

## **Summary of Expansions and Updates in GREET® 2022**

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**Energy Systems and Infrastructure Analysis Division  
Argonne National Laboratory**

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## **Summary of Expansions and Updates in GREET® 2022**

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# CONTENTS

Contents .....	iii
Tables .....	v
Acknowledgements.....	vi
1. Introduction.....	1
2. Major Expansions and Updates in GREET 2022 .....	1
2.1. Energy Products .....	1
2.1.1. Hydrogen.....	1
2.1.2. CO <sub>2</sub> Utilization.....	2
2.1.3. Offshore Macroalgae Production .....	5
2.1.4. Marine Fuel Production Pathways .....	5
2.1.5. 2021 SOT SCSA Pathways.....	6
2.1.6. Biodiesel and Renewable Diesel from Used Cooking Oil.....	6
2.1.7. Post-Use Plastic (PUP) Pyrolysis Conversion .....	7
2.2. Vehicles.....	7
2.2.1. Infrastructure for Electricity Generation.....	7
2.2.2. LDV and MHDV Vehicle Component Updates .....	8
2.2.3. Battery Anodes (Graphite, Lithium, and Silicon).....	9
2.3. Materials .....	9
2.3.1. Waste to Polylactic Acid (PLA) pathways .....	9
2.3.2. Circular Economy Framework for Plastics.....	10
2.3.3. Conventional, Green, and Blue Ammonia Production .....	10
2.3.4. Plastic Upcycling to Lubricant Product .....	11
2.3.5. Poly-alpha Olefins (PAO).....	12
2.3.6. Domestic Li-chemical Production in North America .....	12
2.3.7. Updates on Inventory of Aluminum Production.....	13
2.3.8. Critical Materials (Nickel, Copper, Titanium, and Rare-Earth Elements) .....	13
2.3.9. EOL Displacement Method (Steel/Aluminum) .....	14
2.3.10. Electrolyzers for Hydrogen Production: Solid Oxide, Alkaline, and Proton Exchange Membrane .....	14
3. Other Updates and Additions.....	15

3.1. GREET Modeling Features.....	15
3.1.1. GREET Marine Module.....	15
3.1.2. GREET Aviation Module .....	15
3.1.3. Feedstock Carbon Intensity Calculator (FD-CIC) .....	16
3.1.4. GREET Building Module .....	16
3.2. Other Updates .....	17
3.2.1. Global Warming Potential .....	17
3.2.2. Electricity Generation Mix and Crude Oil Mix Updates .....	17
3.2.3. Methane Leakage of Natural Gas Supply Chain.....	18
3.2.4. Fuel Use for Natural Gas Recovery .....	18
3.2.5. Updates in Plastics Inventories .....	19
3.2.6. Rail Energy Intensity .....	19
3.2.7. Aviation Payload Fuel Energy Intensities and Combustion Emission Factors.....	20
3.2.8. Heavy-Duty Vehicle HEVs.....	21
3.2.9. Light-duty Vehicle Diesel CH <sub>4</sub> Emission Factors .....	21
3.2.10. Update of the U.S. Conventional Feedstock Slate of Steam Crackers .....	21
3.2.11. Air Separation Unit (ASU) .....	22
3.2.12. Update of Uranium Tab for Nuclear Light Water Reactor (LWR) and High Temperature Gas Reactor (HTGR).....	22
3.2.13. Forthcoming Update of Methane and Carbon Dioxide Emissions from Flaring During Petroleum Production and Natural Gas Production.....	22
4. Helps, Tutorials, and Presentation materials .....	23
5. References.....	24
Appendix A: U.S. ELECTRICITY GENERATION MIX .....	27
Appendix B: U.S. Crude Oil Mix .....	31

## TABLES

Table 1. Global Warming Potential (GWP) and Global Temperature Potential (GTP) Values Based on IPCC AR6. ....	17
Table 2. Diesel and Electricity used by Intercity and Commuter Rails.....	20
Table 3. 2019 BTS T-2 Data Aggregated by Aircraft Types.....	20
Table 4. Updated Feedstock Slate of Steam Crackers in The United States .....	22
TABLE A-1. Electric Generation Mix of the United States, Eight NERC Regions, and Three States.....	27
TABLE A-1 (Cont.).....	28
TABLE A-1 (Cont.).....	29
TABLE A-1 (Cont.).....	30
TABLE B-1. Crude Oil Share in the United States by 2050 .....	31

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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 (Argonne) with the support of the U.S. Department of Energy (DOE) and other federal agencies. 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 2022, and this report provides a summary of the release.

## 2. MAJOR EXPANSIONS AND UPDATES IN GREET 2022

### 2.1. Energy Products

#### 2.1.1. Hydrogen

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This section documents updates and expansions of hydrogen pathways including:

- Central Plants: North American Natural Gas (NA NG) Steam Methane Reforming (SMR) to Gaseous Hydrogen (with and without carbon capture and sequestration [CCS])
- Central Plants: Renewable Natural Gas SMR to Gaseous Hydrogen
- Central Plants: PEM Electrolysis to Gaseous Hydrogen
- Central Plants: Coal to Gaseous Hydrogen via Gasification (with and without CCS)
- Central Plants: Nuclear Electricity-based High Temperature Electrolysis with Solid Oxide Electrolyzer Cell (SOEC) to Gaseous Hydrogen
- Central Plants: By-product of Gaseous H<sub>2</sub> from Chlorine plants
- Central Plants: By-product Gaseous H<sub>2</sub> from Natural Gas Liquid (NGL) Steam Crackers
- Developed a separate pathway of SMR hydrogen production for industrial applications (e.g., refineries and ammonia plants)
- Developed a graphical user interface for major hydrogen pathways in a separate worksheet in the GREET Excel version to allow facility-level input data and hydrogen results. This ensures that different scope emissions can be calculated and added into well-to-plant gate greenhouse gas (GHG) emissions, ensuring consistency with the scope of production tax credit (PTC) in the Inflation Reduction Act (IRA)

Minor updates were made in biomass gasification pathway to normalize hydrogen product pressure to 20 bar. Default compression and precooling electricity use at refueling stations were updated from light-duty vehicles (LDVs) to medium- and heavy-duty vehicles (MHDVs). Precooling electricity use at refueling stations was updated with options of -20°C or -40°C (default). The production stage for liquid hydrogen pathways was updated to be consistent with the updates to

gaseous hydrogen pathways. Updates were made to losses incurred in the transportation and distribution of liquid hydrogen. Default trucking transportation distance for all gaseous and liquid hydrogen pathways were updated to 100 miles. SMR for the industrial hydrogen pathway considers similar production stage as default case of Central Plants: NG to Gaseous Hydrogen with a default of 150 miles of pipeline distribution. The GREET Excel version with graphical user interface for major hydrogen pathways is available separately (see link provided below) from the general GREET release. The technical report below offers a detailed discussion of all hydrogen pathway expansions and updates.

*Technical Report:*

<https://greet.es.anl.gov/publication-hydrogenreport2022>

Hydrogen with Graphical User Interface with GREET Excel Link:

[https://greet.es.anl.gov/greet\\_hydrogen](https://greet.es.anl.gov/greet_hydrogen)

### **2.1.2. CO<sub>2</sub> Utilization**

#### **Carbon accounting in CO<sub>2</sub> utilization pathways**

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To clarify the system boundary and carbon accounting of CO<sub>2</sub> utilization pathways, we released a technical memo on accounting for CO<sub>2</sub> sources in analyzing CO<sub>2</sub> emissions of carbon capture and utilization (CCU) technologies. In the memo below, we discuss CO<sub>2</sub> accounting methods depending on the source of CO<sub>2</sub> and the fate of CCU products.

*Technical Memo:*

<https://greet.es.anl.gov/publication-ccu2022>

#### **CO<sub>2</sub> Capture, compression, and transportation**

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In GREET 2022, we added multiple CO<sub>2</sub> sources for e-fuel production. CO<sub>2</sub> sources include ethanol production, ammonia production, natural gas (NG) processing, hydrogen production, cement production, iron/steel production, NG power plants, and coal-fired power plants, which are based on Zang et al. (2021). We added additional direct air capture (DAC) options.

The energy requirements for CO<sub>2</sub> capture from the selected industries are based on ASPEN simulations presented in Zang et al. (2021). The original ASPEN designs in that paper were from two National Energy Technology Laboratory (NETL) reports (NETL 2013, NETL 2015). No capture process is required for high-purity CO<sub>2</sub> sources from ethanol plants, ammonia plants, and

NG processing plants (i.e., zero capture energy use). The Methyl diethylamine (MDEA) CO<sub>2</sub> removal process is assumed to capture CO<sub>2</sub> from medium-purity CO<sub>2</sub> sources from SMR hydrogen plants, cement plants, and iron & steel plants, and to capture low-purity CO<sub>2</sub> sources from NG power plants and coal power plants.

The MDEA removal process requires low-pressure steam which we assume to be generated by NG boilers (with assumed 80% energy efficiency). We applied the NG input to the boilers for CO<sub>2</sub> capture from SMR hydrogen plants, cement plants, and iron & steel plants. Because power plants already produce steam, we assumed no dedicated fuel use for steam generation for CO<sub>2</sub> capture. Instead, the loss of the net power generation due to steam use for CO<sub>2</sub> capture is converted as additional electricity requirements for CO<sub>2</sub> capture.

In GREET 2022, we also updated the CO<sub>2</sub> compression energy use that is calculated with the thermodynamic compression formula in GREET. It follows the CO<sub>2</sub> compressor table in the *Compression* tab. The compression conditions (the inlet temperature, the inlet and outlet pressures) for each industry are specified in Zang et al. (2021) and the two NETL reports (NETL 2013, NETL 2015).

In addition, we included additional electricity requirements for operating booster compression stations while transporting CO<sub>2</sub> through long-distance pipelines. The pipeline upstream and downstream pressures are set at 2,200 psia and 1,500 psia. CO<sub>2</sub> temperature is set to 25°C (an ambient temperature). CO<sub>2</sub> is in liquid phase at 25°C under the transported pressure of 1,500–2,200 psia. The booster compression energy efficiency is set as 75%. At a given temperature with fixed inlet and outlet pressures, the average CO<sub>2</sub> density (calculated by the z-factor) is used for the compression electricity requirement. The electricity requirement to operate one booster compressor at the given condition is 7.7 MJ/metric ton of CO<sub>2</sub>.

A rule-of-thumb assumption of distance between booster compression stations is 100 miles. The GREET default pipeline distance is 200 miles. This results in one booster compression station as the default. GREET user can manually change the pipeline distance between booster compression stations, pressures, pressure ratio per stage, and compression energy efficiency. GREET then calculates the corresponding number of booster compressors and the corresponding electricity requirement.

*Publication:*

Zang, G., Sun, P., Yoo, E., Elgowainy, A., Bafana, A., Lee, U., Wang, M. and Supekar, S. Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO<sub>2</sub> from Industrial and Power Plants in the United States. 2021. *Environmental Science & Technology*, 55, 11, 7595–7604. Doi.org/10.1021/acs.est.0c08674

## **Direct Air Capture (DAC)**

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We expanded the DAC option in the *E\_fuel* tab to include (1) infrastructure impacts for the low-temperature (LT) DAC system and (2) a high-temperature (HT) liquid absorption-based DAC system.

Various facility infrastructure and solid sorbent scenarios were introduced in Deutz & Bardow (2021). Although the impacts on GHG emissions from these may appear small compared to operational activities (natural gas for heating and grid power), infrastructure impacts become the major contributing factor to GHG emissions if low-burden or burden-free energy sources (waste heat and renewable electricity) are used for DAC.

Facility material use is dependent on the scale of DAC. Deutz & Bardow (2021) introduced the LT DAC technology at a 4 kiloton per year (kty) capacity for an individual plant but noted that plants should scale to 100 kty capacity to meet a capture target of 1% of annual global CO<sub>2</sub> emissions. Facility material use, or bill of materials, was provided by correspondence with Bardow (2021) for 4 kty and 100 kty facility capacity, which is now available in GREET 2022. GREET users can include or exclude the impact of the LT DAC facility construction.

Ozkan et al. (2021) recently reviewed the current state of DAC technologies and presented the techno-economic and energy use metrics of LT and HT systems. The HT system requires natural gas to achieve adequate liquid solvent (CaCO<sub>3</sub>) regeneration and has higher net energy use compared to the LT system, but it remains a relevant DAC technology contender for its lower cost and easier scalability. Thus, we include the HT DAC system using the parameters presented in Keith et al. (2018). Facility infrastructure data for HT DAC systems are not currently available, which means that even if the facility infrastructure option is selected in GREET, facility construction is not simulated in GREET modeling.

### **CO<sub>2</sub>-derived FT fuel production integrated with nuclear power generation**

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We added a new pathway to the *E-fuel* tab based on the model in Zang et al. (2022). This pathway is for a FT fuel plant co-located with a light water reactor (LWR) based nuclear power plant which provides electricity to an on-site Solid Oxide Electrolyzer Cell (SOEC) for H<sub>2</sub> and O<sub>2</sub> generation, as well as for day-to-day plant operation. Therefore, the inputs for this system are simply electricity and CO<sub>2</sub>. As H<sub>2</sub> and O<sub>2</sub> are supplied using the on-site SOEC, they do not incur any transportation-related emissions. The CO<sub>2</sub> is assumed to be obtained from nearby sources and transported via pipeline to the facility, incurring capture, compression, and transportation emissions. The material and energy inputs for this FT-fuel production system are generated using an ASPEN Plus model. Medium-quality steam is also co-produced, which generates displacement emission credits equivalent to the emissions from an industrial NG boiler with the energy conversion efficiency of 80%.

#### *Technical report:*

Zang, Guiyan; Sun, Pingping; Delgado, Hernan; Cappello, Vincenzo; Ng, Clarence; Elgowainy, Amgad. The Modeling of the Synfuel Production Process: Process models of Fischer-Tropsch

production with electricity and hydrogen provided by various scales of nuclear plants. 2022. ANL/ESD 22/8. <https://www.osti.gov/biblio/1868524>

### 2.1.3. Offshore Macroalgae Production

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The commercialization of offshore macroalgae production in the U.S. has the potential to provide valuable biomass for targeted conversion to fuels and products and aid the nation in achieving energy security, environmental sustainability, and economic development goals without the use of land or freshwater. To realize this potential, the DOE's Advanced Research Projects Agency-Energy (ARPA-E) has initiated the Macroalgae Research Inspiring Novel Energy Resources (MARINER) program to develop advanced cultivation technologies that enable the low-cost and energy-efficient production of macroalgal biomass in the ocean at scale.

With the support from the MARINER program, we created a *Macroalgae* tab to characterize the life cycle energy and environmental effects of cradle-to-gate activities associated with offshore macroalgae production such as hatchery/nursery, farm infrastructure, cultivation, and harvest. Note that estimates of the key parameters in the tab are still under review and thus preliminary. We will update the estimates in an interim release of GREET 2022.

### 2.1.4. Marine Fuel Production Pathways

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Five new marine fuel production pathways were added: (a) hydrothermal liquefaction (HTL) of wastewater sludge, (b) HTL of manure, (c) fast pyrolysis (FP) of biomass, (d) catalytic fast pyrolysis (CFP) of biomass with ZSM5 catalyst, and (e) CFP of biomass with Pt/TiO<sub>2</sub> catalyst. Life cycle inventory (LCI) for both HTL and all three fast pyrolysis pathways were collected from Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL), respectively. Collection radii for sludge and manure were assumed to be 47 and 114 km, respectively. The life cycle analysis reveals that marine biofuels' life cycle GHG emissions span from -50 to 20 gCO<sub>2</sub>e/MJ, representing 79% to 152% reduction compared with the conventional low-sulfur fuel oil (LSFO), demonstrating a significant capacity for decarbonization by marine fuels. Both waste-based pathways, HTL of sludge and manure, showed over 100% GHG reduction potential with respect to LSFO due to the avoided methane emissions associated with business-as-usual waste management practices.

*Publication*

<http://greet.es.anl.gov/publication-marine-biooil>

### 2.1.5. 2021 SOT SCSA Pathways

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We include the Supply Chain Sustainability Analysis (SCSA) results of the 2021 state of technology (SOT) of five biofuel production pathways via a range of conversion technologies. The SCSA takes the life cycle analysis (LCA) approach to identify energy and environmental sustainability hotspots that could be mitigated through improved process materials and energy conversion efficiencies. The SCSA results provide guidance to ongoing R&D efforts of the Bioenergy Technologies Office (BETO) to achieve multiple performance targets including sustainability. Additionally, the SCSA tracks and demonstrates the progress of energy and environmental performances of the individual biofuel pathways that undergo continuous development.

In GREET 2022, we added detailed material and energy balances as well as SCSA results of the 2021 SOT cases for 1) renewable high-octane gasoline via indirect liquefaction (IDL) of woody lignocellulosic biomass (in the *Pyrolysis\_IDL* tab); 2) renewable diesel via hydrothermal liquefaction (HTL) of wet sludge from a wastewater treatment plant (in the renewable natural gas [*RNG*] tab); 3) renewable hydrocarbon fuels via biochemical conversion of herbaceous lignocellulosic biomass (in the integrated biorefinery [*IBR*] tab); 4) renewable diesel via HTL of algae (in the *Algae* tab); and 5) renewable diesel via combined algae processing (in the *Algae* tab). We present the SCSA results with different co-product handling methods including a process-level allocation method, a displacement method, and a biorefinery-level method to provide a complete picture of the emission performances of fuel products and non-fuel co-products for pathways with significant co-products.

#### *Technical Report:*

Cai, H., Ou, L., Wang, M., Davis, R., Dutta, A., Harris, K., Wiatrowski, M.R., Tan, E., Bartling, A., Klein, B. and Hartley, D., 2022. Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2021 State-of-Technology Cases. (No. ANL/ESD-22/5). Argonne National Lab (ANL), Argonne, IL (United States)

### 2.1.6. Biodiesel and Renewable Diesel from Used Cooking Oil

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We added biodiesel (BD) and renewable diesel (RD) production from used cooking oil (UCO) pathways to the *BioOil* tab in GREET 2022. We used data from a 2021 Argonne industry survey of domestic animal fat and UCO renders, covering operation data for 2018 and 2019. Other updates related to the BD and RD pathways include herbicide and insecticide use for carinata production. In addition, propylene, energy consumption and emissions results of chlorine, and sodium hydroxide (NaOH) in the *BioOil* tab were linked to existing pathways in GREET.

#### *Publication:*

Xu, H., Ou, L., Li, Y., Hawkins, T., and Wang, M. (2022). Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States. *Environmental Science & Technology*. [doi.org/10.1021/acs.est.2c00289](https://doi.org/10.1021/acs.est.2c00289)

### 2.1.7. Post-Use Plastic (PUP) Pyrolysis Conversion

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Building on a collaboration between Argonne and the American Chemistry Council (ACC), we updated a version of the life cycle analysis (LCA) of post-use plastic (PUP) conversion via pyrolysis. We incorporated updates and improvements of PUP conversion pathways into the *PUP\_conversion* tab. We used new industry data to conduct a LCA to characterize the environmental benefits and tradeoffs of PUP conversion pathways, including production of an intermediate product such as pyrolysis oil and fuel such as ultra-low sulfur (ULS) diesel. Pyrolysis oil is considered a valuable precursor comparable to naphtha that can eventually be upgraded into new plastic products.

As in previous efforts, we collected the data via a survey of eight pyrolysis companies. We classified companies based on their annual capacities and allocated the results accordingly. In the *PUP\_conversion* tab, we presented data for two types: (1) pioneer plant, and (2) N<sup>th</sup>-plant. Pioneer plants have a capacity less than 50,000 tonnes of PUP per year. Plants with capacity higher than 50,000 tonnes are referred to as N<sup>th</sup>-plants. The update also included new data for plastic sorting at material recovery facilities (Franklin Associates, 2018), updated distances for collection and transportation of PUP and co-products, updated properties and prices of products like fuel gas and char, and information on properties and production yields of newly added co-products: waxes and pyrolysis oil. Details are given in the technical report below.

#### *Technical Report:*

Benavides P.T., Gracida-Alvarez U., Lee U., Wang M. Life-cycle Analysis of Conversion of Post-Use Plastic via Pyrolysis with the GREET Model. 2022. (No. ANL/ESD-22/5) <https://www.osti.gov/biblio/1885570/>

## 2.2. Vehicles

### 2.2.1. Infrastructure for Electricity Generation

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In the GREET model, we calculated energy consumption and emissions embodied in power infrastructure construction in the *ElecInfra* tab of GREET1. For GREET 2022, we updated the analysis for embodied emissions of renewable and nuclear power infrastructure, and used the

Wind\_Turbine, Solar\_PV, Hydropower, *Nuclear\_Power* tab in GREET2 to estimate energy consumption and emissions from material processing, component manufacturing, infrastructure installation and maintenance for wind turbine, solar PV, hydroelectric and nuclear power generation facilities, respectively. We compiled the bill-of- material data for different power infrastructures, analyzed key parameters affecting the lifetime electricity generation, and thus calculate embodied emissions for per kWh/mmBtu of electricity generated. The update reflects recent progress and current production status in renewable and nuclear power generation technologies. Calculation results from the *Wind\_Turbine*, *Solar\_PV*, *Hydropower*, *Nuclear\_Power* tab of GREET2 are connected to GREET1 to replace previous estimations for renewable and nuclear power infrastructure in the *ElecInfra* tab of GREET1. Details are reported in Gan et al. (2022).

*Technical memo:*

<https://greet.es.anl.gov/publication-elecInfra2022>

*Publication:*

<https://greet.es.anl.gov/publication-solarpv2022>

### **2.2.2. LDV and MHDV Vehicle Component Updates**

Rakesh Krishnamoorthy Iyer ([riyer@anl.gov](mailto:riyer@anl.gov)), Jarod C. Kelly ([jckelly@anl.gov](mailto:jckelly@anl.gov))

We updated three specific components of both light-duty vehicles (LDVs) and medium- and heavy-duty vehicles (MHDVs). Material composition of select components – traction motor, electronic controller, and lithium-ion batteries (LIBs) – has been updated for all vehicles in their respective GREET2 tabs (*Car*, *SUV*, and *PUT* tabs for LDVs; *Class 6 PnD*, *Class 8 day-cab trucks* and *Class 8 sleeper-cab trucks* tabs for MHDVs). These updates are used to compute energy use and emissions for manufacturing these components – traction motor and electronic controller in *Vehi\_Comp\_Sum* tab, and LIBs in the *Battery\_Sum* tab of GREET2. We used existing literature to update the material composition of both traction motor and electronic controller of hybrid, electric, and fuel-cell powertrains for all vehicles. For LIBs, material composition and specific power/energy (power for hybrid and fuel-cell, and energy for plug-in hybrid electric and electric powertrains) are based on Argonne’s most recent Battery Performance and Cost (BatPaC) 5.0 model (Argonne, 2022). More details on these updates are provided in a technical memo.

*Technical Memo:*

[https://greet.es.anl.gov/publication-ldv\\_mhdv\\_updates\\_2022](https://greet.es.anl.gov/publication-ldv_mhdv_updates_2022)

### 2.2.3. Battery Anodes (Graphite, Lithium, and Silicon)

Rakesh Krishnamoorthy Iyer ([riyer@anl.gov](mailto:riyer@anl.gov)), Jarod C. Kelly ([jckelly@anl.gov](mailto:jckelly@anl.gov))

Lithium-ion batteries (LIBs) are important for a clean-energy transition, making it critical to secure a robust and reliable long-term supply of their constituent materials. There is new interest in LIB anodes— both the conventional graphite anode and other alternatives such as lithium and silicon. GREET 2021 covered three LIB anodes: synthetic graphite, lithium, and silicon.

In the GREET 2022 *Anode* tab, we updated the inventory details for two anodes (synthetic graphite and silicon) based on the most recent literature. We also provided a new inventory for natural graphite – a form of graphite that is equally suitable and used as LIB anodes. We calculated the energy use and emission impacts for producing these anodes based on their respective supply mix data to the U.S., as available in the public domain (United States Geological Survey 2022) and/or other assumptions. More details are reported below.

*Technical Report:*

[https://greet.es.anl.gov/publication-battery\\_anode\\_2022](https://greet.es.anl.gov/publication-battery_anode_2022)

## 2.3. Materials

### 2.3.1. Waste to polylactic acid (PLA) pathways

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Production of polylactic acid (PLA) resin from three different waste feedstocks (i.e., wastewater sludge, food waste, and swine manure) was added to the GREET 2022, *Plastics* tab, subsequent to the waste-to-lactic acid (LA) production pathways implemented in GREET 2021 (Lee et al., 2021). The expanded system boundary includes the polymerization of LA into PLA and end-of-life of PLA. The waste-to-LA fermentation, transportation, and landfill treatment of digestate, counterfactual scenario of waste feedstocks were also included within the system boundary. One of the material inputs for waste-to-PLA production, sorbitol, was not included in GREET 2021. Because this material is frequently used in biochemical conversion processes, we implemented its life cycle inventory (LCI) in GREET 2022 in the *Enzymes\_Yeast* tab. The LCI of sorbitol accounts for the glucose-to-sorbitol conversion process (Moreno, 2019) and is used with glucose inventories to calculate the life cycle analysis results for sorbitol. We also updated the end-of-life emissions for landfilled PLA. In GREET 2021, the end-of-life emissions for PLA did not account for the landfill gas collection or oxidation of methane in landfills. For GREET 2022, we considered the methane capture when calculating the end-of-life emissions of PLA. We used the landfill gas collection rate and oxidation rate referenced in the EPA Waste Reduction Model (EPA, 2020). Details of the PLA pathways from wastewater sludge, food waste, and swine manure feedstock are presented in the manuscript below.

*Publication:*

<https://greet.es.anl.gov/publication-pla2022>

### **2.3.2. Circular Economy Framework for Plastics**

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We included a circular economy framework for plastics in GREET 1 in the new Circular Economy Sustainability Analysis (CESA) tab. This framework combines material flow analysis and life cycle analysis (LCA) to determine the circularity metrics (solid waste generation and virgin material use) life cycle impacts (energy requirements, water consumption, criteria air pollutant, [CAP] and GHG emissions) of different strategies to enable the circular economy of plastics.

The framework analyzes and compares two case studies: 1) Business as usual (BAU) and 2) user defined. The BAU case represents the current state of the supply chain of polyethylene terephthalate (PET) bottles, with a recycling rate of 29% and the use of mechanical recycling as the only technology to convert post-use PET bottles into recycled bottles. The user-defined case represents the transition from the current state to a circular economy through two strategies: 1) increasing the recycling rate of bottles from 29% to 90% and 2) including of chemical recycling through enzymatic hydrolysis. The user-defined case can be adapted to other examples of a circular economy strategy as reported by Gracida-Alvarez et al. (2022).

As part of the framework, we included new inventories for recycling of post-use plastic (PUP) in the *PUP\_conversion* tab: reclaiming operations of PET bottles (PET bottle-to-PET flake conversion), mechanical extrusion (PET flake-to-mechanically recycled PET resin), and enzymatic hydrolysis (PET flake converted to purified terephthalic acid and ethylene glycol). We also present material flow factors, based on statics of PET bottle collection and production and data of recycling technologies yields, to enable calculations for the material flow analysis. Details on the methodology and inventory data used in the circular economy framework is provided in the publication below.

*Publication:*

<https://greet.es.anl.gov/publication-cesa2022>

### **2.3.3. Conventional, Green, and Blue Ammonia Production**

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We updated and expanded ammonia production pathways in GREET 2022. In previous GREET versions, ammonia production pathways considered either steam reforming of natural gas (steam methane reforming [SMR]) or electrolysis of water for the hydrogen supply to the Haber-Bosch process. These two production options are referred to as conventional and green ammonia production, respectively. We updated both production pathways based on energy and mass balance from ASPEN Plus modeling. Potential emission credits for steam or electricity byproducts exports are considered.

We also expanded GREET to include an additional ammonia production pathway with carbon capture and storage (CCS) for the natural gas SMR-based production, also known as “blue” ammonia production. For this pathway, we considered cases for capturing approximately 98 mol% of CO<sub>2</sub> from SMR process and 90 mol% of CO<sub>2</sub> from combustion gases. In all cases, the captured CO<sub>2</sub> is assumed to be compressed to 2,200 psig and transported via pipelines for CO<sub>2</sub> storage. More details can be found in the following publication.

#### *Publication*

Lee, K., Liu, X., Vyawahare, P., Sun, P., Elgowainy, A., and Wang, M., Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production. *Green Chemistry* 24, 4830—4844, 2022. <https://doi.org/10.1039/D2GC00843B>

### **2.3.4. Plastic Upcycling to Lubricant Product**

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The conversion of post-consumer plastics to a high-quality liquid lubricants (PTHQL) pathway is incorporated in the post-use plastic (*PUP*)\_conversion tab. This work provides the energy use and emissions profile for a hydrogenolysis process to upcycle plastic to a lubricant product. The process parameters are based on 1 lb of lube and total energy use and process fuel share are also provided. Raw materials input includes electricity and hydrogen along with post-consumer plastics. Fuel gas produced in the process is combusted onsite while credit is taken for naphtha generated in the process. See publication below for details on this pathway including a techno-economic and life cycle analysis study for plastics to lubricant production.

#### *Publication*

Cappello, V., Sun, P., Zang, G., Kumar, S., Hackler, R., Delgado, H.E., Elgowainy, A., Delferro, M. and Krause, T. (2022). Conversion of plastic waste into high-value lubricants: techno-economic analysis and life cycle assessment. *Green Chemistry*. Doi.org/10.1039/D2GC01840

### 2.3.5. Poly-alpha olefins (PAO)

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Poly-alpha olefins (PAO) are a class of synthetic lubricants used in varied applications as vehicle fluids. PAO are industrially synthesized using ethylene as a raw material. This pathway is included in the *Chemicals* tab along with ethylene and its upstream burdens. Energy is required and process emissions are associated chiefly with the ethylene, heat, and power use. Natural gas (NG) is the source for heat generation with an NG boiler, while electricity is considered to be part of the U.S. grid mix. The process inputs and emissions for this pathway are chiefly obtained from the publication below.

#### *Publication*

Cappello, V., Sun, P., Zang, G., Kumar, S., Hackler, R., Delgado, H.E., Elgowainy, A., Delferro, M. and Krause, T. (2022). Conversion of plastic waste into high-value lubricants: techno-economic analysis and life cycle assessment. *Green Chemistry*. [doi.org/10.1039/D2GC01840C](https://doi.org/10.1039/D2GC01840C)

### 2.3.6. Domestic Li-chemical production in North America

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The strategic importance of lithium-ion batteries (LIBs) on multiple fronts (economic, environmental, and social) has led to a strong push for commercial production of battery-grade lithium (Li) chemicals in the U.S. and North America. The bulk of these efforts is centered on using direct lithium extraction (DLE) technology, given the much lower Li content of brines in North America compared to Li content in brines in Chile and Argentina. Thus, it is important to understand the environmental impacts of this technology compared to conventional Li chemical production from Salar brines and spodumene reserves.

In GREET 2022, we provided an introductory inventory for production of two major battery-grade Li chemicals – lithium carbonate ( $\text{Li}_2\text{CO}_3$ ) and lithium hydroxide ( $\text{LiOH}$ ) – using DLE technology in the *Li\_Chemicals* tab of GREET2. This inventory (Huang et al., 2021) envisages producing these chemicals from brines located in the Salton Sea Known Geothermal Resource Area in California. The technology includes four major steps: (a) production of sorbent (lithium-aluminum-layered double hydroxide chloride or LDH); (b) loading and unloading of sorbent with Li content from brine reserves; (c) forward osmosis (to separate Li from other content in adsorbed brine); and (d) production of Li-chemicals. More details on this effort are provided in our publication below. Since this inventory is based on scaling up the data obtained for small-scale production of Li chemicals using various assumptions, we provide this inventory as a separate setup in the *Li\_Chemicals* tab.

#### *Technical Report:*

[https://greet.es.anl.gov/publication-domestic\\_li\\_2022](https://greet.es.anl.gov/publication-domestic_li_2022)

### 2.3.7. Updates on Inventory of Aluminum Production

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We updated the inventory for production of both wrought and cast aluminum in GREET 2022 (in W.Al and C.Al tabs of GREET2 respectively), based on the most recent Aluminum Association (AA) report published in 2022 (Wang, 2022).

We accounted for the domestic production and imports of both alumina (for domestic aluminum production) and primary aluminum (in total primary aluminum consumption) in North America, inclusive of the share-wise imports from different nations. We also updated the electric grid mix used in various stages of aluminum production, both domestic and abroad. This includes North American aluminum smelters as well as material/energy/emission inputs and outputs for different processes. Finally, we expanded the total number of semi-fabricated aluminum products from three in the previous GREET version to six in GREET 2022, including automotive and non-automotive products. We also provided detailed energy use and emissions for their respective production. More details are provided in the publication below.

*Technical Memo*

[https://greet.es.anl.gov/publication-alum\\_update\\_2022](https://greet.es.anl.gov/publication-alum_update_2022)

### 2.3.8. Critical Materials (Nickel, Copper, Titanium, and Rare Earth Elements)

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The United States has published a list of materials that are critical for multiple sectors and has pushed for production of these materials in domestic and/or favorable international locations to ensure security (US Department of the Interior, 2022; US Department of Energy, 2011; US Department of Energy, 2020). These materials include: (a) Nickel (critical for lithium-ion batteries that are vital to the transition to clean energy and U.S. energy security); (b) Copper (important for various sectors); (c) Titanium (relevant for several green energy technologies, such as electrolyzers used for hydrogen production and fuel cells that convert hydrogen to electricity); and (d) Rare-earth elements (used in electrolyzers, motors, batteries, and other green energy technologies). Along with the critical focus on production location, there is a strong effort to understand the baseline environmental impacts of their current production mix in the U.S. supply chain, as well as the likely differences in these impacts on their production location. (Babbitt et al., 2021; U.S. Department of Energy, 2020).

In GREET 2022, we provided the baseline inventory and resultant energy use and environmental impacts of producing these four critical materials (or material systems), considering their actual supply chain to the U.S. For nickel and copper, we provided details on the variation in their material and energy use as a function of ore grade and source, along with the effect on their environmental impacts. These details are given in *Nickel* and *Copper* tabs of GREET2, respectively. Two types of ores – sulfide and oxide (laterite) – are considered for these metals,

accounting for their production via use of pyrometallurgy and hydrometallurgy technologies at present. For titanium (Ti), we provided details on its production in various forms – sponge metal, metal ingot, forged metal, and powder – used across different sectors in the *Titanium* tab of GREET2. The last material system – rare-earth elements (multiple elements produced together) – is updated in the *Rare\_Earth* tab of GREET2. We considered the production of these elements only in China because of the scarcity of production inventory data in other locations and given China’s dominance in both the global production and U.S. import of these elements. (USGS, 2022). For each element, we also provided inventory details on intermediate materials used in their production across any of the concerned processing steps. More details are provided in the publication below.

*Technical Report:*

[https://greet.es.anl.gov/publication-critical\\_mat\\_2022](https://greet.es.anl.gov/publication-critical_mat_2022)

### **2.3.9. EOL Displacement Method (Steel/Aluminum)**

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We added the End-of-Life Recycling Method for select materials in the GREET 2022 model for an additional perspective on the life cycle burdens of those materials. We applied this methodological addition to steel, wrought aluminum, and cast aluminum. This allows users to see how end-of-life “credit” from material recycling can impact life cycle burdens. We added this method in addition to the Recycled Content Method, which has been in the GREET model since it began covering the vehicle material life cycle. The assumed rates of material recycling at the end of their automotive life are taken from literature and incorporated into the model, as well. The GREET default methodology is still the Recycled Content Method. See more details in the following publication:

*Technical Memo:*

Kelly, J.C. and Kolodziej, C.P. Addition of End-of-Life Recycling Methodology to GREET® 2022 for Steel and Aluminum. 2022. [https://greet.es.anl.gov/publication-eolr\\_method\\_2022](https://greet.es.anl.gov/publication-eolr_method_2022)

### **2.3.10. Electrolyzers for Hydrogen Production: Solid Oxide, Alkaline, and Proton Exchange Membrane**

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Hydrogen has emerged as a key energy carrier for use in major energy generation and consumption sectors, in part due to the likely potential of its production through water electrolysis using clean energy (solar and wind). An environmental assessment of this technology necessitates analyzing the environmental impacts of manufacturing electrolyzers to produce hydrogen.

In GREET 2022, we provide the bill-of-materials for three major electrolyzer technologies: solid oxide electrolyzers (SOEC), alkaline electrolyzers (AEC), and proton exchange membrane electrolyzers (PEMEC) – all of which were obtained from Strategic Analysis (Strategic Analysis, 2022). The bill-of-materials encompasses both the stack and balance-of-plant for all three electrolyzers, which we use to compute and provide the energy use and emissions for producing these electrolyzers (both total and per kg-H<sub>2</sub> produced basis). We provided all data in a new *Electrolyzer* tab of GREET2 along with more information in the publication below.

*Technical Report:*

[https://greet.es.anl.gov/publication-electrolyzers\\_2022](https://greet.es.anl.gov/publication-electrolyzers_2022)

### 3. OTHER UPDATES AND ADDITIONS

#### 3.1. GREET Modeling Features

##### 3.1.1. GREET Marine Module

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The standalone GREET Marine Module is new with this GREET release. The module includes a representative set of conventional and alternative marine fuels which will be expanded in future releases to include all marine fuels available in GREET. The module enables maritime shipping stakeholders to view harmonized and consistent life cycle assessment (LCA) results for marine fuel pathways for both an energy functional unit and one based on a specific vessel and trip. The DOE Bioenergy Technologies Office and the Vehicle Technologies Office supported development of the Marine Module in support of the Mission Innovation: Zero Emission Shipping Initiative and the International Maritime Administration’s consideration of guidelines for LCA of marine fuels. The pathways leverage studies supported by the U.S. Maritime Administration.

The GREET Marine Module Interacts directly with GREET1\_2022. Users can modify parameters directly from the Marine Module interface. The Marine Module modifies the values directly in GREET and returns results to the Marine Module interface, providing a simplified interface for stakeholders to view the effects of parameter adjustments on pathway and trip results. The module is available via the GREET website along with a guide for new users.

GREET Marine Module: [https://greet.es.anl.gov/greet\\_marine](https://greet.es.anl.gov/greet_marine)

##### 3.1.2. GREET Aviation Module

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We released a standalone GREET Aviation Module in March 2022 ([https://greet.es.anl.gov/greet\\_aviation](https://greet.es.anl.gov/greet_aviation)) based on GREET 2021. The module includes all GREET aviation fuel production pathways. We also included the sustainable aviation fuel (SAF)

production pathways approved by the International Civil Aviation Organization (ICAO) for its carbon offsetting program CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation). The module provides an interactive platform to evaluate various SAF production pathways in a consistent manner.

In this release, we developed a dynamic version of the GREET Aviation Module, which interacts with the GREET fuel cycle model (GREET1) by directly reading upstream life cycle energy uses and emissions for key inputs to various stages in sustainable aviation fuel production pathways. The dynamic version enables changing the default settings of the GREET1 model as related to SAF inputs. After clicking the “Read from GREET” button in the *LCProfile* tab, the module will import updated conditions from the GREET1 file in the same folder. Note that this button will only be applicable with GREET version 2022 or later.

### **3.1.3. Feedstock Carbon Intensity Calculator (FD-CIC)**

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We expanded FD-CIC for the carbon intensity (CI) calculation of international feedstocks, such as Canadian corn and Brazilian sugarcane to address current efforts in developing clean fuel policies in countries other than the U.S.

We extracted the Canada-specific corn farming inputs and the relevant national-average life-cycle inventory (LCI) data of manufacturing those inputs from GHGenius (<https://www.ghgenius.ca/>) and used them to calculate the default CI of Canadian corn production. Meanwhile, we adopted the GREET default LCI data to generate the default CI for Brazilian sugarcane production.

We also incorporated land management practices for corn farming, such as cover cropping and animal manure application. FD-CIC allows the users to choose whether they have implemented these sustainable practices and, if so, specify their own LCI data (e.g., manure application types/rates and cover crop yields). We provided the GREET default LCI data of the practices based on Qin et al. (2015). More details can be found in the updated FD-CIC manual at [https://greet.es.anl.gov/tool\\_fd\\_cic](https://greet.es.anl.gov/tool_fd_cic).

### **3.1.4. GREET Building Module**

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

The GREET Building Module is fully synchronized with the Fuel Cycle and Vehicle Cycle models (GREET1\_2022 and GREET2\_2022), sharing such data as process energy types and common materials. The module is included in the GREET release package and is also available

for free download on the GREET website under the GREET Excel category <https://greet.es.anl.gov>. The module's user guide offers modeling techniques and best practices (Cai et al., 2022).

*Technical Report:*

[https://greet.es.anl.gov/publication-greet\\_building\\_method\\_2022](https://greet.es.anl.gov/publication-greet_building_method_2022)

*Publication:*

Cai, H., Wang, X., Kim, J-H., Gowda, A., Wang, M., Mlade, J., Farbman, S., and Leung, L. (2022). Whole-building life-cycle analysis with a new GREET® tool: Embodied greenhouse gas emissions and payback period of a LEED-Certified library. *Building and Environment* 209: 108664.

### 3.2. Other Updates

#### 3.2.1. Global Warming Potential

Pradeep Vyawahare ([pvyawahare@anl.gov](mailto:pvyawahare@anl.gov)), Uisung Lee ([ulee@anl.gov](mailto:ulee@anl.gov))

The global warming potential (GWP) values for CH<sub>4</sub>, N<sub>2</sub>O, HFC-134a, CF<sub>4</sub>, C<sub>2</sub>F<sub>6</sub>, and SF<sub>6</sub> are updated based on the sixth assessment report (AR6) by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2022) (Table 1). For the biogenic CH<sub>4</sub> emissions, we considered the impact of CO<sub>2</sub> uptake as specified in Wang et. al (2021).

**Table 1. Global warming potential (GWP) and Global Temperature Potential (GTP) values based on IPCC AR6.**

AR Edition/Type	AR6/GWP	AR6/GWP	AR6/GTP	AR6/GTP
Time Horizon (YR)	100	20	100	50
CH <sub>4</sub>	30	82.5	7.5	13.2
N <sub>2</sub> O	273	273	233	290
HFC-134a	1,526	4,144	306	733
CF <sub>4</sub>	7,380	5,300	9,050	7,660
C <sub>2</sub> F <sub>6</sub>	12,400	8,940	15,200	12,900
SF <sub>6</sub>	25,200	18,300	30,600	26,200

#### 3.2.2. Electricity Generation Mix and Crude Oil Mix Updates

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Electricity generation mixes by U.S. regions were updated based on Annual Energy Outlook (AEO) by the Energy Information Administration (EIA) (EIA 2022a) for eight North American

Electric Reliability Corporation (NERC) regions and three states (Alaska [AK], California [CA], and Hawaii [HI]) as presented in Table A-1. Since EIA does not provide electricity generation projection for AK and HI, we use the same mixes for the future years for the two states (EIA 2022b).

We have also updated the projection of the regional crude share by 2050. GREET consists of eight regions – U.S. domestic, Canada (oil sands), Canada (conventional crude), Mexico, Middle East, Latin America, Africa, and others. The projected U.S. domestic share is directly from AEO (EIA 2022a), and the shares of other regions are based on company-level crude import data by EIA (EIA 2022c). Since there is no projection about crude oil share of other regions, we used the current regional split for other regions. For Canadian oil, we assumed the same splits between conventional crude and oil sands through 2050 using the earlier projection by the Canadian Association of Petroleum Producers (CAPP) because CAPP does not release projections of Canadian oil production and exports. The regional crude oil shares from 2021 to 2050 are presented in Table B-1. For the shale oil share, Eagle Ford and Bakken contributes 8.6% and 10.0%, respectively, based on EIA (EIA 2022d; EIA 2022e). The weighted average values of crude oil transportation distances have been updated as well using the company-level import data (EIA 2022c). The distances are estimated at 7,988 miles by ocean tankers for offshore countries and 1,705 miles for Canada and Mexico by pipeline.

### **3.2.3. Methane Leakage of Natural Gas Supply Chain**

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Methane (CH<sub>4</sub>) leakage and CO<sub>2</sub> flaring emissions from the natural gas supply chain are updated based on newly published data. In GREET 2022, we updated the CH<sub>4</sub> leakage rates for both the hybrid top-down and bottom-up approach and the EPA GHGI bottom-up approach. For the hybrid approach, we continued to use production scaling factors from Rutherford et al. (2021) and processing and transmission scaling factors from Alvarez et al. (2018), modifying the most recent EPA GHGI CH<sub>4</sub> emissions data (EPA, 2022).

*Technical Memo:*

[https://greet.es.anl.gov/publication-update\\_ng\\_2022](https://greet.es.anl.gov/publication-update_ng_2022)

### **3.2.4. Fuel Use for Natural Gas Recovery**

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Fuel use for natural gas (NG) recovery which involves NG production and NG gathering & boosting (G&B) phases of NG supply chain is updated based on the select data from the National Energy Technology Laboratory's (NETL) 2020 ONE Future report. In GREET 2022, we updated the fuel used mainly in the form of NG in compressors for both conventional and non-conventional (Shale

&Tight) technologies. The U.S. average values for fuel use are based on basin and technology level information in NETL's One Future data set.

#### *Technical Reference:*

Select data from 2020 ONE Future report scenario:

Rai, Srijana, Littlefield, James, Roman-White, Selina, Zaines, George G., Cooney, Gregory, & Skone, Timothy J. Industry Partnerships & Their Role in Reducing Natural Gas Supply Chain Greenhouse Gas Emissions – Phase 2. United States. <https://doi.org/10.2172/1765004>

### **3.2.5. Updates in Plastics Inventories**

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The *Plastics* tab introduced in GREET 2021 presented updated inventories for five plastic production pathways: high-density polyethylene, low-density polyethylene, polypropylene, polyethylene terephthalate (Purified terephthalic acid + mono ethylene glycol route), and polyethylene terephthalate (Dimethyl terephthalate + mono ethylene glycol route). These inventories included non-combustion emissions data from a previous source (Franklin Associates, 2011) that led to overestimated life cycle impacts for these five plastic production pathways. After confirming with Franklin Associates that the non-combustion emissions from the previous report should not be combined with the new data, we removed these pathways from GREET to provide accurate estimations of life cycle impacts.

### **3.2.6. Rail Energy Intensity**

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Among the passenger rails in the U.S., intercity rails (Amtrak) and commuter rails use both diesel and electricity. In GREET 2022, for these rail modes, we provided the well-to-wheels (WTW) emissions for diesel and electric operation separately. Trains in Amtrak's Northeast Corridor (NEC) use electricity as fuel, whereas the rest of its operations use diesel. Amtrak's annual report for fiscal year (FY) 2019 provides the total passenger-miles for electric and diesel locomotives. The Bureau of Transportation Statistics Table 4.18 provides the total diesel and electricity use for Amtrak (BTS, 2022). The National Transportation Database (NTD) (2019) shows that 5 out of 26 total commuter rail agencies report their combined consumption of diesel and electricity without separating diesel and electric passenger miles. For four out of these five agencies (MTA Metro-North Railroad, New Jersey Transit Corporation, Maryland Transit Administration, and Illinois' Metra Rail), we estimated diesel passenger miles and electric passenger miles using weighted average (by average passengers on board) gal/passenger-mile and kwh/passenger-mile, respectively. We excluded the MTA Long Island Railroad from this calculation, as the total estimated passenger miles for this agency appeared to be an outlier.

We provide a summary of diesel and electricity used by intercity and commuter rails in Table 2. For the combined diesel and electric operation, the average WTW emissions were estimated based on the energy share of diesel and electricity.

**Table 2. Diesel and electricity used by intercity and commuter rails**

Passenger Rail		Diesel	Electric
Intercity (Amtrak) <sup>a</sup>	Energy use	62.8 million gallons	484 million kWh
		8,134 billion Btu	1,652 billion Btu
	Energy share	83.1%	16.9%
Commuter Rail <sup>b</sup>	Energy use	101 million gallons	1780 million kWh
		13,122 billion Btu	6,073 billion Btu
	Energy share	68.4%	31.6%

<sup>a</sup> [BTS Table 4.18](#)

<sup>b</sup> [NTD 2019 Fuel and Energy](#)

### 3.2.7. Aviation Payload Fuel Energy Intensities and Combustion Emission Factors

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When releasing the new GREET Aviation Module in March 2022, we updated the payload fuel energy intensities (PFEIs) and operation statistics by the aircraft type. The updates are also available in the jet modules in GREET1. Combustion emissions by aircraft type are mainly impacted by the PFEIs values (kJ/kg payload-km great circle distance) and emission factors. BlueSky collected the U.S. aircraft operational data – Bureau of Transportation Statistics (BTS) T-2 database (<https://www.transtats.bts.gov/>, Nov. 30, 2021) and calculated the average payload, average trip distance, and jet fuel consumption as presented in Table 3. The new values are now used in GREET to calculate the life cycle results of jet fuels used in various aircraft types.

**Table 3. 2019 BTS T-2 data aggregated by aircraft types**

Aircraft type	Aircraft class <sup>†</sup>	Aircraft operations (thousand)	Average payload (t/operation)	Average trip great circle distance (km/operation)	Average trip petroleum jet fuel consumption (kg/operation)	Average petroleum jet fuel consumption for land and take off (kg/operation)	Payload fuel energy intensity (kJ/kg-km)
Passenger aircraft	SA	5,253	12.8	1,574	6,484	565	13.9
	STA	112	20.6	4,847	29,531	982	12.8
	LTA	196	28.1	6,932	53,898	1,731	12.0
	LQ	1.4	41.9	3,757	48,567	2,484	13.3
	RJ	2,820	5.0	804	2,378	257	25.5
Freight aircraft	SA	142	13.3	1,035	5,434	598	17.1
	STA	239	35.4	1,936	15,123	949	9.5
	LTA	109	45.4	2,200	19,168	1,496	8.3
	LQ	55	71.9	4,921	65,352	2,271	8.0

<sup>†</sup> SA: single aisle, STA: small twin aisle, LTA: large twin aisle, LQ: large quad, RJ: regional jet

### 3.2.8. Heavy-Duty Vehicle HEVs

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Hybrid electric vehicles (HEVs) can be alternatively powered by renewable fuels such as biodiesel, renewable diesel, and dimethyl ether. In this release, we updated the relative fuel economy ratios for HEVs powered by renewable fuels to keep their fuel economies consistent with those powered by low-sulfur diesel within the same heavy-duty vehicle subcategory.

### 3.2.9. Light-duty Vehicle Diesel CH<sub>4</sub> Emission Factors

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For the GREET 2021 update, we generated data using the latest version of the EPA's mobile source emission modeling, MOVES3.01, to estimate the model-year-specific vehicle operation emission factors of the selected gasoline and diesel light-duty vehicle (LDV) and medium- and heavy-duty vehicle types (Burnham, 2021). After noticing that the MOVES output for CH<sub>4</sub> emission factors for diesel LDVs was zero, we contacted the EPA about this issue. After the GREET 2021 update was released, the EPA notified us that CH<sub>4</sub> emissions for all MY 1960-2007 diesels was intended to be zero and was implemented correctly in MOVES3. However, for MY 2010 and newer diesel LDVs, CH<sub>4</sub> emissions should be 38% of the total hydrocarbons. We ran an updated version of MOVES (3.03) and verified that the EPA had corrected the issue. The updated values were implemented in GREET 2022.

### 3.2.10. Update of the U.S. conventional feedstock slate of steam crackers

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Table 4We updated the feedstock slate of steam crackers in the United States in the *Steam\_Cracking* tab to reflect the current U.S average feedstock shares for gases (including ethane, propane, and butane) and naphtha. The most recent survey of U.S ethylene producer capacities presented by Lippe (2020) summarizes feedstock use data for the four quarters of 2019 and the first quarter of 2020. Although the information was presented in barrels of oil equivalents per day, we used the lower heating value of crude oil (5.4 mmBtu per barrel) and the lower heating value of the steam cracking feedstocks already reported in the GREET model, to estimate the share on a mass basis. Lippe (2020) reports ethane, liquefied petroleum gas (LPG), and naphtha as the feedstocks used while GREET separates LPG into its propane and butane components and only includes naphtha as liquid feedstock (Young et al., 2022). To ensure consistency with GREET, we adjusted the feedstocks from Lippe. To obtain separate amounts of propane and butane, we assumed an LPG composition of 85% propane and 15% butane (Zvirin et al., 1998) and we grouped the amount of gasoline with the value reported for naphtha. The updated feedstock slate in weight percentages is presented in Table 4.

**Table 4. Updated feedstock slate of steam crackers in the United States**

Feedstock	Ethane	Propane	Butane	Naphtha
Share	75.6%	15.5%	2.8%	6.1%

**3.2.11. Air Separation Unit (ASU)**

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We created an Air separation unit (ASU) tab to account for the energy use and emissions that occur in the production of O<sub>2</sub> and N<sub>2</sub> in the air separation unit. The energy use is adopted based on the ASPEN modeling of air separation process used in Lee et al. 2022. The electricity use is the U.S. mix by default with the O<sub>2</sub> and N<sub>2</sub> product pressure of 5 bar and 20 bar, respectively.

*Publication:*

Lee, K., Liu, X., Vyawahare, P., Sun, P., Elgowainy, A., and Wang, M. Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production. *Green Chemistry* 24, 4830—4844, 2022. <https://doi.org/10.1039/D2GC00843B>

**3.2.12. Update of Uranium Tab for Nuclear Light Water Reactor (LWR) and High Temperature Gas Reactor (HTGR)**

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We corrected uranium pathways and nuclear electricity pathways to make the GREET Excel and GREET .Net consistent. This correction updates several parameters (i.e., energy and water use) for uranium mining, enrichment, fabrication, and storage based on the input parameter table in GREET Excel. Details on parameter updates and calculations are presented in the report below.

*Technical Report:*

[https://greet.es.anl.gov/publication-uranium\\_updates](https://greet.es.anl.gov/publication-uranium_updates)

**3.2.13. Forthcoming Update of Methane and Carbon Dioxide Emissions from Flaring during Petroleum Production and Natural Gas Production**

A recent *Science* paper (Plant et al., 2022) reported that efficient and unlit natural gas flares during petroleum and natural gas production could contribute a fivefold increase in methane emissions above present assumptions. Argonne is reviewing the details for a possible update of the methane and carbon dioxide emissions associated with flaring for petroleum and natural gas production in GREET.

#### 4. HELPS, TUTORIALS, AND PRESENTATION MATERIALS

The GREET website (<https://greet.es.anl.gov/>) presents all our publications including technical reports, technical memos, journal articles (those with open access from individual journals), and journal article abstracts (those without open access from individual journals). These are technical documentation of GREET development and applications.

As in the past, users can email inquiries, questions, and comments to [greet@anl.gov](mailto:greet@anl.gov).. To streamline our responses to questions, we suggest using one of the topic areas in your email subject line. Please indicate if you use GREET Excel version or .net version.

- GREET1: Oil/gas fuel pathways LCA
- GREET1: Biofuel/waste fuel pathways LCA
- GREET1: Electricity modeling LCA
- GREET1: Hydrogen modeling LCA
- GREET1: Electro-fuel modeling LCA
- GREET1: Plastics/chemicals LCA
- GREET1: Vehicle operations LCA
- GREET Marine LCA
- GREET Aviation LCA
- GREET Rail LCA
- GREET2, Vehicle cycle LCA
- GREET Building LCA Module
- GREET Farm-level biofuel feedstock LCA (FD-CIC).

To help users navigate inside the model, GREET tutorial video clips are available at <https://greet.es.anl.gov/homepage2>. In addition, presentation materials from past GREET user workshops (<https://greet.es.anl.gov/workshops>) are available to help users understand the structure of GREET models, technical approaches, and general coverage.

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## APPENDIX A: U.S. ELECTRICITY GENERATION MIX

**TABLE A-1. Electric Generation Mix of the United States, Eight NERC Regions, and Three States**

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
<b>U.S. Mix</b>										
2021	0.3%	36.5%	23.8%	19.6%	0.3%	6.5%	0.4%	9.5%	2.7%	0.4%
2025	0.2%	34.7%	17.7%	18.9%	0.3%	7.3%	0.4%	12.4%	7.5%	0.6%
2030	0.2%	33.5%	16.1%	16.7%	0.3%	7.1%	0.6%	13.2%	11.0%	1.5%
2035	0.2%	32.6%	14.0%	15.4%	0.3%	6.8%	0.7%	13.0%	14.3%	2.8%
2040	0.1%	33.0%	12.3%	14.7%	0.2%	6.5%	0.9%	12.9%	16.2%	3.1%
2045	0.1%	34.0%	11.1%	14.2%	0.2%	6.2%	0.9%	12.9%	17.2%	3.1%
2050	0.1%	34.2%	10.5%	13.4%	0.2%	5.7%	1.0%	13.0%	18.8%	3.1%
<b>Texas Reliability Entity (TRE) Mix</b>										
2021	0.1%	44.6%	17.8%	10.6%	0.0%	0.2%	0.0%	23.5%	3.1%	0.1%
2025	0.1%	35.5%	13.1%	10.1%	0.0%	0.2%	0.0%	26.9%	13.9%	0.2%
2030	0.1%	33.6%	12.9%	9.8%	0.0%	0.2%	0.0%	26.1%	17.0%	0.3%
2035	0.1%	32.6%	12.8%	9.4%	0.0%	0.2%	0.0%	25.1%	19.3%	0.5%
2040	0.0%	30.7%	9.0%	9.0%	0.0%	0.1%	0.0%	23.2%	27.2%	0.7%
2045	0.0%	33.0%	6.5%	8.7%	0.0%	0.1%	0.0%	21.5%	29.3%	0.8%
2050	0.0%	35.2%	6.4%	8.4%	0.0%	0.1%	0.0%	20.4%	28.5%	1.0%
<b>Florida Reliability Coordinating Council (FRCC) Mix</b>										
2021	0.1%	68.7%	12.4%	13.4%	0.2%	0.8%	0.0%	0.0%	3.4%	1.0%
2025	0.1%	62.4%	9.6%	12.4%	0.2%	0.7%	0.0%	0.0%	13.5%	1.0%
2030	0.1%	54.5%	11.0%	12.0%	0.2%	0.7%	0.0%	0.0%	20.4%	1.2%
2035	0.1%	47.1%	8.9%	11.3%	0.2%	0.6%	0.0%	0.0%	30.5%	1.4%
2040	0.1%	48.2%	8.8%	10.9%	0.2%	0.6%	0.0%	0.0%	29.8%	1.5%
2045	0.0%	49.7%	8.1%	10.7%	0.2%	0.6%	0.0%	0.0%	29.1%	1.6%
2050	0.0%	51.6%	7.7%	10.2%	0.1%	0.6%	0.0%	0.0%	28.1%	1.6%

TABLE A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
Midcontinent ISO (MISO) Mix										
2021	0.2%	28.2%	40.2%	15.0%	0.3%	1.4%	0.0%	13.9%	0.6%	0.4%
2025	0.1%	34.5%	27.9%	13.6%	0.1%	1.5%	0.0%	15.4%	6.2%	0.5%
2030	0.1%	40.1%	28.2%	6.3%	0.2%	1.5%	0.0%	15.3%	7.6%	0.6%
2035	0.1%	40.0%	26.9%	5.0%	0.2%	1.5%	0.0%	15.3%	10.2%	0.8%
2040	0.1%	40.7%	24.8%	4.0%	0.2%	1.4%	0.0%	15.0%	12.9%	0.9%
2045	0.1%	41.2%	23.8%	3.9%	0.2%	1.4%	0.0%	14.8%	13.6%	1.1%
2050	0.1%	40.4%	23.1%	3.8%	0.2%	1.3%	0.0%	14.9%	15.1%	1.2%
Northeast Power Coordinating Council (NPCC) Mix										
2021	0.2%	47.3%	1.2%	27.0%	1.4%	15.8%	0.0%	3.8%	1.6%	1.8%
2025	0.2%	36.3%	0.6%	25.0%	1.4%	18.2%	0.0%	9.9%	5.1%	3.4%
2030	0.1%	28.3%	0.7%	22.2%	1.2%	16.1%	0.0%	12.1%	11.5%	7.8%
2035	0.0%	21.6%	0.2%	21.9%	1.2%	15.8%	0.0%	12.0%	11.5%	15.8%
2040	0.0%	20.3%	0.2%	21.0%	1.2%	15.2%	0.0%	11.5%	11.7%	19.0%
2045	0.0%	20.8%	0.3%	20.7%	1.1%	14.8%	0.0%	11.3%	12.1%	18.8%
2050	0.0%	21.7%	0.3%	20.3%	1.1%	14.3%	0.0%	11.1%	13.0%	18.3%
Pennsylvania, New Jersey, and Maryland (PJM) Mix										
2021	0.1%	38.2%	23.7%	31.9%	0.1%	1.2%	0.0%	3.2%	1.0%	0.5%
2025	0.1%	39.3%	19.2%	30.1%	0.2%	1.4%	0.0%	5.1%	4.0%	0.6%
2030	0.1%	39.3%	14.5%	29.4%	0.0%	1.3%	0.0%	6.3%	6.0%	3.0%
2035	0.1%	42.7%	12.0%	25.6%	0.0%	1.3%	0.0%	6.2%	6.0%	6.1%
2040	0.0%	44.6%	11.1%	24.6%	0.0%	1.3%	0.0%	6.0%	6.1%	6.2%
2045	0.0%	46.5%	10.4%	23.9%	0.0%	1.2%	0.0%	5.7%	6.2%	6.1%
2050	0.0%	47.5%	9.4%	22.4%	0.0%	1.1%	0.0%	5.5%	8.2%	5.9%

TABLE A-1 (Cont.)

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
SERC Reliability Corporation (SERC) Mix										
2021	0.2%	32.5%	28.9%	31.4%	0.4%	4.2%	0.0%	0.0%	2.2%	0.2%
2025	0.2%	35.2%	19.6%	34.9%	0.4%	4.9%	0.0%	0.2%	4.4%	0.3%
2030	0.1%	30.6%	18.8%	33.7%	0.4%	4.9%	0.0%	0.5%	10.7%	0.4%
2035	0.1%	27.5%	16.0%	32.8%	0.4%	4.7%	0.0%	0.5%	17.5%	0.5%
2040	0.1%	28.8%	13.6%	31.8%	0.4%	4.5%	0.0%	0.7%	19.6%	0.6%
2045	0.1%	30.8%	11.5%	29.8%	0.3%	4.2%	0.0%	0.9%	21.8%	0.7%
2050	0.0%	29.3%	10.7%	28.5%	0.3%	4.0%	0.0%	0.9%	25.5%	0.7%
Southwest Power Pool (SPP) Mix										
2021	0.1%	26.0%	29.3%	5.8%	0.0%	5.3%	0.0%	33.1%	0.3%	0.1%
2025	0.1%	18.4%	25.2%	5.3%	0.0%	5.6%	0.0%	37.9%	7.4%	0.2%
2030	0.1%	15.0%	23.9%	3.2%	0.0%	5.5%	0.0%	38.8%	13.2%	0.3%
2035	0.1%	14.0%	21.6%	3.0%	0.0%	5.1%	0.0%	37.0%	18.7%	0.5%
2040	0.1%	15.4%	18.1%	2.9%	0.0%	4.7%	0.0%	35.6%	22.5%	0.6%
2045	0.1%	17.5%	15.3%	2.8%	0.0%	4.4%	0.0%	34.0%	25.1%	0.8%
2050	0.1%	18.1%	15.1%	0.0%	0.0%	4.3%	0.0%	33.6%	27.9%	0.9%
Western Electricity Coordinating Council (WECC) Mix										
2021	0.1%	32.3%	16.7%	8.1%	0.5%	22.3%	2.2%	9.8%	7.6%	0.4%
2025	0.1%	25.7%	12.2%	6.7%	0.4%	25.1%	2.3%	15.9%	11.0%	0.5%
2030	0.1%	25.7%	10.0%	5.4%	0.4%	24.3%	3.1%	17.7%	12.6%	0.8%
2035	0.1%	25.7%	6.9%	5.4%	0.4%	23.4%	4.0%	17.7%	15.4%	1.0%
2040	0.1%	24.4%	6.6%	5.2%	0.4%	22.3%	4.8%	19.1%	15.9%	1.3%
2045	0.1%	22.7%	6.1%	5.0%	0.4%	21.0%	5.2%	21.3%	16.6%	1.5%
2050	0.1%	21.4%	5.6%	4.8%	0.4%	19.4%	5.3%	23.5%	18.0%	1.7%

**TABLE A-1 (Cont.)**

Year	Residual Oil	Natural Gas	Coal	Nuclear	Biomass	Hydroelectric	Geothermal	Wind	Solar PV	Others
California Mix										
2021	0.0%	45.1%	4.0%	8.6%	1.1%	11.9%	4.0%	6.8%	17.5%	0.8%
2025	0.0%	34.9%	0.0%	4.9%	1.1%	15.8%	5.1%	8.8%	28.2%	1.1%
2030	0.0%	32.0%	0.0%	0.0%	1.1%	15.3%	7.4%	8.4%	34.5%	1.3%
2035	0.0%	18.2%	0.0%	0.0%	1.3%	14.8%	10.8%	8.5%	44.9%	1.6%
2040	0.0%	16.6%	0.0%	0.0%	1.2%	14.2%	12.6%	8.1%	45.4%	1.7%
2045	0.0%	16.4%	0.0%	0.0%	1.2%	13.1%	13.9%	7.5%	46.1%	1.8%
2050	0.0%	15.5%	0.0%	0.0%	1.1%	11.3%	13.5%	7.1%	49.6%	1.8%
Alaska Mix										
2021	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
2025	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
2030	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
2035	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
2040	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
2045	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
2050	15.7%	42.1%	11.5%	0.0%	0.6%	28.1%	0.0%	2.0%	0.0%	0.0%
Hawaii Mix										
2020	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%
2025	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%
2030	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%
2035	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%
2040	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%
2045	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%
2050	67.7%	0.0%	12.8%	0.0%	2.8%	1.1%	0.1%	6.5%	5.3%	3.6%

## APPENDIX B: U.S. CRUDE OIL MIX

**TABLE B-1. Crude Oil Share in the United States by 2050**

<b>Year</b>	<b>U.S. Domestic</b>	<b>Canada (Oil Sands)</b>	<b>Canada (Conventional Crude)</b>	<b>Mexico</b>	<b>Middle East</b>	<b>Latin America</b>	<b>Africa</b>	<b>Others</b>
2021	77.5%	7.9%	5.9%	2.1%	2.0%	1.9%	1.1%	1.5%
2025	76.8%	8.1%	6.1%	2.2%	2.1%	1.9%	1.2%	1.6%
2030	77.9%	7.7%	5.8%	2.1%	2.0%	1.9%	1.1%	1.5%
2035	75.2%	8.7%	6.5%	2.4%	2.2%	2.1%	1.2%	1.7%
2050	76.5%	8.2%	6.2%	2.2%	2.1%	2.0%	1.2%	1.6%





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