	0.77%	0.23%
2018	0.22%	35.36%	30.73%	28.48%	0.43%	2.86%	0.00%	0.65%	1.01%	0.26%
2020	0.21%	37.23%	28.18%	28.52%	0.53%	2.97%	0.00%	0.91%	1.20%	0.26%
2025	0.18%	39.19%	25.67%	24.54%	0.51%	3.02%	0.00%	0.95%	5.69%	0.25%
2030	0.11%	41.28%	25.10%	23.38%	0.48%	2.87%	0.00%	0.90%	5.64%	0.24%
2035	0.10%	41.69%	22.39%	22.79%	0.48%	2.79%	0.00%	0.88%	8.65%	0.24%
2040	0.09%	41.10%	21.07%	21.98%	0.46%	2.67%	0.00%	0.87%	11.52%	0.24%
2045	0.08%	39.95%	19.73%	21.06%	0.43%	2.53%	0.00%	0.86%	15.09%	0.26%
2050	0.08%	39.14%	18.79%	20.16%	0.41%	2.33%	0.00%	0.89%	17.91%	0.30%
Southwest Power Pool (SPP) Mix										
2017	1.33%	23.89%	38.11%	4.83%	0.00%	2.48%	0.00%	28.95%	0.36%	0.05%
2018	1.67%	28.82%	34.11%	3.83%	0.00%	3.34%	0.00%	27.84%	0.33%	0.04%
2020	1.64%	26.43%	33.05%	3.74%	0.00%	3.39%	0.00%	31.39%	0.32%	0.04%
2025	0.15%	21.65%	37.58%	0.00%	0.00%	3.56%	0.00%	34.89%	2.14%	0.04%
2030	0.15%	17.10%	36.53%	0.00%	0.00%	3.47%	0.00%	34.10%	8.61%	0.04%
2035	0.13%	20.24%	32.68%	0.00%	0.00%	3.32%	0.00%	32.57%	11.02%	0.04%
2040	0.12%	20.60%	28.83%	0.00%	0.00%	3.09%	0.00%	31.08%	16.24%	0.04%
2045	0.11%	19.20%	27.49%	0.00%	0.00%	2.90%	0.00%	32.40%	17.83%	0.06%
2050	0.11%	15.88%	26.91%	0.00%	0.00%	2.58%	0.00%	31.49%	22.96%	0.07%
Western Electricity Coordinating Council (WECC) Mix										
2017	0.11%	22.93%	21.61%	4.78%	0.49%	34.15%	2.10%	8.47%	4.84%	0.52%
2018	0.16%	24.51%	19.00%	5.13%	0.50%	32.94%	2.10%	9.20%	5.93%	0.53%
2020	0.16%	23.09%	18.24%	5.03%	0.49%	33.76%	2.19%	10.10%	6.40%	0.54%
2025	0.15%	20.46%	15.39%	3.31%	0.49%	34.77%	3.33%	12.52%	9.04%	0.54%
2030	0.12%	24.59%	15.11%	5.61%	0.46%	27.03%	4.54%	10.32%	11.70%	0.52%
2035	0.12%	24.60%	14.50%	5.50%	0.45%	26.18%	6.09%	10.53%	11.41%	0.62%
2040	0.11%	25.14%	13.67%	5.24%	0.44%	24.79%	6.77%	10.68%	12.44%	0.72%
2045	0.11%	26.22%	12.13%	5.20%	0.43%	24.45%	7.15%	11.02%	12.43%	0.87%
2050	0.10%	24.79%	12.11%	5.15%	0.48%	23.92%	7.64%	11.97%	12.80%	1.04%

TABLE A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
					California Mix					
2017	0.03%	39.00%	4.39%	9.36%	1.09%	21.90%	4.56%	6.93%	11.69%	1.05%
2018	0.01%	40.91%	2.11%	9.60%	1.08%	19.19%	4.48%	7.47%	14.14%	1.01%
2020	0.01%	39.90%	1.65%	9.39%	1.08%	19.50%	4.54%	7.65%	15.27%	1.01%
2025	0.00%	33.40%	0.00%	4.90%	1.13%	21.28%	7.38%	8.19%	22.61%	1.11%
2030	0.00%	23.26%	0.00%	0.00%	1.19%	19.85%	11.77%	9.40%	33.35%	1.19%
2035	0.00%	20.63%	0.00%	0.00%	1.13%	18.27%	16.31%	10.43%	32.04%	1.18%
2040	0.00%	17.23%	0.00%	0.00%	1.08%	16.28%	18.00%	11.59%	34.73%	1.09%
2045	0.00%	16.94%	0.00%	0.00%	1.04%	15.88%	19.10%	11.94%	34.02%	1.07%
2050	0.00%	17.30%	0.00%	0.00%	1.22%	15.35%	20.12%	11.68%	33.23%	1.10%
					Alaska Mix					
2017	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2018	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2020	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2025	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2030	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2035	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2040	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2045	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
2050	13.55%	49.79%	8.55%	0.00%	0.67%	25.26%	0.00%	2.18%	0.00%	0.00%
					Hawaii Mix					
2017	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2018	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2020	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2025	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2030	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2035	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2040	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2045	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%
2050	67.61%	0.00%	14.02%	0.00%	2.98%	0.67%	3.29%	5.42%	1.77%	4.23%

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 (Conv. Crude)	Mexico	Middle East	Latin America	Africa	Others
2018	64.4%	8.0%	9.0%	3.1%	6.8%	5.2%	2.2%	1.4%
2020	73.9%	5.9%	6.6%	2.2%	5.0%	3.8%	1.6%	1.0%
2025	82.1%	4.0%	4.5%	1.5%	3.4%	2.6%	1.1%	0.7%
2030	84.2%	3.6%	4.0%	1.4%	3.0%	2.3%	1.0%	0.6%
2035	83.9%	3.6%	4.1%	1.4%	3.1%	2.4%	1.0%	0.6%
2050	69.1%	6.9%	7.8%	2.6%	5.9%	4.5%	1.9%	1.2%

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439

www.anl.gov