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Summary of Expansions and Updates in GREET® 2020

Energy Systems Division

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Summary of Expansions and Updates in GREET® 2020

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1 INTRODUCTION

The GREET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model has been developed by Argonne National Laboratory 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. Argonne has expanded and updated the model in various sectors in GREET 2020, and this report provides a summary of the release.

2 MAJOR EXPANSIONS AND UPDATES IN GREET 2020

2.1 CO_2 UTILIZATION (E-FUELS) AND CARBON CAPTURE AND SEQUESTRATION (CCS)

Carbon dioxide (CO_2) utilization technologies convert waste CO_2 into fuels and products, which can help reduce their life-cycle greenhouse gas (GHG) emissions. Argonne has been examining LCA and techno-economic analysis (TEA) of electro-fuels (e-fuels) from CO_2 and hydrogen based on renewable and low-carbon electricity. In GREET 2020, we add a new "E-fuel" tab that covers several e-fuel production pathways. Users can evaluate the impacts on energy use, water consumption, and emissions of e-fuel production pathways using different hydrogen (H_2) and electricity sources. Further, we implemented a CCS option for capturing and sequestering fermentation CO_2 in corn ethanol plants in the EtOH tab.

2.1.1 CO_2-derived Ethanol

Uisung Lee (ulee@anl.gov), Troy R. Hawkins (thawkins@anl.gov), Eunji Yoo (eyoo@anl.gov)

We evaluated life-cycle greenhouse gas (GHG) emissions of ethanol produced from CO_2 of corn ethanol plants via gas fermentation and electrochemical reduction processes. We add this pathway in the E-fuel tab. The major parameters affecting LCA results of this pathway are H_2 demand and electricity sources. There are three design cases with respect to H_2 and CO ratios for e-fuel ethanol production. The results show that these e-fuel ethanol cases have potentials to produce near-zero GHG emissions with wind electricity for H_2 production and process energy use.

Forthcoming publication:

- Lee, U., T. Hawkins, E. Yoo, M. Wang, Z. Huang, and L. Tao. "Using Waste CO_2 from Corn Ethanol Biorefineries for Additional Ethanol Production: Life Cycle Analysis" (under revision).

2.1.2 CO_2-derived FT Fuels and Methanol

Adarsh Bafana (abafana@anl.gov), Guiyan Zang (gzang@anl.gov), Pingping Sun (psun@anl.gov), Amgad Elgowainy (aelgowainy@anl.gov)

We add two e-fuel pathways with Fischer-Tropsch (FT) synthesis process and two e-fuel pathways for methanol (MeOH) production using CO_2 (from corn ethanol plants) and renewable H_2. The material and energy inputs were estimated through process modeling using Aspen Plus models with two different system designs: a fuel production system with H_2 recycle and without H_2 recycle. For the former, after one-pass conversion, the outflow gas is separated to purify H_2 that is recycled as feedstock to reduce the system energy input, while the remaining gases (mainly CO and some lesser amount of C1-C4 gases) are combusted to generate the electricity and heat needed by the conversion process. For the latter, the outflow gas is not separated and all gases are combusted for process energy supply, while surplus electricity generated is exported. Additionally, stand-alone e-fuel production design and integrated design to produce corn ethanol and e-fuel together were incorporated. For H_2 sources, several renewable H_2 production options with water electrolysis were modeled, including low-temperature electrolysis using electricity from solar/wind and nuclear power, as well as high-temperature electrolysis using solid oxide electrolysis cell (SOEC). The energy efficiency and carbon conversion efficiency of e-fuel production from H_2 and CO_2 were evaluated using Aspen models with detailed information shown in two forthcoming publications. The e-fuel (FT) fuel specifications (calculated from Aspen modeling) have also been incorporated in GREET 2020.

Forthcoming publications:

- Zang, G., P. Sun, A. Elgowainy, A. Bafana, and M. Wang, "Life-Cycle Analysis of Electro-fuels: Fischer-Tropsch Fuel Production from Hydrogen and Corn Ethanol By-product CO_2" (under review).
- Zang, G., P. Sun, A. Elgowainy, A. Bafana, and M. Wang, "Techno-Economic and Life Cycle Analysis of Synthetic Methanol Production from Hydrogen and Industry By-product CO_2" (under review).

2.1.3 Corn Ethanol Carbon Capture and Sequestration (CCS)

Uisung Lee (ulee@anl.gov), Michael Wang (mwang@anl.gov)

In corn ethanol plants, CO_2 from the fermentation process can be captured and sequestrated to reduce the carbon intensities of ethanol. In collaboration with Lawrence Livermore National Laboratory (LLNL) and University of California, Berkeley, we have evaluated the amount of CO_2 that can be captured and sequestrated from the corn ethanol plant fermentation process and the amount of electricity required to do so. This option is implemented in the EtOH tab; one can select it to evaluate the impact of CCS in corn ethanol GHG emissions.

The amount of CO_2 from corn starch fermentation is estimated using the carbon balance approach. Along with the information already in GREET, we have supplemented the carbon contents of corn (45%) (Ma and Dwyer 2001; Tenesaca 2014), DDGS (49%) (Giuntoli et al. 2009; Imam and Gordon 2002), corn gluten meal (CGM) (49%), and corn oil (76%) (Baughman and Jamieson 1921) provided by LLNL and UC Berkeley to track all carbon inputs and outputs in corn biorefineries. We assumed corn gluten feed (CGF) has the same carbon content with CGM. Table 1 presents the carbon inputs and outputs from 1 tonne of corn input. Fermentation CO_2 emissions per gallon of ethanol produced are estimated at 2.24, 2.14, and 1.21 for dry milling without corn oil extraction, dry milling with corn oil extraction, and wet milling, respectively.

Table 1 Carbon balance of corn ethanol plants from 1 tonne corn (unit: kg carbon)

		Dry Milling without Corn Oil Extraction	Dry Milling with Corn Oil Extraction	Wet Milling
Input	Corn	386 (100%)	386 (100%)	386 (100%)
Output	Ethanol	176 (46%)	177 (46%)	164 (43%)
	DDGS	141 (37%)	135 (35%)	
	CGF/CGM			152 (39%)
	Corn oil		7 (2%)	35 (9%)
	Carbon in fermentation CO_2	**69 (18%)**	**66 (17%)**	**35 (9%)**
	kg CO_2/kg EtOH	**0.75**	**0.72**	**0.41**
	kg CO_2/gal EtOH	**2.24**	**2.14**	**1.21**

From our communication with industry, we found that 97 to 98% of fermentation CO_2 can be captured/sequestrated and that electricity requirement to capture and pressurize CO_2 for sequestration is estimated at 175–200 kWh/ton CO_2. In GREET 2020, we use the electricity requirement of 180 kWh/ton CO_2 (Red Trail Energy 2019) with a capture rate of 97.5%. For CO_2 used in a nearby facility, the electricity requirement is estimated at 100 kWh/ton CO_2.

2.2 BIOFUELS AND BIOPRODUCTS

2.2.1 The Supply Chain Sustainability Analysis (SCSA): Indirect Liquefaction (IDL), Catalytic Fast Pyrolysis (CFP), Biochem, Algae Hydrothermal Liquefaction (HTL)/Combined Algae Processing (CAP) Updates

Hao Cai (hcai@anl.gov) and Longwen Ou (oul@anl.gov)

We include the supply chain sustainability analysis (SCSA) results of the 2019 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 consumption and environmental sustainability hotspots that could be mitigated through improved process materials and energy conversion efficiencies. The SCSA results provide guidance to 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 individual biofuel pathways that undergo continuous development.

In GREET 2020, we add detailed material and energy balances, as well as SCSA results, of the 2019 SOT cases of (1) renewable high octane gasoline via 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 HTL of wet sludge from a wastewater treatment plant (in the RNG tab); (4) renewable hydrocarbon fuels via biochemical conversion of herbaceous lignocellulosic biomass (in the IBR tab); (5) renewable diesel via hydrothermal liquefaction of a blend of algae and woody biomass (in the algae tab); and (6) renewable diesel via combined algae processing (in the algae tab).

Technical report:

- Cai, H., L. Ou, M. Wang, E. Tan, R. Davis, A. Dutta, L. Tao, D. Hartley, M. Roni, D. Thompson, L. Snowden-Swan, and Y. Zhu, "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 2019 State-of-Technology Cases." Argonne National Laboratory. Technical Report. ANL/ESD-20/2. 2020.

2.2.2 Woody Feedstocks

Hao Cai (hcai@anl.gov), Longwen Ou (oul@anl.gov), and Hoyoung Kwon (hkwon@anl.gov)

We have made updates to the "Woody" tab to incorporate the latest parametric assumptions for temporal effects and variability of pine biomass growth. First, we include pine biomass growth curves modeled for three growth scenarios that reflect the impacts of different growth conditions and forest management practices. The three pine biomass growth scenarios are (1) low productivity without precommercial thinning, (2) high productivity without precommercial thinning, and (3) high productivity with precommercial thinning. Second, we update a few parameters related to pine farming and residue collection, including the carbon content of pine, mass fraction of pine residues, and diesel usage in farming activities (site preparation, thinning, collection, harvesting, and fertilizer and herbicide application, etc.).

Publication:

- Lan, K., L. Ou, S. Park, S. Kelley, P. Nepal, J. Kwon, H. Cai, and Y. Yao, "Dynamic Life Cycle Carbon Analysis for Fast Pyrolysis Biofuel Produced from Pine Residues: Examine Carbon-Neutral Assumption for Woody Biomass" (under review).

2.2.3 Delivery of High-Purity CO_2 for Algae Growth

Longwen Ou (oul@anl.gov) and Hao Cai (hcai@anl.gov)

Energy consumption for the compression and delivery of high-purity (>95%) CO_2 from natural gas steam methane reforming, ammonia manufacturing facilities, and corn ethanol plants are added to the "Algae" tab. The industrial high-purity CO_2 is compressed to a supercritical state and transported to an algae farm through a pipeline. Energy consumption of CO_2 compression is 100 kWh/ton CO_2. No energy is required for pipeline transportation of supercritical CO_2 over a short transportation distance (< 150 km) since recompression is not required.

Publication:

- Ou, L., S. Banerjee, H. Xu, A. Coleman, H. Cai, and U. Lee, M. Wigmosta, T. Hawkins, "Utilizing High-purity CO_2 Sources for Algae Cultivation and Biofuel Production in the United States: Opportunities and Challenges." (in preparation)

2.2.4 PFAD to Renewable Diesel

Hui Xu (hui.xu@anl.gov), Uisung Lee (ulee@anl.gov), and Michael Wang (mwang@anl.gov)

We add a pathway of palm fatty acid distillate (PFAD) to renewable diesel (RD) to the "BioOil" tab. Life-cycle fossil energy use and GHG emissions for renewable diesel were quantified, taking into consideration different feedstock classifications that are applicable to PFAD (residue, by-product, or co-product), and incorporating updated data for key processes. A physical refining process for crude palm oil, which separates PFAD from refined palm oil, is added to GREET 2020. If PFAD is classified as a co-product, it shares upstream burdens associated with palm plantation and palm oil production. In this release, we update farming-related data using statistical data from literature review and official statistics released by the governments of Malaysia and Indonesia. If PFAD is treated as residue or by-product, it does not share upstream emissions related to farming and crude palm oil production, though PFAD as a by-product shares burdens associated with physical refining of crude palm oil. We assume PFAD collected from Malaysian and Indonesian oil mills is shipped to Singapore for RD conversion. The PFAD to RD conversion process is modeled based on RD production certified by the California Air Resources Board (CARB).

Publication:

- H. Xu, U. Lee, and M. Wang. 2020. "Life-Cycle Energy Use and Greenhouse Gas Emissions of Palm Fatty Acid Distillate Derived Renewable Diesel," *Renewable and Sustainable Energy Reviews*, 134, 110144. https://doi.org/10.1016/j.rser.2020.110144

2.2.5 New Pathways for Co-Optimized Fuels and Engines

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

We add four pathways for fuels for use in engines co-optimized with drop-in biofuel blends to improve engine performance. Two of the pathways produce isobutanol and aromatic rich hydrocarbons (ARHC) as two bio-blendstocks. Blended with a petroleum gasoline blendstock, these bio-blendstocks are designed to improve engine efficiency for light-duty, boosted-spark ignition (BSI) engines. The other two pathways produce bio-blendstocks capable of reducing engine-out emissions for mixing-controlled compression ignition (MCCI) engines in heavy-duty vehicles. These MCCI fuels are both diesel-like bio-blendstocks blended with conventional diesel.

The full LCA of the isobutanol and ARHC bio-blendstock pathways were originally published by Cai et al. (2018), including process design, technoeconomic analysis (TEA), and LCA. Two production cases for both BSI bio-blendstocks were presented – a state-of-technology (SOT) case reflecting current status of technology development and a target case that reflects technology advancements required to meet cost, sustainability, and performance targets. For GREET implementation, we focused on the target case, which is in the timeline of rolling out the Co-Optima technologies to the market, i.e., starting 2025. The new isobutanol production pathway is added to the GREET Integrated Biorefinery module (IBR tab). The ARHC pathway is added to the GREET Pyrolysis Indirect Liquefaction module (Pyrolysis_IDL tab). New light-duty vehicles with co-optimized BSI engines, i.e., Co-Optima Vehicle - Boosted Spark Ignition (BSI), Isobutanol and Co-Optima Vehicle - Boosted Spark Ignition (BSI), ARHC, are added to GREET. Due to limited fuel property data for ARHC, fuel properties (i.e., density, lower heating value, sulfur content, carbon content) of renewable gasoline were used as a proxy for ARHC in GREET 2020.

The production pathways for the MCCI diesel bioblendstocks are described by Cai et al. (2020). The first pathway is conversion of wastewater sludge via hydrothermal liquefaction (HTL) to produce biocrude, followed by catalytic hydrotreating to upgrade the biocrude to the diesel bioblendstock. The pathway is added to the renewable natural gas module in GREET (RNG tab). The second pathway is conversion of the oil from saltwater-grown algal biomass via hydrogenation to upgrade to the diesel bioblendstock. This pathway is added to the algae module in GREET 2020 (Algae tab). Both SOT and target cases are available for HTL from wastewater sludge while the second algae pathway is parameterized based on their 2019 state of technology (SOT) performance given lack of a target case for this pathway. Additional details for these pathways are provided in Section 2.2.1.

In this GREET update, we consider the 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 with 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 selective catalytic reduction (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.

Publications:

- Cai, H, J. Markham, S. Jones, P.T. Benavides, J. Dunn, M. Biddy, L. Tao, P. Lamers, S. Phillips. 2018. "Techno-Economic Analysis and Life-Cycle Analysis of Two Light-Duty Bioblendstocks: Isobutanol and Aromatic-Rich Hydrocarbons." *ACS Sustainable Chem. Eng.*, DOI: 10.1021/acssuschemeng.8b01152.
- Ou, L., H. Cai, H.J. Seong, D. Longman, J.B. Dunn, J. Storey, T.J. Toops, J. Pihl, M. Biddy, M. Thornton. 2019. "Co-Optimization of Heavy-Duty Fuels and Engines: Cost Benefit Analysis and Implications." *Environ. Sci. Technol.* 2019, 53, 21, 12904–12913. https://doi.org/10.1021/acs.est.9b03690.
- Dunn, J.B., E. Newes, H. Cai, Y. Zhang, A. Brooker, L. Ou, N. Mundt, A. Bhatt, S. Peterson, M. Biddy. 2020. "Energy, Economic, and Environmental Benefits Assessment

of Co-Optimized Engines and Bio-Blendstocks." *Energy & Environmental Science.* https://doi.org/10.1039/D0EE00716A.
- Cai, H., L. Ou, M. Wang, E. Tan, R. Davis, A. Dutta, L. Tao, D. Hartley, M. Roni, D. Thompson, L. Snowden-swan, and Y. Zhu. 2020. "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 2019 State-of-Technology Cases." ANL/ESD-20-2.

2.2.6 Renewable Natural Gas and Lactic Acid Production from Wet Waste Feedstocks

Uisung Lee (ulee@anl.gov), Troy R. Hawkins (thawkins@anl.gov), Pahola Thathiana Benavides (pbenavides@anl.gov)

We evaluated the life-cycle GHG emissions of renewable natural gas (RNG) and lactic acid (LA) production from four waste feedstocks (wastewater sludge, food waste, swine manure, and fats, oil, and grease [FOG]) via anaerobic digestion (AD) and arrested AD, respectively, in collaboration with National Renewable Energy Laboratory (NREL). The results show that both waste-derived RNG and LA production pathways bring significant GHG emission reduction benefits. In particular, we examine the impact of the combinations of waste feedstocks and conversion technologies (plus, corresponding products) on the carbon intensities of the products. Along with NREL's recent TEA of these pathways (Bhatt and Tao 2020; Bhatt, Ren, and Tao 2020), our LCA shows potential for waste valorization. The new pathways are added to the RNG tab in GREET 2020.

Forthcoming publication:
- Lee, U., A. Bhatt, T.R. Hawkins, L. Tao, P.T. Benavides, and M. Wang. "Life-Cycle Analysis of Renewable Natural Gas and Lactic Acid Production from Waste Feedstocks." (in preparation).

2.2.7 Land Management Change Emissions from Corn Stover Ethanol Pathways

Hoyoung Kwon (hkwon@anl.gov) and Xinyu Liu (xinyu.liu@anl.gov)

Since 2015, the Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB) module has included the calculation of U.S. domestic soil carbon emission factors (EFs) associated with land management change (LMC) scenarios, which include conservation farming options that could be practiced when corn stover is harvested as cellulosic ethanol feedstock.

In the 2020 version of CCLUB, we update the current LMC-driven soil carbon EFs with two modifications of 1) adopting a weighted average based upon county-level corn harvested areas as a U.S. national EF and 2) refining a new baseline for soil carbon stock levels by considering a share of corn planted areas typically treated with animal manure to enhance soil fertility. Accordingly, we revise LMC emissions from corn stover ethanol pathways in GREET 2020 as well.

Additionally, GREET Open-Source Database (https://greet.es.anl.gov/databases) was expanded to include spatio-temporal crop/soil/climate data that have supported U.S. county-level modeling of soil carbon changes in CCLUB. The soil carbon modeling uses a process-based simulation model (i.e., a parameterized CENTURY) along with the data as model inputs and has provided GREET biofuel LCA with the soil carbon sequestration/emission potentials of land use and land management changes resulting from U.S. corn grain and cellulosic feedstock production. More information is available in Liu et al. (2020).

Publications:

- Kwon, H., X. Liu, J.B. Dunn, S. Mueller, M.M. Wander, and M. Wang, 2020. "Carbon Calculator for Land Use Change from Biofuels Production (CCLUB). (ANL/ESD/12-5 Rev. 6). Argonne National Laboratory, Argonne, IL.
- Liu, X., H. Kwon, D. Northrup, and M. Wang, 2020. "Shifting Agricultural Practices to Produce Sustainable, Low Carbon Intensity Feedstocks for Biofuel Production," *Environ. Res. Lett.* 15 084014.

2.2.8 Green Ammonia

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

Conventionally, ammonia is mostly produced from natural gas steam methane reforming, which accounts for approximately 2% of worldwide fossil energy use and 1.2% of the global anthropogenic CO_2 emissions. Therefore, alternative ammonia production pathways from renewable resources and industrial by-products are of increasing interest.

The following low-carbon alternative ammonia production pathways have been implemented in GREET 2020 release. The stoichiometric N_2 and H_2 is compressed and enters the electricity-driven Haber-Bosch synthesis loop to produce ammonia, with high purity N_2 obtained from air separation technologies, namely, cryogenic distillation and pressure swing adsorption; and high purity H_2 produced from various technologies: 1) low-temperature electrolysis; 2) high-temperature electrolysis; 3) as a by-product from chlor-alkali processes; and 4) as a by-product in steam cracker plants. Users can choose between different N_2 and H_2 production technologies. In addition, users can specify the shares between conventional and low-carbon ammonia production pathways to determine the impacts of ammonia production on the downstream activities.

Publication:

- X. Liu, A. Elgowainy, and M. Wang. 2020. "Life-Cycle Energy Use and Greenhouse Gas Emissions of Ammonia Production from Renewable Resources and Industrial By-Products." *Green Chemistry*. https://doi.org/10.1039/D0GC02301A.

2.2.9 Feedstock Carbon Intensity Calculator

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With the support from U.S. Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) program, we developed a transparent and easy-to-use tool for feedstock-specific, farm-level CI calculation of feedstocks: the Feedstock Carbon Intensity Calculator (FD-CIC). The first version of the FD-CIC with GREET 2020 release accounts for user-specific, farm-level input data for corn production, coupled with the life-cycle inventory (LCI) data of key farming inputs from the GREET model. The system boundary of FD-CIC covers the cradle-to-farm-gate activities, including upstream emissions related to farming input manufacturing and feedstock production. The FD-CIC tool helps users to assess the effects of changing farm-level input parameters on corn CI scores in the context of corn ethanol LCA.

Currently, two versions of FD-CIC are available, namely, the dynamic version and the standalone version. The dynamic version interacts with the GREET model (in particular, GREET1, the fuel cycle model of GREET) by directly reading the LCI data of key farming inputs from GREET1. The dynamic version suits well when users want to change the default settings of the GREET1 model as related to farming inputs. The standalone version suits well for users who are not familiar with the GREET1 model and contains the default LCI data for key farming inputs from GREET1. It is worth mentioning that the interacting feature with the dynamic version will work only if users have GREET version 2020 or later and keep the GREET1 Excel file in the same folder with the FD-CIC tool. More detailed information on the tool is provided in the following technical memo.

Technical memo:

- X. Liu, H. Kwon, and M. Wang. "Feedstock Carbon Intensity Calculator (FD-CIC): Users' Manual and Technical Documentation" https://greet.es.anl.gov/tool_fd_cic

Publication:

- X. Liu, H. Kwon, D. Northrup, and M. Wang. "Sustainable Farming Practices to Potentially Lower Carbon Intensity of Feedstock Production for Biofuels." *Environmental Research Letters*. DOI: https://doi.org/10.1088/1748-9326/ab794e.

2.3 HYDROGEN AND FUEL CELL VEHICLES: BY-PRODUCT H_2 FROM STEAM CRACKER

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H_2 is generated as a by-product of the steam cracking process that converts natural gas liquids or naphtha to ethylene, propylene, and other petrochemical products. To estimate the energy use and air emissions of by-product H_2 from steam crackers (listed as steam cracker by-product H_2 pathway in the Hydrogen tab of GREET1 Excel version), Argonne has updated the steam cracking process using reported operational data from the U.S. steam cracking facilities. The results were aggregated in two scenarios, scenario A (co-produced H_2 is combusted onsite) and scenario B (co-produced H_2 is exported), with the results also shown in a newly added Chemical tab, which includes new pathways for stream cracking main products (see Section 3.1). For the by-product H_2 allocation scenario (Scenario B), H_2 is treated as a co-product along with ethylene, methane, ethyne, ethylene, propyne, propylene, butatriene, butadiene, butene, benzene, toluene, styrene, xylene, ethylbenzene, pyrolysis gasoline, and fuel oil. The mass allocation method is used as a default to distribute the cracking process energy use and air emissions burden among all co-products, including H_2.

Forthcoming publication:

- Young, B., C. Chiquelin, T. R. Hawkins, P. Sun and A. Elgowainy, **"**Environmental Life Cycle Assessment of Olefins and By-Product Hydrogen from Steam Cracking.**"** (in preparation).

2.4 ELECTRICITY AND ELECTRIC VEHICLES

2.4.1 Electricity Generation Efficiency and Criteria Air Pollutant Emission Factors

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We have made several updates to characterize emission factors, generation efficiencies, and generation technology mixes of the U.S. electricity generation sector. First, we updated the electricity generation technology mixes and generation efficiencies at both the national level and for North American Electric Reliability Corporation (NERC) regions with electricity generation data (EIA-923) in 2017. Second, we estimated GHG and criteria air pollutant (CAP) emission factors of electricity generation using a new top-down approach, leveraging data available on air pollutant emissions measured from online continuous emission monitoring systems installed in some power plants and data available on electricity generation. The CAP emissions data for the year 2017 are obtained from National Emissions Inventory and Clean Air Markets Division's Power Sector Emission Data. The power generation data are from Energy Information Administration's 2017 EIA-923. Third, we updated national average transmission and distribution loss factors using the latest (2018) data from EIA's State Electricity Profiles.

We also generated state-specific life-cycle energy usage, water consumption, and pollutant emission results from electricity generation based on state-specific fuel and generation technology mixes, electricity generation efficiencies, and transmission and distribution losses. We note that we used national average emission factors as surrogate for state-specific emission factors for the same fuel type and generation technology, the former is not available in many states due to data limitation.

Technical report:

- Ou, L., and H. Cai, 2020. "Update of Emission Factors of Greenhouse Gases and Criteria Air Pollutants, and Generation Efficiencies of the U.S. Electricity Generation Sector." ANL-20/41. https://greet.es.anl.gov/publication-ele_2020.

2.4.2 Future Electricity Generation Mixes

Uisung Lee (ulee@anl.gov)

We annually update regional U.S. electricity generation mixes through 2050 based on the Annual Energy Outlook (AEO), including the grid generation mixes of U.S. average, eight NERC regions, and three states (Alaska [AK], California [CA], and Hawaii [HI]). In GREET

2020, we update the grid generation mixes using AEO 2020 (EIA 2020a), which are presented in Table A-1 of the Appendix. Note the changes in NERC regions this year, as presented in Table 2 (details can be found in the linked map http://www.eia.gov/outlooks/aeo/pdf/nerc_map.pdf).

Table 2 Changes in NERC regions in GREET 2020 versus GREET 2019

	GREET 2019	GREET 2020
NERC	Florida Reliability Coordinating Council (FRCC)	Same
	Midwest Reliability Organization (MRO)	Midcontinent ISO (MISO)
	Northeast Power Coordinating Council (NPCC)	Same
	Reliability First Corporation (RFC)	Pennsylvania, New Jersey, and Maryland (PJM)
	SERC Reliability Corporation (SERC)	Same
	Southwest Power Pool (SPP)	Same
	Texas Reliability Entity (TRE)	Same
	Western Electricity Coordinating Council (WECC)	Same

2.4.3 Update of Specific Energy and Bill of Materials of Lithium-Ion Batteries

Olumide Winjobi (owinjobi@anl.gov), Qiang Dai (qdai@anl.gov), and Jarod C. Kelly (jckelly@anl.gov)

In GREET 2020 we update the specific energy and bill-of-materials (BOMs) of lithium-ion batteries (LIBs) for electric vehicles (EVs), including battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in electric vehicles (PHEVs). Updates to the specific energy and BOMs were based on the most recent version of Argonne's Battery Performance and Cost (BatPaC) model (version 4). We also add a new LIB cathode chemistry, $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC 532), to the battery LCA module. The specific energy and BOM for the NMC 532 cathode were also obtained from BatPaC v.4, while the LCI for the production of the NMC 532 cathode was adapted from existing LCIs in GREET for other lithium nickel manganese cobalt oxide (NMC) chemistries.

Technical memo:

- Winjobi, O., Q. Dai, and J.C. Kelly, 2020, "Update of Bill-of-Materials and Specific Energy of Lithium-ion Batteries in the GREET Model" https://greet.es.anl.gov/publication-bom_lib_2020

2.4.4 Nickel Pathway Updates and Additions

Qiang Dai (qdai@anl.gov) and Jarod C. Kelly (jckelly@anl.gov)

We update life-cycle analyses of the production of class I nickel and battery-grade nickel sulfate based on industry data, compiled by the Nickel Institute, that represent 52% of global class I nickel production and 15% of global nickel sulfate production in 2017. We also add a pathway for battery-grade nickel sulfate production from mixed hydroxide precipitate in the GREET2 “Nickel” tab, which has recently become an important source of nickel sulfate supply, based on industry reports and literature.

Technical memo:

- Dai, Q., and J. C. Kelly, 2020, “Nickel Life Cycle Analysis Updates and Additions in the GREET Model.” https://greet.es.anl.gov/publication-vmc_2020

2.4.5 Vehicle Material Composition

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

We update the material composition of vehicle systems for Conventional Type 1 vehicles including the midsize sedans (Cars), small sport-utility vehicle (SUV), and pickup truck (PUT). The data for the updates are based on an aggregation of vehicles from the A2Mac1 dataset for internal combustion engine vehicles (ICEVs) Cars, SUVs, and PUTs which reflects the current state of the vehicle market. We also used the dataset to update aspects of the hybrid electric vehicle (HEVs), plug-in electric vehicle (PHEV), battery electric vehicle (BEV), and fuel cell electric vehicle (FCEV) component systems.

Technical memo:

- Kelly, J.C., and O. Winjobi, 2020, “Update of Vehicle Material Composition in the GREET Model,” https://greet.es.anl.gov/publication-vmc_2020

2.4.6 Lithium Pathway Updates and Additions

Jarod C. Kelly (jckelly@anl.gov), Qiang Dai (qdai@anl.gov), and Olumide Winjobi (owinjobi@anl.gov)

We expand and update the structure of lithium production pathways in the GREET2 model — specifically, the expansion and updating of pathways for lithium extracted from spodumene ore and converted into lithium carbonate (Li_2CO_3) and lithium hydroxide (LiOH). Within the currently released GREET 2020, no numerical data are provided for these ore-based pathways. The brine-based lithium pathways are retained, but modifications to the calculation methods of some precursor materials are made. However, these do not impact any current data for the lithium pathways currently in GREET 2020. The impetus for this update is a forthcoming release of a lithium production pathways report that will provide the numerical basis to populate the new and updated pathways.

Technical memo:

- Kelly, J.C., Q. Dai, and O. Winjobi, 2020, “Lithium Pathway Updates and Additions in the GREET Model,” https://greet.es.anl.gov/publication-li_update_2020

3 OTHER UPDATES AND ADDITIONS

3.1 CHEMICALS FROM STEAM CRACKING

Ulises R. Gracida-Alvarez (ugracida@anl.gov), Adarsh Bafana (abafana@anl.gov), Troy R. Hawkins (thawkins@anl.gov), Pingping Sun (psun@anl.gov), Pahola Thathiana Benavides (pbenavides@anl.gov), and Amgad Elgowainy (aelgowainy@anl.gov)

A new "Chemicals" tab is added to GREET 2020 that summarizes the energy uses and emissions for the products from the stream cracking process, including methane, ethyne, ethylene, propyne, propylene, butatriene, butadiene, butene, benzene, toluene, styrene, xylene, ethylbenzene, pyrolysis gasoline, and fuel oil. This new tab presents aggregated data from U.S. steam cracking processes by using facility operational data accounting for the energy requirements, water consumption, and emissions of the different chemicals produced. H_2 from steam cracking can be combusted onsite for fuel supply or can be separated as a product for export. Thus, the U.S. steam cracking processes were aggregated in two scenarios: complete combustion of H_2 in the cracker (Scenario A) and H_2 sold externally as a co-product (Scenario B). In Scenario A, internal H_2 and methane fulfill the energy requirements of the cracker, thus avoiding the need for external energy sources. In contrast, with H_2 export, Scenario B requires the use of external natural gas to fulfill the energy requirements of the cracking process. For scenario B, the pathway of the by-product (exported) H_2 is shown in the "Hydrogen" tab. Energy requirements and emissions of the process are distributed among the different products using mass, energy, and value allocation approaches, with mass-based allocation as the default method.

Calculation of the average energy requirements and air emissions of steam cracking products relies on the assumption that 70% of steam cracker plants burn H_2 while only 30% sell it as co-product.

The "Chemicals" tab presents new pathways for ethyne, propyne, propylene, butatriene, butadiene, butene, benzene, toluene, styrene, xylene, ethylbenzene, pyrolysis gasoline, and fuel oil while the pathways for ethylene, propylene and benzene now consider the U.S. average production from steam cracking and petrochemical processes (Table 3). This information is used to update the existing pathways in the "Bioproducts" tab.

Table 3 Contribution of steam cracking and petrochemical processes to the U.S. national production of chemicals

Product	Steam Cracking	Petrochemical Processes	Reference
Ethylene	100%	0%	(U.S. EIA 2020; Koottungal 2015)
Propylene	73.8%	26.2%	(Lippe 2020)
Benzene	50%	50%	(CIEC 2016)

Forthcoming publication:

- Young, B., C. Chiquelin, T.R. Hawkins, P. Sun, and A. Elgowainy, 2020. "Environmental Life Cycle Assessment of Olefins and By-product Hydrogen from Steam Cracking." (in preparation).

3.2 METHANOL AS MARINE FUELS

Troy R. Hawkins (thawkins@anl.gov), George G. Zaimes (gzaimes@anl.gov), and Paola Vega Jaquez

Six discrete methanol pathways for maritime applications are added to the GREET Marine Fuels Module (Marine_WTH tab). These pathways include methanol derived from natural gas, flare gas, biomass, renewable natural gas, coal, and black liquor. Cradle-to-gate LCI for these pathways was derived from existing GREET fuel pathways provided in the Methanol and Fischer-Tropsch Diesel module ('MeOH_FTD'); see Table 4.

Table 4 GREET 2020 marine methanol pathways

	Marine Methanol Pathway	Methanol Feedstock	GREET Module Cradle-to-Gate LCI	GREET Pathway Cradle-to-Gate LCI
1	Methanol (Natural Gas)	Natural Gas	MeOH_FTD	Natural Gas to Methanol
2	Methanol (Flare Gas)	Flare Gas	MeOH_FTD	Flare Gas to Methanol
3	Methanol (RNG)	Renewable Natural Gas	MeOH_FTD	RNG to Methanol
4	Methanol (Biomass)	Biomass	MeOH_FTD	Biomass to Methanol
5	Methanol (Coal)	Coal	MeOH_FTD	Coal to Methanol
6	Methanol (Black Liquor)	Black Liquor	MeOH_FTD	Black Liquor to Methanol

Well-to-hull life cycle analysis for marine methanol pathways is developed by coupling cradle-to-gate LCI for the methanol 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 methanol for maritime applications, considering specific fuel properties (e.g., methanol heating value, carbon content, sulfur content, etc.) as well as user-defined vessel engine, emissions regulations, and trip characteristics.

3.3 FEED FOR SWINE AND POULTRY ANIMALS

Pahola Thathiana Benavides (pbenavides@anl.gov) and Hao Cai (hcai@anl.gov)

Swine and poultry meat production are two important sectors in the U.S. economy. They also contribute to GHG emissions of agriculture. In GREET 2020, we add a new tab, "Animal Feed," for swine (i.e., pork) and poultry (i.e., broiler chicken) production and formulating animal feeds including soybean meal, corn, distiller-dried grains with solubles (DDGS), and synthetic amino acids. Pork is the most widely consumed meat in the world, while poultry is the fastest-growing meat industry (World Watch Institute 2019). The United States is the world's largest producer and the second-largest exporter of poultry meat (USDA 2019b), while it is the world's third-largest producer and consumer of pork and pork products (USDA 2019a). For animal feed ingredients we leveraged BioOil and ethanol pathways already available in GREET to obtain inventory information for soybean meal, DDGS, and corn. We have added new inventory inputs for different amino acids used in animal diets, including L-lysine hydrochloride (HCL), threonine, and DL-methionine. These amino acids are used as animal feed additives and are produced from different bio-based sources such as sugarcane, soybeans, corn, or natural protein resources (keratin, soybean) (Scheper, Faurie, and Thommel 2003). With the new Animal Feed tab, GREET users can calculate the energy and environmental effects of using a variety of animal feed diets based on the key animal feed ingredients for swine and poultry production. The system boundary covers all material and energy flows associated with the production of animal feed ingredients (including crop cultivation and processing and chemical production such as amino acids), formulation of diets, and animal farming.

Publication:

- Benavides P.T., H. Cai, M. Wang, and N. Bajjalieh. 2020. "Life-Cycle Analysis of Soybean Meal, Distiller-Dried Grains with Solubles, and Synthetic Amino Acid-Based Feeds for Swine and Poultry Production." *Animal Feed Science and Technology*. 268. https://doi.org/10.1016/j.anifeedsci.2020.114607.

3.4 EVAPORATIVE VOC EMISSIONS OF NATURAL GAS AND LPG VEHICLES

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In GREET 2020, the evaporative volatile organic compound (VOC) emissions of both light-duty and heavy-duty dedicated natural gas vehicles (NGVs) and propane (i.e., LPG) vehicles (LPGVs) are assumed to be zero. There is limited information available on evaporative VOC emissions of NGVs and LPGVs, but EPA on- and off-road vehicle emission modeling assumes that the values are zero for these alternative fuel vehicles (EPA 2010; 2014). The assumptions are not changed for bi-fuel natural gas and gasoline vehicles (a 50% reduction versus gasoline), as they can have both fuels stored onboard, nor for liquefied natural gas (LNG) vehicles with diesel pilot ignition as they always store diesel fuel onboard.

The composition of these fuels is the major driver for this, as unlike gasoline, these fuels contain little to no VOCs that are reactive with NO_x to form ozone pollution. Compressed natural gas (CNG) fuel composition is typically greater than 90% methane with a small amount of inert gases and ethane; Cummins Westport default fuel specification is 95% methane, 3% inerts, and

2% ethane (CARB 2010; Cummins Westport 2020). Liquefied natural gas (LNG) for vehicular use will likely have even higher methane content as the fuel's impurities drop out during the liquefaction process (US DOE 2020). LPG vehicle fuel composition is typically greater than 90% propane, no more than 5% propylene, and no more than 2.5% butanes (or heavier) (Rood Werpy, Burnham, and Bertram 2010). In addition, NGV and LPGV fuel storage systems and refueling procedures are less prone to evaporation and spilling, which are concerns for such liquid petroleum fuels as gasoline and diesel (EPA 2014).

3.5 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 new published data. Default CH_4 emissions are updated based on the 2020 EPA Greenhouse Gas Emission Inventory (EPA 2020). In addition, we update the optional CH_4 emissions data from Alvarez et al. (2018) for GREET 2020, which is referred to as EDF 2020 (Environmental Defense Fund).

Technical memo:

- Burnham, A. 2020, "Updated Natural Gas Pathways in the GREET1_2020 Model." https://greet.es.anl.gov/publication-update_ng_2020

3.6 CRUDE OIL MIX

Uisung Lee (ulee@anl.gov)

We annually update the regional shares of U.S. crude oil supply based on EIA's AEO. In GREET 2020, we updated U.S. domestic crude oil production shares based on EIA's AEO projection by 2050 (EIA 2020a). Crude oil import shares (Canada, Mexico, the Middle East, Latin America, and Africa) were estimated using EIA's company-level import data (EIA 2020b). We assumed current crude oil import splits remain the same through 2050, since there is no projection of future import shares by region. Note that the split between Canadian conventional crude and Canadian oil sands was estimated using reports from the Canadian Association of Petroleum Producers (CAPP 2016; 2019). Projected regional crude oil shares in the United States through 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 2019 were estimated at 10.1% and 11.5%, respectively, based on EIA (EIA 2020d; 2020c). We updated the crude oil transportation distance based on company-level import data from EIA (EIA 2020b). Weighted average distances are estimated at 8,204 miles by ocean tankers for offshore countries and 1,671 miles for Canada and Mexico by pipeline.

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APPENDIX A: PROJECTED U.S. ELECTRICITY GENERATION MIXES

Table A-1 Electric generation mixes of the United States, eight NERC regions, and three states

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
U.S. Mix										
2019	0.41%	36.72%	24.64%	20.42%	0.32%	7.29%	0.42%	7.47%	1.84%	0.47%
2020	0.40%	36.81%	22.76%	20.32%	0.34%	7.49%	0.42%	8.61%	2.39%	0.47%
2025	0.25%	36.37%	17.67%	18.30%	0.33%	7.13%	0.48%	12.46%	5.87%	1.15%
2030	0.20%	34.36%	18.11%	16.25%	0.32%	6.94%	0.63%	12.43%	8.79%	1.96%
2035	0.18%	35.96%	17.14%	15.04%	0.31%	6.70%	0.80%	12.14%	9.02%	2.70%
2040	0.16%	36.41%	15.91%	14.26%	0.30%	6.40%	0.95%	11.94%	10.79%	2.88%
2045	0.12%	35.06%	14.93%	13.53%	0.29%	6.05%	1.02%	11.96%	14.13%	2.90%
2050	0.12%	35.13%	14.29%	12.88%	0.28%	5.73%	1.05%	12.14%	15.33%	3.06%
Texas Reliability Entity (TRE) Mix										
2019	0.08%	49.82%	18.54%	10.80%	0.03%	0.22%	0.00%	19.27%	1.14%	0.10%
2020	0.07%	48.36%	15.68%	10.85%	0.03%	0.23%	0.00%	22.54%	2.15%	0.10%
2025	0.05%	46.15%	10.74%	10.20%	0.03%	0.21%	0.00%	24.42%	7.86%	0.35%
2030	0.06%	44.06%	13.85%	9.90%	0.03%	0.20%	0.00%	23.66%	7.83%	0.41%
2035	0.06%	46.19%	13.20%	9.46%	0.03%	0.20%	0.00%	22.61%	7.72%	0.53%
2040	0.05%	41.84%	12.52%	9.05%	0.03%	0.19%	0.00%	21.43%	14.15%	0.74%
2045	0.05%	39.21%	11.00%	8.62%	0.02%	0.17%	0.00%	20.22%	19.75%	0.96%
2050	0.05%	40.81%	11.10%	8.23%	0.02%	0.16%	0.00%	19.08%	19.36%	1.18%
Florida Reliability Coordinating Council (FRCC) Mix										
2019	0.18%	69.90%	13.22%	13.35%	0.23%	0.78%	0.00%	0.00%	1.27%	1.07%
2020	0.18%	68.66%	13.56%	13.32%	0.20%	0.78%	0.00%	0.00%	2.22%	1.07%
2025	0.18%	60.39%	14.08%	13.05%	0.20%	0.75%	0.00%	0.00%	10.26%	1.09%
2030	0.09%	49.37%	14.25%	12.55%	0.19%	0.70%	0.00%	0.00%	21.62%	1.22%
2035	0.08%	50.38%	13.13%	11.88%	0.18%	0.67%	0.00%	0.00%	22.53%	1.15%
2040	0.06%	50.92%	12.42%	11.26%	0.17%	0.63%	0.00%	0.00%	23.28%	1.26%
2045	0.06%	52.18%	11.84%	11.07%	0.16%	0.61%	0.00%	0.00%	22.53%	1.54%
2050	0.05%	54.18%	11.36%	10.39%	0.15%	0.56%	0.00%	0.00%	21.73%	1.58%

Table A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Midcontinent ISO (MISO) Mix										
2019	0.77%	28.51%	43.33%	15.39%	0.17%	1.39%	0.00%	9.77%	0.31%	0.36%
2020	0.77%	28.88%	40.37%	15.75%	0.17%	1.45%	0.00%	11.87%	0.39%	0.36%
2025	0.18%	32.00%	38.63%	11.80%	0.15%	1.37%	0.00%	12.40%	2.84%	0.64%
2030	0.18%	36.70%	38.30%	5.06%	0.15%	1.31%	0.00%	12.13%	5.52%	0.64%
2035	0.17%	39.38%	36.62%	3.73%	0.14%	1.28%	0.00%	11.94%	6.06%	0.68%
2040	0.16%	39.86%	35.19%	3.74%	0.15%	1.25%	0.00%	11.99%	6.91%	0.75%
2045	0.16%	38.33%	34.26%	3.67%	0.14%	1.22%	0.00%	11.77%	9.58%	0.85%
2050	0.15%	35.99%	32.43%	3.46%	0.15%	1.15%	0.00%	11.70%	13.39%	1.57%
Northeast Power Coordinating Council (NPCC) Mix										
2019	0.28%	42.15%	2.44%	32.32%	0.12%	16.49%	0.00%	3.53%	0.88%	1.77%
2020	0.27%	42.68%	1.84%	30.64%	0.13%	17.31%	0.00%	3.95%	1.35%	1.83%
2025	0.18%	37.99%	0.00%	24.05%	0.13%	16.91%	0.00%	14.15%	2.73%	3.86%
2030	0.17%	31.17%	0.00%	22.68%	0.12%	15.86%	0.00%	20.81%	5.26%	3.94%
2035	0.07%	25.92%	0.00%	21.38%	0.12%	14.93%	0.00%	28.76%	4.94%	3.87%
2040	0.01%	23.48%	0.00%	21.30%	0.12%	14.87%	0.00%	31.26%	4.92%	4.02%
2045	0.02%	23.19%	0.00%	21.47%	0.13%	14.83%	0.00%	31.17%	4.95%	4.24%
2050	0.01%	24.17%	0.00%	20.95%	0.13%	14.34%	0.00%	30.79%	4.99%	4.62%
Pennsylvania, New Jersey, and Maryland (PJM) Mix										
2019	0.18%	35.21%	25.23%	33.87%	0.16%	1.38%	0.00%	2.83%	0.54%	0.60%
2020	0.17%	37.34%	23.03%	33.39%	0.16%	1.41%	0.00%	3.16%	0.76%	0.57%
2025	0.11%	42.21%	16.42%	30.54%	0.14%	1.37%	0.00%	4.24%	3.99%	0.98%
2030	0.07%	37.37%	16.72%	29.57%	0.14%	1.30%	0.00%	4.47%	7.08%	3.28%
2035	0.07%	40.69%	15.80%	26.43%	0.14%	1.27%	0.00%	4.40%	6.99%	4.20%
2040	0.06%	44.34%	14.65%	24.40%	0.14%	1.22%	0.00%	4.25%	6.71%	4.24%
2045	0.06%	44.12%	13.94%	23.80%	0.15%	1.17%	0.00%	4.14%	8.44%	4.18%
2050	0.06%	44.59%	13.47%	22.90%	0.13%	1.12%	0.00%	4.09%	9.45%	4.19%

Table A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
SERC Reliability Corporation (SERC) Mix										
2019	0.28%	37.98%	23.23%	31.85%	0.41%	4.60%	0.00%	0.01%	1.46%	0.19%
2020	0.27%	38.59%	21.39%	32.30%	0.52%	4.75%	0.00%	0.01%	2.00%	0.19%
2025	0.22%	38.10%	14.36%	33.66%	0.50%	4.53%	0.00%	0.61%	6.96%	1.05%
2030	0.09%	34.17%	15.71%	33.06%	0.50%	4.56%	0.00%	0.63%	10.23%	1.06%
2035	0.08%	36.33%	14.80%	32.00%	0.48%	4.38%	0.00%	0.81%	10.07%	1.05%
2040	0.06%	36.66%	13.37%	30.22%	0.45%	4.13%	0.00%	1.03%	13.03%	1.05%
2045	0.05%	34.41%	12.15%	26.92%	0.42%	3.82%	0.00%	1.04%	20.15%	1.05%
2050	0.05%	36.30%	11.50%	25.67%	0.40%	3.63%	0.00%	1.14%	20.08%	1.23%
Southwest Power Pool (SPP) Mix										
2019	0.15%	24.44%	37.45%	5.91%	0.00%	5.25%	0.00%	26.44%	0.29%	0.06%
2020	0.14%	23.49%	35.68%	5.85%	0.00%	5.28%	0.00%	29.16%	0.33%	0.06%
2025	0.10%	17.52%	25.43%	3.35%	0.00%	4.98%	0.00%	39.83%	8.05%	0.74%
2030	0.10%	17.15%	25.04%	0.00%	0.00%	4.86%	0.00%	39.41%	12.63%	0.80%
2035	0.10%	19.40%	23.92%	0.00%	0.00%	4.70%	0.00%	38.42%	12.62%	0.85%
2040	0.08%	21.70%	19.78%	0.00%	0.00%	4.48%	0.00%	37.90%	15.18%	0.88%
2045	0.07%	21.57%	18.40%	0.00%	0.00%	4.17%	0.00%	35.54%	19.35%	0.89%
2050	0.07%	22.09%	17.66%	0.00%	0.00%	4.05%	0.00%	34.73%	20.47%	0.93%
Western Electricity Coordinating Council (WECC) Mix										
2019	0.14%	31.24%	17.38%	8.40%	0.45%	25.58%	2.26%	7.65%	6.50%	0.40%
2020	0.13%	29.66%	16.19%	8.47%	0.46%	26.15%	2.27%	8.55%	7.72%	0.41%
2025	0.11%	27.11%	10.13%	6.80%	0.43%	24.80%	2.60%	19.26%	7.55%	1.21%
2030	0.10%	27.20%	9.73%	5.50%	0.45%	24.42%	3.46%	19.02%	8.79%	1.32%
2035	0.10%	27.14%	9.27%	5.46%	0.44%	23.52%	4.39%	18.62%	9.60%	1.46%
2040	0.09%	26.70%	8.75%	5.22%	0.42%	22.37%	5.21%	18.32%	11.31%	1.61%
2045	0.09%	24.23%	8.13%	4.94%	0.40%	20.83%	5.52%	20.27%	13.87%	1.74%
2050	0.08%	22.45%	7.69%	4.61%	0.39%	19.33%	5.55%	22.12%	15.96%	1.83%

Table A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
California Mix										
2019	0.00%	42.53%	0.00%	10.26%	1.17%	14.06%	4.53%	8.09%	18.30%	1.06%
2020	0.00%	35.00%	0.00%	10.87%	1.25%	15.15%	4.83%	9.01%	22.74%	1.14%
2025	0.00%	34.10%	0.00%	5.96%	1.38%	16.12%	6.28%	9.69%	24.92%	1.54%
2030	0.00%	24.99%	0.00%	0.00%	1.61%	17.24%	10.35%	10.33%	33.61%	1.87%
2035	0.00%	20.00%	0.00%	0.00%	1.56%	16.45%	14.28%	10.05%	35.77%	1.87%
2040	0.00%	17.29%	0.00%	0.00%	1.40%	14.17%	15.54%	9.18%	40.53%	1.89%
2045	0.00%	15.34%	0.00%	0.00%	1.27%	12.36%	15.89%	8.34%	44.92%	1.88%
2050	0.00%	15.59%	0.00%	0.00%	1.21%	10.58%	15.07%	7.77%	47.97%	1.80%
Alaska Mix										
2019	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2020	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2025	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2030	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2035	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2040	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2045	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
2050	12.95%	47.19%	10.06%	0.00%	0.73%	26.59%	0.00%	2.48%	0.00%	0.00%
Hawaii Mix										
2019	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2020	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2025	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2030	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2035	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2040	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2045	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%
2050	68.89%	0.00%	13.88%	0.00%	3.12%	0.99%	1.12%	6.14%	1.88%	4.47%

APPENDIX B: U.S. CRUDE OIL SUPPLY MIXES

Table B-1 Crude Oil Shares in the United States through 2050

Year	U.S. Domestic	Canada (Oil Sands)	Canada (Conventional Crude)	Mexico	Middle East	Latin America	Africa	Others
2019	74.9%	6.5%	7.6%	2.2%	3.2%	3.0%	1.4%	1.2%
2020	75.6%	6.3%	7.4%	2.2%	3.1%	2.9%	1.4%	1.2%
2025	80.2%	5.1%	6.0%	1.8%	2.5%	2.3%	1.1%	1.0%
2030	80.7%	5.0%	5.9%	1.7%	2.5%	2.3%	1.1%	0.9%
2035	80.3%	5.1%	6.0%	1.7%	2.5%	2.3%	1.1%	0.9%
2050	66.5%	8.6%	10.2%	3.0%	4.3%	4.0%	1.9%	1.6%

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