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Summary of Expansions and Updates in GREET® 2018

Energy Systems Division

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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 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). There are two GREET modeling platforms; GREET Excel is a multidimensional spreadsheet model that provides a comprehensive LCA tool, and GREET.Net provides an interactive graphical toolbox to perform LCA. The GREET 2018 release includes expansions and updates for both platforms, and this report provides a summary of the release.

2 MAJOR EXPANSIONS AND UPDATES IN GREET 2018

2.1 BIOFUELS AND BIOPRODUCTS

2.1.1 Bioproducts

Pahola Thathiana Benavides (pbenavides@anl.gov)

GREET 2018 continues to expand the GREET bioproduct module to assess environmental impacts of bio-derived chemicals produced from biochemical, biological, and thermochemical conversion technologies. For the 2018 release, we added three bio-derived products: bio-ethylene oxide (EO), bio-ethylene glycol (EG), and bio-terephthalic acid (TPA). These bio-derived products can be used in the production of polyester and plastics such as polyethylene terephthalate (PET, the raw material for plastic bottles), liquid coolants, and solvents. EO is produced via direct oxidation of bio-derived ethylene with oxygen, while bio-derived EG is produced by the hydration of bio-derived EO. There are several pathways to produce bio-TPA, such as direct fermentation of sugars and via an isobutanol intermediate to paraxylene. However, we assessed the latter because companies are actively working to produce paraxylene from isobutanol at a demonstration scale (e.g., Gevo), while the direct fermentation pathway is now less mature than the isobutanol route.

Publication: Benavides, Pahola Thathiana, Jennifer B. Dunn, Jeongwoo Han, Mary Biddy, and Jennifer Markham. "Exploring Comparative Energy and Environmental Benefits of Virgin, Recycled, and Bio-Derived PET Bottles." ACS Sustainable Chemistry & Engineering 6, no. 8 (2018): 9725–9733. (https://pubs.acs.org/doi/10.1021/acssuschemeng.8b00750).

2.1.2 Carbon Calculator for Land Use Change from Biofuels Production (CCLUB)

Hoyoung Kwon (hkwon@anl.gov)

In CCLUB 2018, users can select additional option for tillage practice - *U.S. Average* - to calculate soil organic carbon (SOC) changes at a national level. This option calculates the weighted average of SOC changes based on the share of corn-planted area using different types of tillage - no till (16%), reduced tillage (59%), and conventional tillage (25%). CCLUB now uses the *U.S. Average* for a baseline tillage practice. For soy biodiesel land use change (LUC) scenarios, CCLUB includes new updates to specifically estimate emissions associated with peatland loss in Southeast Asia.

Updated technical report: Zhangcai Qin, Hoyoung Kwon, Jennifer B. Dunn, Steffen Mueller, Michael M. Wander, and Michael Wang. 2018. "Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) – Users' Manual and Technical Documentation" (https://greet.es.anl.gov/publication-cclub-manual-r5).

Technical memo: Zhangcai Qin and Hoyoung Kwon. 2018 "Estimating emissions related to indirect peatland loss in Southeast Asia due to biofuel production" (https://greet.es.anl.gov/publication-iluc_peat).

2.1.3 Algae Biofuel Production Pathways

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

Argonne updated two algae biofuel pathways, combined algae processing (CAP) and hydrothermal liquefaction (HTL), based on pathway parameters identified in an Argonne collaboration with the National Renewable Energy Laboratory (NREL) and Pacific Northwest National Laboratory (PNNL) to harmonize LCA results (together with techno-economic analysis [TEA] results) for algal biofuel production pathways (Davis et al. 2018). A key difference between the pathways included in this update and those presented in the report is that the harmonization study considered polyurethane and succinic acid coproducts from the CAP pathway with associated displacement of emissions and resource use for those coproducts; GREET 2018-relevant default pathways only consider the option without production of coproducts.

Technical Report: Ryan E. Davis, Jennifer N. Markham, Christopher M. Kinchin, Christina Canter, Jeongwoo Han, Qianfeng Li, Andre Coleman, Mark Wigmosta, and Yunhua Zhu. 2018. "2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling." National Renewable Energy Laboratory (NREL), Golden, CO (United States) (https://www.nrel.gov/docs/fy18osti/70715.pdf).

2.1.4 Supply Chain Sustainability Analysis (SCSA)

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

Argonne updated the pathway to produce high-octane gasoline via indirect liquefaction. The update takes into account the newly developed design case by a joint national lab team for the DOE Bioenergy Technology Office, which uses logging residues as the feedstock. The update reflects improvements in biofuel yield and process material, energy, and water consumption in the conversion step, as well as improvements in the energy efficiency of the advanced feedstock logistics.

Argonne also added a new pathway that examines renewable hydrocarbon fuels produced from ex-situ catalytic fast pyrolysis. The update takes into account the newly developed design case by the joint national lab team for a conversion that uses a blend of logging residues and clean pine as the feedstocks. The update reflects improvements in biofuel yield and process material, energy, and water consumption in the conversion step, as well as improvements in the energy efficiency of the advanced feedstock logistics for both logging residues and clean pine.

Technical report (will be available in December 2018): Hao Cai, Pahola Thathiana Benavides, Uisung Lee, Michael Wang, Eric Tan, Ryan Davis, Abhijit Dutta, Mary Biddy, Ling Tao, Jennifer Clippinger, Jennifer Markham, Damon Hartley, Roni Mohammad, D. Thompson, Lesley Snowden-Swan, Yunhua Zhu, Sue Jones. "Supply chain sustainability analysis of renewable hydrocarbon fuels via indirect liquefaction, ex situ catalytic fast pyrolysis, hydrothermal liquefaction, and biochemical conversion: update of the 2018 state-of-technology cases and design cases," 2018 (https://greet.es.anl.gov/publication-supply_renewable_hc).

2.2 HYDROGEN AND FUEL CELL VEHICLES

2.2.1 Byproduct Hydrogen Production from Steam Crackers

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Hydrogen is generated as a byproduct of the steam cracking processes that convert natural gas liquids or naphtha to ethylene and other petrochemical products. Byproduct hydrogen from such petrochemical facilities can be a valuable source to supply the increasing demand for hydrogen in fuel-cell electric vehicles, ammonia production, and other market demands. To estimate the energy use and air emissions of byproduct hydrogen from steam crackers, Argonne added a *by-product hydrogen production from steam crackers* pathway to GREET 2018. Two byproduct hydrogen treatment scenarios were included: substitution and mass allocation. In the first scenario (substitution), byproduct hydrogen, which is used internally as a combustion fuel for the cracking process, may be diverted from the combustion fuel stream, and its thermal energy that was used for the cracking process is substituted with combustion of natural gas. The second scenario refers to byproduct hydrogen that is already being exported to external markets. In this case, hydrogen is a coproduct, along with ethylene and other products, and the mass allocation method is appropriate to distribute the cracking process energy use and air emissions burden between all products, including hydrogen.

Publication: D-Y Lee and Elgowainy, A. (2018). "By-product hydrogen from steam cracking of natural gas liquids (NGLs): Potential for large-scale hydrogen fuel production, life-cycle air *emissions reduction, and economic benefit." International Journal of Hydrogen Energy. (https://doi.org/10.1016/j.ijhydene.2018.09.039).*

2.2.2 Hydrogen Fuel-Cell Electric Transit Bus (FCEB)

D-Y Lee (dongyeon.lee@anl.gov) and Amgad Elgowainy (aelgowainy@anl.gov)

In addition to the hydrogen fuel-cell electric freight trucks and school buses that were already included in GREET 2017, Argonne added FCEB technology to GREET 2018. Transit bus fleets are one of the early applications of fuel-cell electric vehicle technology. The addition of hydrogen FCEBs fills a gap in terms of available medium- and heavy-duty fuel-cell electric vehicle types in GREET. It allows the users to compare FCEBs with conventional transit bus internal combustion engine technology powered by petroleum diesel on a life-cycle basis.

Publication: Currently under review.

2.3 ELECTRICITY AND ELECTRIC VEHICLES

2.3.1 Electricity Transmission and Distribution (T&D) Losses

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In GREET 2018, the electricity loss factor associated with T&D of electricity was updated to reflect the current status of operations within the United States. For this release, data from both the U.S. Environmental Protection Agency (EPA 2018a) and the Energy Information Administration (EIA 2018a) were examined. The EIA data serves as the source data for the EPA's calculations. We noted differences between the EPA and EIA T&D factors, which is also referred to as the grid gross loss factor. Further investigation with those agencies identified a discrepancy in EPA's formulation, which will be updated in the future. Thus, for this update we chose to utilize the EIA source data, from which we derived a U.S. T&D loss factor of 4.9%.

Technical memo: Jarod C. Kelly and Amgad Elgowainy. "Updating Transmission and Distribution Losses in the GREET® Model." (https://greet.es.anl.gov/publication-Update_td_losses_2018).

2.3.2 Electricity Mix

Uisung Lee (ulee@anl.gov)

Since GREET is used to simulate changes in life-cycle results due to technological improvements, GREET provides projected U.S. electricity mixes through 2050 based on Annual Energy Outlook (AEO) by the EIA (2018b). In particular, in order to reflect regional variations in the share of power generation technologies, we provided regional electricity mixes grouped by North American Electric Reliability Corporation (NERC) regions. NERC covers the contiguous United States, which is divided into eight 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). AEO also provides sub-NERC regions, and we updated the California mix in GREET 2018. In addition, EIA's state-level electricity generation data are used for Alaska and Hawaii (EIA 2018a). Note that EIA does not provide projections at the state level, which is why historic data from 2016 is used in place of future electricity generation mix for state-specific mixes. Table A1 in Appendix A presents the electricity mixes of each NERC region and the three states used in GREET 2018.

2.4 BATTERY LCA

2.4.1 Cobalt and Cobalt Chemicals

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

Refined metallic cobalt and cobalt chemical production pathways were updated in GREET 2018. The updated life-cycle inventory (LCI) covers material and energy flows associated with cobalt ore mining, cobalt ore processing, cobalt chemicals production, cobalt metal production, and pertinent transportation activities. The updates were based on recent literature, industry statistics, and company reports, and represent current practices of the global cobalt industry.

Technical memo: Qiang Dai, Jarod C. Kelly, and Amgad Elgowainy (2018). "Update of Life Cycle Analysis of Cobalt in the GREET® Model"(https://greet.es.anl.gov/publication-update_cobalt).

2.4.2 Update of Bill of Materials of Lithium-Ion Batteries and Cathode Materials Production

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

In GREET 2018, updates were made in the battery LCA module for (1) bill-of-materials (BOMs) of lithium-ion batteries (LIBs) for electric vehicles (EVs), including hybrid electric vehicles (HEVs), plug-in hybrid vehicles (PHEVs), and battery electric vehicles (BEVs); (2) LCI for the production of LIB cathode materials, including lithium cobalt oxide, lithium nickel cobalt manganese oxide, and lithium nickel cobalt aluminum oxide. The BOM update was based on the most recent version of Argonne's Battery Performance and Cost (BatPaC) model. The cathode LCI update was based on a site visit to a leading cathode material producer, literature, and industry reports. These updates therefore represent current material compositions of LIBs for transportation applications and the state-of-the-art of industrial production of LIB cathode materials.

Technical memo: Qiang Dai, Jarod C. Kelly, Jennifer Dunn, and Pahola Thathiana Benavides (2018). "Update of Bill-of-Materials and Cathode Materials Production for Lithium-ion Batteries in the GREET® Model" (https://greet.es.anl.gov/publication-update_bom_cm).

3 OTHER UPDATES AND ADDITIONS

3.1 Fuel Economy Updates for Light Duty Vehicles

Uisung Lee (ulee@anl.gov)

To generate LCA results per mile travelled for on-road vehicles, fuel economy values are needed to convert the energy use and emissions embedded in fuels (per energy content) to travel on a per-mile basis. In GREET, various vehicle operation combinations are available (i.e., vehicle type, fuel type, power type, and vehicle materials); these are presented in Table B1 in Appendix B. We estimate the fuel economy of baseline conventional gasoline vehicles for three vehicle types (i.e., cars, light-duty truck [LDT] 1, and LDT2) in miles-per-gallon gasoline equivalent (MPGGE); the fuel economy values of other types of vehicles are expressed relative to those of baseline gasoline vehicle technologies. These are listed in the Car_TS, LDT1_TS, and LDT2_TS tabs of the GREET Excel.

The GREET model provides time series (TS) fuel economy values in 5-year intervals starting from 1990, which enables the model to simulate the impacts of changes in fuel economy over time. We also provide projected fuel economy TS values through 2050 considering potential improvements in fuel economy over time. MPGGE values and relative fuel economy changes are presented based on vehicle model year (MY). Note that the GREET model uses the MY that is 5 years earlier than the simulation year to reflect changes in emission rates over time due to vehicle emission deterioration over time (Wang et al. 2007). For example, when 2017 is selected as the simulation year, the fuel economy values of MY 2012 vehicles are used.

The GREET model relies on Autonomie results (Moawad et al. 2016) to estimate the fuel economy for the various vehicle/fuel combinations in Table B1 for MYs 2015–2050. Autonomie, software developed by Argonne, is designed to simulate vehicle energy consumption and performance. It has the capability to simulate improvements in vehicle technologies in the future by taking into account progress levels (i.e., low, medium, and high). Based on MPGGE results for urban and highway driving cycles, we adjusted the fuel economy using two formulas (EPA 2006) to reflect real-world driving conditions. With these, 43% of urban and 57% of highway driving distances are used to calculate weighted average fuel economies (EPA 2018c):

On-road urban fuel economy = 1/(0.003259 + 1.1805/UDDS fuel economy)

On-road highway fuel economy = 1/(0.001376 + 1.3466/HWFET fuel economy)

For PHEVs, power-split between charge depleting (CD) and charge sustaining (CS) modes should be considered. We used Autonomie's results to estimate fuel consumption (Btu/mi) and electricity consumption (Wh/mi) in CD mode as wells as fuel economy in CS mode for four rated-all-electric-range (RAER) PHEVs. Vehicle-miles-traveled shares by CD and CS operations were estimated based on Elgowainy et al. (2010). Detailed processes to estimate fuel consumption and electricity consumption for PHEVs were described in Elgowainy et al. (2010) and Section 6 of Elgowainy et al. (2016). For BEVs, Autonomie's electricity consumption (Wh/mi) values for two RAER BEVs were used to present the fuel economy in terms of MPGGE.

Table B2-B4 in Appendix B summarized fuel economy values implemented in GREET 2018.

3.2. Methane Leakage of Natural Gas Supply Chain

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We updated CH_4 emissions from natural gas supply chain based on new data. In GREET 2018, default CH_4 emissions were updated based on the 2018 EPA Greenhouse Gas (GHG) Emission Inventory (EPA 2018b). Meanwhile, Argonne reviewed and added the option to use CH_4 emissions data from Alvarez et al. (2018) for GREET 2018, which is referred to as EDF 2018 (Environmental Defense Fund) in GREET.

Technical memo: Andrew Burnham, 2018. Updated Natural Gas Pathways in the GREET1_2018 Model. (https://greet.es.anl.gov/publication-update_ng_2018).

3.3. Vented, Flaring, and Fugitive Greenhouse Gas Emissions from Crude Oil Production

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Argonne updated vented, flaring, and fugitive GHG emissions associated with crude oil production to reflect recent updates on both data and methodology used for these emissions in the 2018 GHG Emission Inventory (EPA 2018b).

Technical memo: Longwen Ou, Hao Cai, 2018. Updated Vented, Flaring, and Fugitive Greenhouse Gas Emissions for Crude Oil Production in the GREET1_2018 Model. (https://greet.es.anl.gov/publication-update_ghg_emi_2018).

3.4 Crude Oil Mix

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

Petroleum products (e.g., gasoline, diesel, and jet fuels) produced in refineries in the United States may have significantly different life-cycle energy and emission values depending on the sources of crude oil. The properties of crude oil such as the API (American Petroleum Institute) gravity and sulfur content cause different energy and emission burdens to refine the crude oil into products. In addition, transportation distances from oil fields to refineries vary significantly depending on the crude oil sources. We categorized U.S. crude oil sources into six regions: the United States, Canada, Mexico, the Middle East, Latin America, and Africa. We further separated Canadian crude into conventional crude oil and Canadian oil sands due to their different characteristics. Using the best available data, regional crude oil shares are projected by 2050.

EIA's AEO (EIA 2018b) projects U.S. domestic crude oil production share through 2050. We used this projection as a baseline in GREET 2018. Imported crude oil shares from other regions in 2017 were estimated using company level import data by EIA (2018c). The projection of crude oil imported from Canada was estimated on the basis of two reports from Canadian Association of Petroleum Producers (CAPP) (2016, 2018). CAPP no longer provides projections for crude oil exports. Therefore, we used Canadian crude oil projection data by Petroleum Administration for Defense Districts (PADDs) by 2020 in CAPP (2016), while using the projected ratios of oil sands among total heavy oil supply in CAPP (2018) to differentiate between conventional crude oil and oil sands. Due to limited information on Canadian oil imports in the future, we assumed that the amount of imported crude oil from Canada would remain the same after 2020. We allocated the remaining portions other than U.S. and Canadian crude to other regions based on their relative shares in 2017 EIA (2018c). Table C1 in Appendix C shows the projected crude oil share by region in the United States by 2050.

To estimate weighted average distance for importing crude oil, we used company-level import data (EIA 2018c). We estimated the distance between the importing state and the origin country of each imported crude oil product, and then aggregated the data to calculate weighted average distances. The same method was used to update previous GREET versions, and detailed processes were explained 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.

3.5 Transportation And Distribution Energy Intensity

Hao Cai (hcai@anl.gov)

We made several updates in relation to modeling energy intensities of transportation and distribution by rail, barge, and truck:

1. Energy intensity of rail transportation—We made an update based on recent energy intensity of rail transportation given in Table 9.8 of the Transportation Energy Data Book (ORNL 2018). We made adjustments to the Btu per ton-mile energy intensity based on the lower heating value and higher heating value ratio in GREET, and estimated that diesel-powered rail transportation had an energy intensity of 242 Btu/ton-mile, which reflects the energy intensities of all types of rail trips carrying all types of commodities.
2. Energy intensity and fuel type of barge transportation—We made an update based on a study by Texas Transportation Institute (TTI) (Kruse et al. 2007), which updated its 1994 report that was used in previous GREET versions. The new TTI study reported that barge usage efficiency is 576 ton-mile/gallon of fuel (Kruse et al. 2007). Assuming that the fuel is conventional diesel fuel, based on various sources of publically available information, this translates to an energy intensity of 233 Btu/ton-mile. TTI did not disaggregate outgoing and return trips (Kruse et al. 2007). Therefore, we used the 233 Btu/ton-mile energy intensity for both outgoing and return trips in GREET 2018. This value is lower than our previous values for outgoing and return trips (423 and 312 Btu/ton-mile,

respectively), for the reason noted in the TTI study: "Since that study (the 1994 one), technology has advanced, operating conditions have changed, and new and updated data are available" (Kruse et al. 2007).

3. Fuel economy of empty-loaded Class 6 medium-duty and Class 8b heavy-duty trucks—We made an update was on the relationship between truck fuel economy and their payloads. This update was developed using real-world driving data by Oak Ridge National Laboratory (Franzese and Davidson 2011). According to Figure 34 in Franzese and Davidson (2011), truck fuel economy is a function of vehicle weight:

$$FE = -5 \times 10^{-10} \times VW^2 + 8 \times 10^{-6} \times VW + 9.6687 \; (R^2 = 0.953),$$

where FE is the truck fuel economy in MPG (diesel gallon); and VW is the vehicle weight including payload in pounds.

Based on this relationship, we estimated that an empty loaded Class 8 truck has a fuel economy of 9.2 MPG, compared to 7.3 MPG with a payload of about 20.4 tons. Assuming that this relationship is applicable to Class 6 MDT, we estimated that an empty loaded Class 6 truck has a fuel economy of 8.9 MPG, compared to 8.3 MPG with a payload of about 4.8 tons.

3.6 Biodiesel Update to Address Fossil Carbon From Methanol

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

We revised the biogenic CO_2 emission credit associated with biodiesel pathways to address the fact that a portion of the CO_2 emissions from biodiesel are from fossil-based methanol. "Fossil-derived" methanol is one of the major inputs to biodiesel production, and this methanol input ends up comprising about 5% of the total carbon content of the biodiesel after the transesterification reactions (Clifford 2018). Note that co-produced glycerin can be considered as renewable glycerin with all the carbon therein coming from vegetable oil that is used in the transesterification reactions.

3.7 Carinata Hydroprocessed Esters and Fatty Acids (HEFA) Jet Fuel Production

Uisung Lee (ulee@anl.gov)

In GREET 2018, we added carinata-derived jet fuel production pathways via hydroprocessed esters and fatty acid (HEFA) conversion pathways. GREET 2017 already included aviation fuels produced from soybean, palm, jatropha, rapeseed, and camelina, and canola through HEFA conversion (Han et al. 2013; A. Elgowainy et al. 2012; Han et al. 2017). The new pathway reflects a new attempt to use oil extracted from brassica carinata seeds to produce jet fuels via the HEFA conversion pathway.

Farming energy and fertilizer application rates were collected from Moeller et al. (2017) and Sieverding et al. (2016) that reflect carinata farming in northern United States and Canada. For oil extraction, we assume organic solvent (n-hexane) is used, and chemical and energy use are estimated based on Rispoli (2014). For the HEFA conversion process, Han et al. (2013)

estimated hydrogen, natural gas, and electricity inputs and yields of jet fuel, propane, and naphtha based on fatty acid profiles. We used this data to estimate the inputs required for carinata HEFA conversion. Note that this expansion is intended to serve as a placeholder for the carinata HEFA jet fuel production pathway, for which more detailed datasets for a comprehensive LCA can be conducted in the future. In addition, considering carinata used as a cover crop could affect the farming inputs, in contrast to the case in GREET 2018, where the pathway is based on farming carinata as a primary growing season crop.

4 REFERENCES

Alvarez, Ramón A., Daniel Zavala-Araiza, David R. Lyon, David T. Allen, Zachary R. Barkley, Adam R. Brandt, Kenneth J. Davis, et al. 2018. “Assessment of Methane Emissions from the U.S. Oil and Gas Supply Chain.” *Science*, June, eaar7204. https://doi.org/10.1126/science.aar7204.

CAPP (Canadian Association of Petroleum Producers). 2016. “2016 CAPP Crude Oil Forecast, Markets & Transportation.” http://www.capp.ca/publications-and-statistics/crude-oil-forecast.

CAPP. 2018. “2018 CAPP Crude Oil Forecast, Markets & Transportation.” https://www.capp.ca/publications-and-statistics/crude-oil-forecast.

Clifford, Caroline Burgess. 2018. “Alternative Fuels from Biomass Sources.” https://www.e-education.psu.edu/egee439/node/684.

Davis, Ryan E., Jennifer N. Markham, Christopher M. Kinchin, Christina Canter, Jeongwoo Han, Qianfeng Li, Andre Coleman, Mark Wigmosta, and Yunhua Zhu. 2018. “2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling.” National Renewable Energy Lab (NREL), Golden, CO (United States).

EIA (Energy Information Administration). 2018a. “EIA Electricity.” https://www.eia.gov/electricity/state/hawaii/index.php.

EIA. 2018b. “Annual Energy Outlook 2018.” https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf.

EIA. 2018c. “Company Level Imports.” https://www.eia.gov/petroleum/imports/companylevel/.

Elgowainy, Amgad, Jeongwoo Han, Michael Wang, Nicholas Carter, Russell Stratton, James Hileman, Andrew Malwitz, and Sathya Balasubramanian. 2012. “Life-Cycle Analysis of Alternative Aviation Fuels in GREET.” ANL/ESD/12-8. Argonne National Laboratory.

Elgowainy, Amgad, Jeongwoo Han, Leslie Poch, Michael Wang, Anant Vyas, Matthew Mahalik, and Aymeric Rousseau. 2010. “Well-to-Wheels Analysis of Energy Use and Greenhouse Gas Emissions of Plug-in Hybrid Electric Vehicles.” ANL/ESD/10-1. Argonne National Laboratory, Argonne, IL (United States).

Elgowainy, Amgad, Jeongwoo Han, Jacob Ward, Fred Joseck, David Gohlke, Alicia Lindauer, Todd Ramsden, et al. 2016. “Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies.” ANL/ESD-16/7 Rev. 1. Argonne National Laboratory, Argonne, IL (United States). https://www.osti.gov/scitech/biblio/1324467-cradle-grave-lifecycle-

analysis-light-duty-vehicle-fuel-pathways-greenhouse-gas-emissions-economic-assessment-current-future-technologies.
EPA (U.S. Environmental Protection Agency). 2018a. “Emissions & Generation Resource Integrated Database (EGRID) 2016.” https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.

EPA. 2018b. “Inventory of U.S. Greenhouse Gas Emissions and Sinks:1990 - 2016.” EPA 430-R-18-003. https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf.

EPA. 2018c. “Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 through 2017.” EPA-420-R-18-001. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100TGDW.pdf.

EPA. 2006. “Fuel Economy Labeling of Motor Vehicles: Revisions to Improve Calculation of Fuel Economy Estimates.” EPA420-R-06–017. Office of Transportation and Air Quality Washington, DC.

Franzese, Oscar, and Diane Davidson. 2011. “Effect of Weight and Roadway Grade on the Fuel Economy of Class-8 Freight Trucks.” Oak Ridge National Laboratory.

Han, Jeongwoo, Amgad Elgowainy, Hao Cai, and Michael Wang. 2013. “Life-Cycle Analysis of Bio-Based Aviation Fuels.” Bioresource Technology 150 (December): 447–56. https://doi.org/10.1016/j.biortech.2013.07.153.

Han, Jeongwoo, Ling Tao, and Michael Wang. 2017. “Well-to-Wake Analysis of Ethanol-to-Jet and Sugar-to-Jet Pathways.” Biotechnology for Biofuels 10 (1): 21.

Kruse, Carl James, Annie Protopapas, Leslie E. Olson, and David H. Bierling. 2007. “A Modal Comparison of Domestic Freight Transportation Effects on the General Public.”

Lee, Uisung, Jeongwoo Han, and Hao Cai. 2016. “Update of Electric Generation Mix and Crude Oil Share.” https://greet.es.anl.gov/publication-electricity-crude-share-2016.

Michael Wang, Ye Wu, and Amgad Elgowainy. 2007. “Operating Manual for GREET: Version 1.7.” Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.

Moawad, Ayman, Namdoo Kim, Neeraj Shidore, and Aymeric Rousseau. 2016. “Assessment of Vehicle Sizing, Energy Consumption and Cost through Large Scale Simulation of Advanced Vehicle Technologies.” ANL/ESD-15/28. Argonne National Laboratory, Argonne, IL (United States). https://www.osti.gov/scitech/biblio/1245199.

Moeller, Devin, Heidi L. Sieverding, and James J. Stone. 2017. “Comparative Farm-Gate Life Cycle Assessment of Oilseed Feedstocks in the Northern Great Plains.” BioPhysical Economics and Resource Quality 2(4): 13. https://doi.org/10.1007/s41247-017-0030-3.

ORNL (Oak Ridge National Laboratory). 2018. “Transportation Energy Data Book. Edition 36.” ORNL/TM-2017/513. ORNL, Oak Ridge, Tennessee. https://cta.ornl.gov/data/index.shtml.

Rispoli, Katherine. 2014. “Life Cycle and Supply Assessment of Aviation Biofuels in the Canadian Context.” Master Thesis. University of Toronto. https://tspace.library.utoronto.ca/handle/1807/82670.

Sieverding, Heidi L., Xianhui Zhao, Lin Wei, and James J. Stone. 2016. “Life-Cycle Assessment of Oilseeds for Biojet Production Using Localized Cold-Press Extraction.” Journal of Environmental Quality 45 (3): 967–76. https://doi.org/10.2134/jeq2015.06.0313.

APPENDIX A – U.S. ELECTRICITY GENERATION MIX

TABLE A1 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										
2016	0.6%	32.7%	31.4%	20.5%	0.3%	6.9%	0.4%	5.8%	0.9%	0.5%
2017	0.5%	29.8%	32.7%	20.6%	0.1%	7.7%	0.4%	6.4%	1.2%	0.5%
2020	0.3%	31.3%	29.6%	19.1%	0.2%	7.4%	0.4%	8.7%	2.4%	0.5%
2025	0.3%	32.2%	28.6%	17.6%	0.2%	7.3%	0.7%	9.9%	2.7%	0.5%
2030	0.2%	33.0%	28.2%	16.6%	0.2%	7.1%	1.0%	9.7%	3.4%	0.6%
2035	0.2%	33.2%	26.9%	15.6%	0.2%	6.9%	1.2%	9.5%	5.8%	0.6%
2040	0.2%	33.7%	26.0%	15.0%	0.2%	6.7%	1.2%	9.3%	7.0%	0.6%
2045	0.2%	34.4%	25.3%	14.4%	0.2%	6.5%	1.3%	9.3%	7.9%	0.6%
2050	0.2%	35.2%	24.5%	13.5%	0.2%	6.3%	1.4%	9.3%	8.7%	0.6%
Texas Reliability Entity (TRE) Mix										
2016	0.0%	45.6%	29.1%	12.1%	0.0%	0.5%	0.0%	12.2%	0.2%	0.2%
2017	0.1%	45.5%	28.9%	11.5%	0.0%	0.2%	0.0%	13.1%	0.5%	0.2%
2020	0.1%	52.8%	19.1%	10.8%	0.0%	0.2%	0.0%	15.7%	1.1%	0.2%
2025	0.1%	51.3%	21.0%	10.9%	0.0%	0.2%	0.0%	15.0%	1.3%	0.2%
2030	0.1%	55.4%	20.1%	8.2%	0.0%	0.2%	0.0%	14.3%	1.5%	0.2%
2035	0.1%	56.4%	19.1%	6.7%	0.0%	0.2%	0.0%	13.7%	3.6%	0.3%
2040	0.1%	57.7%	18.2%	6.4%	0.0%	0.2%	0.0%	13.1%	4.1%	0.3%
2045	0.1%	59.4%	17.3%	6.1%	0.0%	0.2%	0.0%	12.5%	4.0%	0.4%
2050	0.1%	60.9%	16.5%	5.9%	0.0%	0.2%	0.0%	12.0%	4.0%	0.5%
Florida Reliability Coordinating Council (FRCC) Mix										
2016	1.2%	67.5%	16.3%	13.0%	0.1%	0.7%	0.0%	0.0%	0.1%	1.0%
2017	0.2%	71.1%	14.1%	12.5%	0.1%	0.7%	0.0%	0.0%	0.3%	1.0%
2020	0.2%	73.9%	11.2%	12.1%	0.1%	0.7%	0.0%	0.0%	0.7%	1.2%
2025	0.2%	70.1%	13.6%	11.7%	0.1%	0.7%	0.0%	0.0%	2.4%	1.2%
2030	0.2%	68.4%	13.3%	11.4%	0.1%	0.6%	0.0%	0.0%	5.0%	1.1%
2035	0.1%	66.3%	9.2%	10.9%	0.1%	0.6%	0.0%	0.0%	11.6%	1.1%
2040	0.2%	59.4%	10.9%	10.1%	0.1%	0.5%	0.0%	0.0%	17.9%	1.0%
2045	0.1%	59.9%	10.9%	9.6%	0.1%	0.5%	0.0%	0.0%	17.6%	1.2%
2050	0.1%	59.0%	10.3%	9.1%	0.1%	0.4%	0.0%	0.0%	19.8%	1.1%

TABLE A1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Midwest Reliability Organization (MRO) Mix										
2016	0.2%	8.1%	51.2%	12.7%	0.4%	5.6%	0.0%	21.2%	0.1%	0.7%
2017	0.3%	5.0%	54.2%	10.6%	0.3%	5.3%	0.0%	23.8%	0.3%	0.3%
2020	0.2%	8.3%	46.5%	9.3%	0.2%	5.0%	0.0%	29.7%	0.4%	0.3%
2025	0.2%	9.7%	45.6%	3.0%	0.3%	4.9%	0.0%	35.6%	0.4%	0.3%
2030	0.2%	9.7%	46.1%	2.7%	0.3%	4.8%	0.0%	35.6%	0.4%	0.3%
2035	0.2%	10.8%	45.4%	2.0%	0.3%	4.7%	0.0%	35.9%	0.4%	0.3%
2040	0.2%	11.9%	44.8%	2.0%	0.3%	4.7%	0.0%	35.4%	0.4%	0.3%
2045	0.2%	10.2%	43.7%	2.1%	0.3%	4.7%	0.0%	38.0%	0.4%	0.3%
2050	0.2%	10.0%	42.6%	2.0%	0.3%	4.5%	0.0%	39.5%	0.4%	0.4%
Northeast Power Coordinating Council (NPCC) Mix										
2016	0.5%	46.8%	1.6%	30.7%	1.8%	14.1%	0.0%	2.7%	0.4%	1.4%
2017	0.3%	40.0%	4.8%	32.5%	0.4%	16.5%	0.0%	3.2%	0.5%	1.9%
2020	0.2%	45.2%	2.5%	27.7%	0.3%	17.1%	0.0%	4.3%	0.8%	2.0%
2025	0.2%	49.0%	2.5%	24.1%	0.4%	16.9%	0.0%	4.2%	0.8%	2.0%
2030	0.2%	50.8%	1.5%	22.6%	0.6%	17.3%	0.0%	4.3%	0.8%	2.0%
2035	0.1%	51.4%	0.8%	21.4%	0.6%	18.2%	0.0%	4.6%	0.8%	2.1%
2040	0.1%	53.7%	0.8%	18.7%	0.6%	18.4%	0.0%	4.7%	0.8%	2.2%
2045	0.1%	54.1%	0.8%	18.6%	0.6%	18.2%	0.0%	4.7%	0.7%	2.2%
2050	0.1%	55.9%	0.8%	16.3%	0.7%	18.4%	0.0%	4.9%	0.7%	2.3%
Reliability First Corporation (RFC) Mix										
2016	0.4%	24.6%	39.4%	30.9%	0.1%	1.2%	0.0%	2.7%	0.2%	0.6%
2017	0.2%	19.6%	45.1%	30.1%	0.1%	1.3%	0.0%	2.7%	0.2%	0.7%
2020	0.2%	24.0%	43.4%	26.6%	0.1%	1.3%	0.0%	3.6%	0.2%	0.7%
2025	0.2%	27.9%	41.4%	24.6%	0.1%	1.3%	0.0%	3.6%	0.2%	0.7%
2030	0.2%	28.8%	41.7%	23.6%	0.1%	1.3%	0.0%	3.5%	0.2%	0.7%
2035	0.2%	30.9%	40.9%	22.3%	0.1%	1.2%	0.0%	3.4%	0.3%	0.7%
2040	0.2%	32.9%	39.9%	21.4%	0.1%	1.2%	0.0%	3.3%	0.3%	0.7%
2045	0.2%	34.8%	39.4%	20.0%	0.1%	1.2%	0.0%	3.3%	0.3%	0.7%
2050	0.2%	37.4%	38.7%	18.1%	0.1%	1.2%	0.0%	3.3%	0.4%	0.7%

TABLE A1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
SERC Reliability Corporation (SERC) Mix										
2016	0.4%	32.9%	35.2%	27.4%	0.3%	2.8%	0.0%	0.4%	0.4%	0.2%
2017	0.3%	30.9%	34.4%	29.4%	0.2%	3.3%	0.0%	0.6%	0.7%	0.2%
2020	0.3%	31.1%	31.8%	29.4%	0.3%	3.2%	0.0%	1.0%	2.7%	0.2%
2025	0.2%	33.3%	30.6%	28.2%	0.3%	3.1%	0.0%	0.9%	3.1%	0.2%
2030	0.1%	34.5%	29.6%	27.4%	0.3%	2.9%	0.0%	0.9%	4.1%	0.2%
2035	0.1%	33.0%	26.9%	26.2%	0.2%	2.8%	0.0%	0.8%	9.7%	0.2%
2040	0.1%	34.1%	25.7%	25.7%	0.2%	2.7%	0.0%	0.8%	10.5%	0.2%
2045	0.1%	35.1%	24.6%	24.6%	0.2%	2.6%	0.0%	0.8%	11.9%	0.2%
2050	0.1%	35.2%	24.4%	23.8%	0.2%	2.5%	0.0%	0.8%	12.7%	0.2%
Southwest Power Pool (SPP) Mix										
2016	1.4%	29.2%	39.7%	3.7%	0.0%	2.8%	0.0%	23.0%	0.2%	0.0%
2017	1.7%	30.8%	32.5%	3.9%	0.0%	3.9%	0.0%	26.9%	0.3%	0.0%
2020	0.1%	24.5%	35.8%	3.5%	0.0%	3.4%	0.0%	32.3%	0.3%	0.0%
2025	0.2%	17.0%	38.5%	3.2%	0.0%	3.2%	0.0%	37.6%	0.3%	0.0%
2030	0.2%	17.5%	37.0%	3.2%	0.0%	3.1%	0.0%	37.4%	1.7%	0.0%
2035	0.2%	16.9%	36.2%	3.1%	0.0%	3.0%	0.0%	36.9%	3.7%	0.0%
2040	0.1%	17.5%	33.2%	3.2%	0.0%	2.9%	0.0%	35.0%	8.0%	0.0%
2045	0.1%	17.2%	31.9%	3.1%	0.0%	2.8%	0.0%	34.1%	10.9%	0.0%
2050	0.1%	18.3%	29.4%	2.9%	0.0%	2.6%	0.0%	33.7%	13.0%	0.0%
Western Electricity Coordinating Council (WECC) Mix										
2016	0.1%	29.4%	23.5%	8.6%	0.5%	24.4%	2.2%	7.2%	3.8%	0.4%
2017	0.2%	25.5%	24.7%	8.3%	0.1%	26.7%	2.3%	6.9%	4.7%	0.4%
2020	0.1%	23.2%	21.1%	8.1%	0.1%	25.8%	2.2%	11.5%	7.5%	0.5%
2025	0.1%	22.3%	17.6%	6.8%	0.4%	25.7%	3.6%	14.3%	8.6%	0.6%
2030	0.1%	21.6%	17.2%	5.6%	0.4%	25.6%	5.3%	14.3%	9.3%	0.6%
2035	0.1%	20.9%	17.0%	4.3%	0.4%	25.5%	6.6%	14.4%	10.0%	0.7%
2040	0.1%	19.5%	16.5%	4.5%	0.4%	25.1%	7.1%	14.2%	11.8%	0.8%
2045	0.1%	18.1%	16.3%	4.5%	0.3%	24.7%	7.7%	14.0%	13.5%	0.8%
2050	0.1%	17.8%	15.0%	4.4%	0.3%	24.2%	8.1%	13.9%	15.3%	0.8%

TABLE A1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
California Mix										
2016	0.0%	45.5%	4.6%	10.3%	1.2%	15.2%	4.8%	7.7%	9.6%	1.1%
2017	0.0%	41.3%	6.3%	9.7%	0.5%	17.9%	5.0%	7.1%	11.1%	1.2%
2020	0.0%	33.1%	4.2%	9.8%	0.5%	18.1%	4.7%	9.0%	19.3%	1.3%
2025	0.0%	30.4%	0.0%	4.6%	1.5%	17.2%	8.6%	14.8%	21.7%	1.3%
2030	0.0%	27.4%	0.0%	0.0%	1.6%	17.6%	14.0%	15.3%	22.8%	1.4%
2035	0.0%	22.2%	0.0%	0.0%	1.6%	17.7%	18.6%	15.5%	23.1%	1.4%
2040	0.0%	20.1%	0.0%	0.0%	1.5%	17.7%	20.9%	15.6%	22.9%	1.4%
2045	0.0%	19.1%	0.0%	0.0%	1.1%	17.3%	23.2%	15.3%	22.5%	1.4%
2050	0.0%	17.4%	0.0%	0.0%	0.9%	16.8%	24.7%	14.9%	23.9%	1.4%
Alaska Mix										
2016	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2017	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2020	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2025	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2030	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2035	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2040	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2045	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
2050	13.1%	48.0%	9.4%	0.0%	0.7%	26.2%	0.0%	2.7%	0.0%	0.0%
Hawaii Mix										
2016	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2017	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2020	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2025	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2030	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2035	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2040	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2045	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%
2050	66.7%	0.0%	15.1%	0.0%	3.6%	0.9%	2.6%	6.4%	0.9%	3.8%

APPENDIX B – UPDATED FUEL ECONOMY VALUES

TABLE B1 Vehicle Operation Combinations in GREET

Parameter	Description
Vehicle types	Car: midsize sedan Light duty truck 1 (LDT1): midsize sports utility vehicle (SUV) LDT2 – pickup truck (PUT)
Fuel type	Gasoline (E10) Renewable gasoline Compressed natural gas (CNG) Liquefied natural gas (LNG) Liquefied petroleum gas (LPG) Methanol (for flexible-fuel vehicle [FFV]) Ethanol (for FFV) Butanol (for FFV) Diesel Dimethyl ether (DME) Fischer-Tropsch diesel (FT diesel) Biodiesel Renewable diesel Ethanol-diesel (E-diesel)
Powertrain type	Spark ignition (SI) Spark ignition direct injection (SIDI) Compression ignition direct injection (CIDI) Grid-independent hybrid electric vehicle (HEV) Grid-connected plug-in hybrid electric vehicle (PHEV) Battery electric vehicle (BEV) Fuel-cell electric vehicle (FCEV)
Vehicle materials	Conventional materials Light-weight materials

TABLE B2 Fuel Economy Time Series for Passenger Cars

Fuel/Vehicle Type	Model Year 1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2050
Gasoline (MPGGE)	**22.10**	**21.70**	**22.00**	**23.40**	**26.08**	**26.16**	**30.93**	**33.74**	**35.55**	**37.82**	**41.38**
Diesel (MPGGE)	**26.52**	**26.04**	**26.40**	**28.08**	**31.30**	**31.58**	**34.58**	**37.06**	**39.41**	**42.74**	**46.88**
CIDI Vehicles (CD / Low-Sulfur Diesel / DME / FT Diesel / Biodiesel / RD / E-diesel)	120%	120%	120%	120%	120%	121%	112%	110%	111%	113%	113%
SI HEV	100%	100%	100%	140%	140%	139%	150%	149%	153%	154%	156%
PHEV Gasoline (CD)	100%	100%	100%	349%	363%	312%	308%	302%	310%	320%	312%
PHEV Gasoline (CS)	100%	100%	100%	111%	140%	136%	143%	147%	152%	155%	155%
CIDI HEV	100%	100%	100%	160%	160%	138%	137%	133%	139%	146%	143%
CIDI PHEV (CD)	100%	100%	100%	350%	354%	304%	300%	293%	302%	311%	303%
CIDI PHEV (CS)	100%	100%	100%	115%	135%	131%	133%	133%	143%	148%	146%
EVs	300%	300%	400%	400%	425%	384%	367%	357%	371%	381%	370%
H2 FCV	100%	100%	100%	210%	210%	207%	199%	214%	224%	238%	241%
FC PHEV H2 (CD)	100%	100%	100%	426%	382%	295%	286%	281%	292%	301%	296%
FC PHEV H2 (CS)	100%	100%	100%	177%	177%	194%	188%	183%	189%	195%	192%

TABLE B3 Fuel Economy Time Series for LDT1

Fuel/Vehicle Type	Model Year										
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2050
Gasoline (MPGGE)	**16.60**	**16.20**	**16.30**	**17.30**	**20.06**	**20.06**	**22.65**	**23.96**	**24.70**	**27.39**	**29.59**
Diesel (MPGGE)	**19.92**	**19.44**	**19.56**	**20.76**	**24.07**	**25.54**	**27.29**	**28.75**	**29.76**	**31.34**	**33.38**
CIDI Vehicles (CD / Low-Sulfur Diesel / DME / FT Diesel / Biodiesel / RD / E-diesel)	120%	120%	120%	120%	120%	127%	120%	120%	120%	114%	113%
SI HEV	100%	100%	100%	135%	135%	148%	159%	164%	170%	162%	175%
PHEV Gasoline (CD)	100%	100%	100%	302%	395%	310%	305%	309%	312%	289%	287%
PHEV Gasoline (CS)	100%	100%	100%	101%	135%	136%	145%	161%	164%	154%	158%
CIDI HEV	100%	100%	100%	160%	160%	148%	147%	150%	155%	148%	147%
CIDI PHEV (CD)	100%	100%	100%	303%	387%	304%	299%	303%	305%	283%	282%
CIDI PHEV (CS)	100%	100%	100%	105%	130%	132%	136%	145%	153%	147%	149%
EVs	300%	300%	400%	400%	485%	377%	362%	364%	370%	342%	338%
H2 FCV	100%	100%	100%	210%	200%	206%	197%	217%	222%	211%	217%
FC PHEV H2 (CD)	100%	100%	100%	309%	267%	290%	284%	289%	292%	273%	274%
FC PHEV H2 (CS)	100%	100%	100%	155%	155%	195%	189%	210%	217%	207%	213%

TABLE B4 Fuel Economy Time Series for LDT2

Fuel/Vehicle Type	Model Year										
	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2050
Gasoline (MPGGE)	**13.40**	**13.10**	**13.60**	**14.70**	**16.43**	**16.43**	**18.68**	**19.78**	**20.40**	**23.55**	**24.55**
Diesel (MPGGE)	**16.08**	**15.72**	**16.32**	**17.64**	**19.72**	**20.82**	**22.86**	**24.20**	**24.95**	**27.43**	**28.26**
CIDI Vehicles (CD / Low-Sulfur Diesel / DME / FT Diesel / Biodiesel / RD / E-diesel)	120%	120%	120%	120%	120%	127%	122%	122%	122%	116%	115%
SI HEV	100%	100%	100%	130%	130%	147%	162%	170%	176%	162%	178%
PHEV Gasoline (CD)	100%	100%	100%	280%	425%	298%	303%	308%	312%	280%	281%
PHEV Gasoline (CS)	100%	100%	100%	102%	138%	143%	147%	165%	168%	153%	159%
CIDI HEV	100%	100%	100%	160%	160%	148%	150%	156%	161%	148%	151%
CIDI PHEV (CD)	100%	100%	100%	274%	416%	294%	298%	306%	306%	275%	277%
CIDI PHEV (CS)	100%	100%	100%	105%	134%	143%	147%	165%	168%	153%	159%
EVs	300%	300%	400%	400%	565%	360%	358%	365%	370%	332%	332%
H2 FCV	100%	100%	100%	210%	205%	201%	197%	216%	221%	204%	212%
FC PHEV H2 (CD)	100%	100%	100%	297%	265%	277%	281%	290%	293%	264%	267%
FC PHEV H2 (CS)	100%	100%	100%	153%	153%	190%	190%	212%	219%	201%	210%

APPENDIX C – U.S. CRUDE OIL MIX

TABLE C1 Crude Oil Share in the United States by 2050

Year	U.S. Domestic[1]	Canada (Oil Sands)[2]	Canada (Conv. Crude)[2]	Mexico[3]	Middle East[3]	Latin America[3]	Africa[3]	Others[3]
2017	57.4%	10.3%	10.2%	3.0%	8.5%	6.7%	3.1%	0.8%
2020	60.3%	11.7%	7.1%	2.8%	8.0%	6.3%	2.9%	0.8%
2025	65.5%	12.0%	7.1%	2.1%	5.9%	4.7%	2.1%	0.6%
2030	68.2%	12.4%	7.1%	1.7%	4.7%	3.7%	1.7%	0.5%
2035	68.0%	12.4%	6.9%	1.7%	4.9%	3.9%	1.8%	0.5%
2050	65.7%	12.6%	7.0%	2.0%	5.7%	4.5%	2.0%	0.6%

[1] EIA (2018b).
[2] CAPP (2016) and CAPP (2018).
[3] EIA (2018c).

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