

REET Aviation Module Instruction Manual

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1. Introduction

Recently, there are many activities to reduce greenhouse gas (GHG) emissions from the aviation sector. To achieve the goals, airline operators may adopt engines with higher efficiencies and use better routes to reduce fuel consumption for each operation. More importantly, using sustainable aviation fuels (SAFs) may contribute to the reduction of GHG emissions. Unlike the on-road transportation sector where electrification can play an important role, the aviation sector needs liquid fuels with high energy density to support increasing aviation activities (Prussi et al. 2021).

This REET aviation life-cycle analysis (LCA) module developed by Argonne National Laboratory (Argonne) is derived from Argonne's REET® (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model. It is intended to evaluate the environmental impact of various aviation fuel production pathways, including both fossil- and bio-derived aviation fuels.

LCA is often performed to evaluate the environmental impacts of various technologies, which enables a holistic comparison of the environmental metrics of various systems. The REET model has been developed and updated annually with the support of several programs in the U.S. Department of Energy (DOE), which is structured to systematically examine the energy and environmental effects of a wide variety of products, including petroleum-based aviation fuels and SAFs. Using the REET model, users can generate the LCA results at the process level and help identify emission hotspots along the supply chain of technologies. In REET and the aviation module, users can change the key parameters for LCA simulation. In the aviation module, users can add new SAF production pathways and then generate LCA results. In addition to DOE, the Federal Aviation Administration has supported the development and application of the REET aviation module.

Argonne has also participated in the International Civil Aviation Organization's (ICAO's) Fuels Task Group (FTG) to contribute to calculating the life-cycle greenhouse gas emissions (also known as carbon intensities [CIs]) of SAF production pathways for the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO 2019b). The REET model has been used by Argonne and other institutions participating in FTG to generate the core LCA values (CIs) of various SAF production pathways. In particular, Argonne has developed a version of REET for ICAO CORSIA (ICAO-REET), embedded in REET 2019, which includes parameters for ICAO-approved pathways used for CORSIA. Since then, ICAO-REET has been actively used to calculate the SAF CIs within FTG. In this new REET aviation module, we implemented ICAO data so users can generate results for certain SAF pathways based on ICAO LCA methods and data. It is helpful to understand the differences between ICAO CORSIA LCA methods and data and REET default LCA methods and data as embedded in the aviation module.

Historically, a GREET aviation module included inside of the GREET model and ICAO-GREET have been used to evaluate the environmental effects of aviation fuels and aircraft. There has been increasing interest in a standalone and user-friendly version of the aviation module with all available life-cycle inventory (LCI) from GREET and ICAO that enables users to readily generate results for aviation fuels and aircraft operations. For this purpose, Argonne has developed an interactive, standalone aviation module to have a consistent aviation LCA platform with the most up-to-date datasets. For easy access, this module uses Microsoft Excel with Visual Basic for Applications (VBA) to enable an interactive user interface. This module will generate comparable LCA results based on reliable and consistent datasets by using a user-friendly interface. Most of all, we focused on developing a consistent data structure that can be used for all pathways to enable a transparent comparison of inputs and outputs of various processes/pathways. With this consistent structure, datasets can be easily imported from other sources, and the data/results can be exported for other purposes. In addition, we intended to make this module user-friendly and interactive with a dashboard where users can select pathways, change parameters, and interactively check the corresponding results. The dashboard in the standalone aviation module interacts with the tabs with input datasets from GREET and ICAO (ICAO 2019b) and supporting information imported from GREET (Wang et al. 2021).

This instruction manual is to inform the structure of the GREET aviation module, features, calculation processes, and the source of supporting information. Note that this version currently relies on GREET 2021 datasets. We are designing additional features to enable the module to interact with the latest version of the GREET model in the future so that the most up-to-date GREET data can be used. If there are any questions related to this aviation module, please send an email to greet@anl.gov.

2. LCA Methods

The LCA system boundary of aviation fuels is presented in Figure 1. The system boundary covers all stages of the supply chain of aviation fuel production pathways, including feedstock production, feedstock transportation, jet fuel production, jet fuel transportation and distribution, and jet fuel combustion. The life cycle of aviation fuels is typically called well-to-wake (WTWa) cycle. All emissions from each process and emissions from the production of the input energy and materials are accounted for in the life cycle. The WTWa results are presented in terms of MJ (or gallon, for example) of jet fuel production. For waste/residue feedstocks, feedstock production starts from the collection of feedstocks (e.g., corn stover produced from corn farming) since the main product (e.g., corn grain) would take the emission burdens. When there are any co-products, the emission burdens are allocated based on the selected allocation method (i.e., energy allocation, mass allocation, market allocation, or displacement [system expansion]). GREET implements all these methods and in most cases, the displacement method is the default method. On the other hand, ICAO uses the energy allocation for handling all co-products (ICAO 2019b).

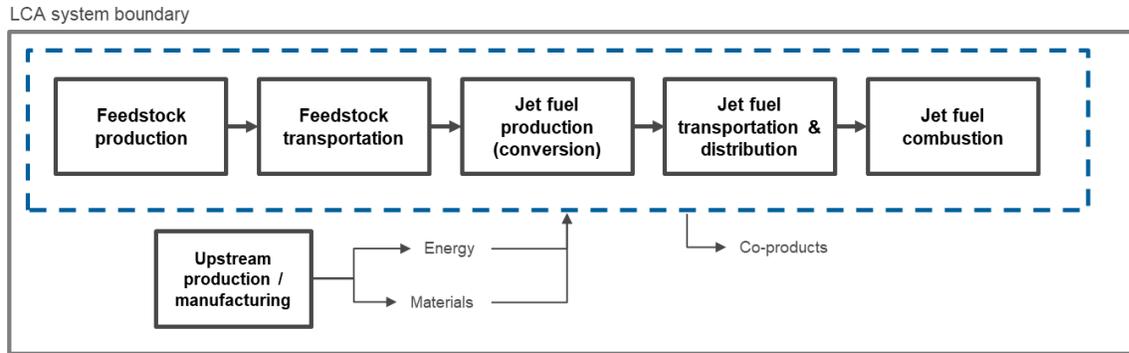


Figure 1. The LCA System Boundary of Aviation Fuel Production Pathways.

The environmental metrics that the aviation module covers are the same as those in the GREET model. The LCA results can be generated for energy use by type (i.e., total energy, fossil energy, petroleum, natural gas, and coal), water consumption, six air criteria pollutant emissions (volatile organic compounds [VOCs], CO, SO_x, NO_x, PM₁₀, and PM_{2.5}), and GHG emissions (CO₂, CH₄, and N₂O). For GHG emissions, the module uses the global warming potential (GWP) values from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) with a 100-year time horizon (IPCC 2013), which generates the results in terms of grams of CO₂ equivalent (gCO₂e). Note that biogenic carbon is considered carbon neutral in GREET simulations.

All upstream production and transportation of energy/materials are from GREET. Emission factors of energy inputs (e.g., natural gas combustion for heat demand) and transportation-related emissions are also from GREET. The detailed information about the supporting datasets from GREET is presented in the next section. Note that the simulation year of the current module is 2020 and is based on using the default conditions of GREET 2021, which would be updated in the future when a new version of GREET is released.

The major parameters associated with feedstock production (e.g., fertilizer uses) or jet fuel production (e.g., energy or chemical inputs) are listed in the data structure. By default, we provide two major datasets: GREET and ICAO. The GREET datasets include all pathways in the existing aviation module inside of GREET, which have been generated from extensive research activities for more than 10 years. The ICAO datasets include the data in all of the ICAO-approved pathways listed in the CORSIA document (ICAO 2019a)¹, with the detailed parameters used to calculate the CI values by ICAO FTG experts (ICAO 2019b). Because the underlying upstream and transportation datasets are from GREET, the ICAO results may not be replicated even with the ICAO fuel production datasets.

¹ Some pathways with data sources other than GREET have been excluded in this version because of noticeable differences between the values from the GREET aviation module and those in the CORSIA supporting document. Limited information is available in the CORSIA supporting document (ICAO 2019a) to replicate assumptions between different underlying datasets, which affects upstream and transportation emission calculations. The excluded pathways in this version are sugarcane ETJ (JRC and CTBE), corn grain ETJ (JRC), sugarbeet SIP (JRC), and eucalyptus FT (JRC).

3. Aviation Module Structure

This is a standalone module, which means it would work even without the GREET model. However, it uses the latest GREET datasets (Figure 2). The aviation module includes upstream inventories for the energy and material inputs used for feedstock and fuel production, which have been imported from GREET (Wang et al. 2021). Also, emission factors, transportation modes, and jet fuel combustion emissions in various aircraft types are imported from the GREET model. In addition, the module includes the datasets regarding the process inputs and outputs. For example, we have implemented the major parameters for feedstock cultivation, feedstock transportation, fuel production, and fuel transportation information collected from GREET (Wang et al. 2021) and ICAO (ICAO 2019b). Combining the jet fuel production parameters and GREET upstream and emission inventories, WTWa results can be generated, including GHG, energy use by type, water consumption, and crucial air pollutant emissions by life-cycle stages.

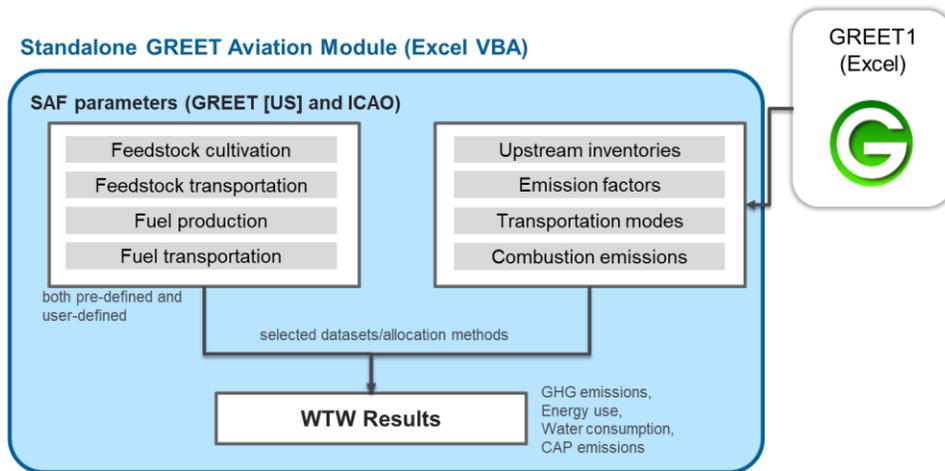


Figure 2. Structure and Data Interaction of GREET Aviation Module.

The dashboard tab is where users can select the options, change the parameters, and check the corresponding results without going to each tab of the aviation module. The input tabs colored in yellow (Processes, LCI, Transportation, Combustion) are where all major datasets are listed. The supporting information tabs colored in grey (LCProfile, EFs, and Payload) are where imported information from GREET is presented. These supporting tabs are used to calculate the WTWa results, along with the process inputs/outputs information in the inputs tab.

3.1. Dashboard

The dashboard has five major panels as in Figure 3: (1) pathway selection, (2) input parameters, (3) results (by MJ or gal fuel produced and used), (4) input contribution, and (5) results (by aircraft types). These panels are explained in detail in the following sections.

3.1.2. Input Parameters

Once the ‘Run Calculations’ button is clicked, the ‘Input Parameters’ panel is updated. It includes three major tables: (1) Process Input Parameters, (2) Allocation, and (3) Transportation.

Process Input Parameters

The Process Input Parameters table includes all inputs and outputs at a process level. This table reads the information of the selected pathway from the LCI tab. This table is interactive; users can update the values or add new items, which would be added to the LCI datasets, and the results would be updated accordingly. The Process Input Parameters table shows the inputs and outputs for each process. The process name and the functional unit of each process are presented at the header of each process. There are six columns in this table: (1) Inputs, (2) Type, (3) User-defined, (4) Default, (5) Unit, (6) Technology, and (7) Deactivate. The input is where users can select input energy/materials. The module will calculate the upstream emissions (e.g., production and transportation of the input items). In the Technology column, users can select associate technologies. For example, if diesel fuel is selected in the Inputs column, available diesel combustion technologies are presented in the dropdown menu of the Technology column. If a given technology is selected, the impact of using the energy input is accounted for (e.g., diesel combustion). Users also can add non-combustion emissions in the Inputs column if ‘Emission’ is selected in the Type column. When the output of a process is used as an input for the next process, the Type can be ‘sourcing.’ In this case, the impact of the previous process is carried over.

Two columns with the values (User Defined and Default) present the values used in the calculation and the default values, respectively. If a user changes the User Defined values, the changes would be made in the LCI tab, and the results in the dashboard will be updated. The Unit column represents the unit of the values of each row.

Users can add a new item by selecting options and typing in the values in the yellow-colored rows. The new row would be added to the LCI, and the results would be updated. In case a user would remove the impact of a certain input, the Deactivate column can be used. By selecting or typing “1” to a row, the row would be removed from the calculation.

Allocation

This table presents the co-product allocation method of each process, which is read from the Processes tab. The allocation method can be selected among mass, energy, and market. Depending on the selection defined in the Processes tab, the corresponding allocation factors would be presented. Users can change the allocation method or change the allocation factors.

To account for the displacement impact, users can use the Process Input Parameters table. Users may add a displaced item like other inputs but with a negative value in the User Defined column. This is like considering the credits of the co-products as the negative inputs.

Transportation

This table presents all the transportation for feedstocks, intermediates, and fuels, which are read from the Transportation tab. Users can select the items to be transported, transportation mode, share, distance, and urban share. Detailed information about these items is explained in the Transportation tab.

3.1.3. Results (by MJ or gal fuel produced)

This panel shows the LCA results of the selected pathways in terms of MJ or gallon of fuel produced. There is a metric selection on the left-hand side with all of the available environmental metrics (energy use, water consumption, air pollutant emissions, and GHG emissions) explained in Section 2. In addition, users can define the units and the functional units to present the results. The first figure shows the LCA results of selected metrics of the selected fuel production pathway. The results are presented at the process level, and the contribution is mainly split into two impacts: upstream and on-site. Other than the processes presented in the Input Parameters tab, there are two more processes: transportation and combustion. In case land-use change (LUC) impact is available and selected to be presented, the figure would show the LUC impact, too. The bottom pie chart shows the aggregated contribution at the process level.

3.1.4. Input Contributions

The table in this panel shows the contribution of the input parameters defined in the Input Parameters tab. Note that this table does not include transportation, combustion, and LUC emissions.

3.1.5. Results: By Aircraft Types

Different aircraft types may result in different LCA results in terms of service functional units (kg-km for freight and passenger-km for passengers) because of different rates of fuel consumption rates and types of trips. This panel shows the LCA results for the selected functional units (per kg-km or per passenger-km) for 6 passenger aircraft types (Single Aisle [SA], Small Twin Aisle [STA], Large Twin Aisle [LTA], Large Quad [LQ], Regional Jet [RJ], and Business Jet [BJ]) and 4 freight aircraft types (Single Aisle [SA-F], Small Twin Aisle [STA-F], Large Twin Aisle [LTA-F], and Large Quad [LQ-F]). Note that the datasets cover the U.S. domestic and international only. Thus, we present the kg-km and passenger-km results only when 'GREET' is selected for U.S. simulations in the Data Source panel.

3.2. Input data

3.2.1. Processes

The processes tab is where the major life-cycle stages are set up. This tab, like other tabs, has four shared columns: Feedstock, Conversion, Data Source, and Option. The combination of these defines a pathway. The pathway may have multiple processes. Since transportation and combustion are defined in different tabs, these should be excluded when setting up the processes. For each process, we provide the process number (Process No.), Process Name, Output item, and Functional unit. The process number starts from 1, which increases by 1 to the number of processes. The process name is to specify each process (e.g., farming, oil extraction, and jet fuel production). Each process may have the main output, which can be a final product or an input of the following process. And the functional unit of each process is used when we construct the inputs and outputs of the process in the LCI tab. The functional unit can be mass, energy, and volume units.

If there are co-products, the main product of the process may take the shared burdens with the co-products. In each row (each process), users may define three different allocation factors (mass, energy,

and market allocation). The module would use the allocation factor for the selected allocation method. If not defined, the module would consider there is no co-product, which leads to an allocation factor of 100% to the main product. As mentioned earlier, note that the co-product can be listed in the LCI tab as a negative input in order to consider displacement impact of a co-product.

3.2.2. LCI

For each process defined in the processes tab, we now define all energy and material inputs for each process. This tab also has four shared columns (Feedstock, Conversion, Data Source, and Option) for the specified pathways, and these columns (Inputs, Type, User Defined, Default, Unit, Technology, and Deactivate) are explained in Section 3.1.2. The Process No. column is used to link the information in the LCI tab with other tabs (e.g., the processes tab). The urban share column is to define the portion of emissions that are released in urban areas (which are defined as the U.S. metropolitan areas by the Census Bureau). The input parameters can be dependent on other parameters in the LCI tab (e.g., N₂O emissions relies on nitrogen fertilizer inputs). In this case, typical Excel formulas can be used to calculate the dependent variable. To avoid directly changing the dependent parameter in the dashboard, users can mark '1' for the item in the 'Hidden' column; the selected input may not be presented in the dashboard table while it is still used to calculate the life-cycle results.

3.2.3. Transportation

The transportation tab is where the information about transporting materials is listed. The transportation tab also has four shared columns (Feedstock, Conversion, Data Source, and Option) for the specified pathways. The materials for transportation can be selected for those with the payload determined in the Payload tab. There are four modes (ocean tanker, barge, heavy-heavy truck, and medium-heavy truck), which require defining the payloads. In addition, two modes (pipeline and rail) can be selected. Once a material to transport is selected, available transportation modes are presented in dropdown menus. If payload is not available, users may add the payload information for the item in the Payload tab, and then they can select the option in the Transportation tab. For each transportation mode, share (%), distance (miles), and urban share (%) need to be defined. Table 1 shows an example for Figure 4. If soybean is transported 10 miles with medium-heavy trucks and another 40 miles with heavy-heavy trucks, the share should be 100% for each. On the other hand, if soyoil is split into three modes (barge, heavy-heavy truck, and rail), the share should represent the mass share of soyoil for each mode.

Table 1. An Example of Transportation Inputs

Transportation materials	Mode	Share (%)	Distance (mi)
Soybean	Medium-heavy Truck	100%	10
Soybean	Heavy-heavy Truck	100%	40
Soyoil	Barge	40%	520
Soyoil	Heavy-heavy Truck	40%	80
Soyoil	Rail	20%	700

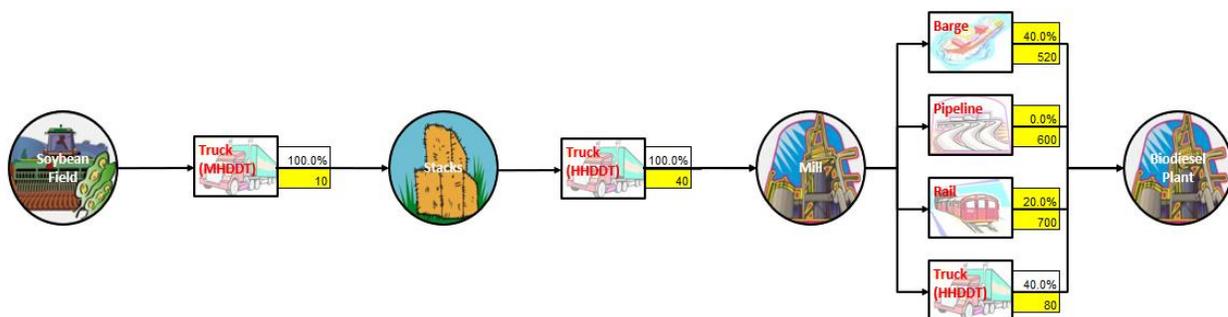


Figure 4. An Example of Transportation Mode from GREET (soybean-derived biodiesel production).

When the LCI uses the mass units for sourcing items, it can be defined as the either wet or dry basis. If the inputs in the LCI tab are presented in dry mass, the moisture content for materials should be considered for transportation. Otherwise, we may underestimate the impact of transportation by only considering the dry portion of the materials. Thus, if the sourcing item in the LCI is specified on a dry mass basis, the ‘dry’ option should be selected in the Dry/Wet column along with the moisture content of the item. In this case, the module would adjust the amount of transported item considering the moisture content. If not specified in the Dry/Wet column, the module would assume that no adjustment is needed.

With the trip information defined in this tab and energy intensity and emission factors defined in the payload tab, the module calculates all environmental metrics (energy use, water consumption, and emissions) per short ton material transported. By combining this with the material input for the process, the module calculates the transportation impact.

3.2.4. Combustion

This tab is to define the combustion characteristics of different fuel types (petroleum and SAF) for different aircraft types. The payload fuel energy intensities (PFEIs) and emission factors are from the recent datasets from The Bureau of Transportation Statistics (BTS) T-2 database (retrieved from <https://www.transtats.bts.gov/> on November 30, 2021), which have been processed by BlueSky (FAA 2022). As mentioned earlier, since the datasets only include U.S. domestic and international flights, kg-km and passenger-km results are valid for U.S. trips. Further analyses are warranted to cover other world regions.

3.2.5. LUC

This tab presents the list of available LUC values in terms of gCO₂e/MJ jet fuel by world region. If the LUC option is selected in the dashboard and the corresponding LUC value is available for the selected pathway, the LUC impact is presented in the dashboard. The LUC tab also has four shared columns (Feedstock, Conversion, Data Source, and Option) for the specified pathways.

The GREET LUC values are mainly from the aviation tab inside of GREET. GREET has LUC values for biodiesel from soybean and ethanol produced from corn, corn stover, switchgrass, and miscanthus. Thus, in case we do not have jet-specific LUC values using these feedstocks, we calculate the LUC values in MJ for a jet using the available ethanol and biodiesel LUC values. The ICAO LUC values are from the CORSIA document (ICAO 2019a; 2019b).

3.3. Supporting information

This part is where the supporting information extracted from GREET is listed. This section mainly provides the calculation processes in the module. Although users may add new information here to enable additional items in the LCI tab, changing the existing values may cause unintended consequences, which lead to different results.

3.3.1. LCProfile

The LCProfile tab includes all upstream impacts of the energy/materials used in the LCI tab, which are all from GREET. For example, Table 2 presents the life-cycle energy use, water consumption, and emissions for 1 mmBtu of diesel fuels (except for the use stage; diesel combustion in this example). With this, the module calculates the upstream impact of diesel use when diesel is listed as an input of a process in the LCI. For example, if 0.5 mmBtu of diesel is used for 1 mmBtu of jet fuel production, GHG emissions associated with diesel production/transportation are estimated at 8,165 gCO₂e/mmBtu jet (16,330 gCO₂e/mmBtu diesel × 0.5 mmBtu diesel/mmBtu/jet). The LCProfile will be updated regularly to reflect the changes in the upstream values.

Table 2. The Data Structure of the LCProfile Tab

Raw_Material	Input_Type	LC Metric	Metric Unit	Functional Unit	Life-Cycle Profile
Diesel	Energy	Total Energy	Btu	mmBtu	182,677
Diesel	Energy	Fossil Fuels	Btu	mmBtu	176,795
Diesel	Energy	Coal	Btu	mmBtu	7,940
Diesel	Energy	Natural Gas	Btu	mmBtu	122,277
Diesel	Energy	Petroleum	Btu	mmBtu	46,578
Diesel	Energy	Water Consumption	Gal	mmBtu	22.78
Diesel	Energy	VOC	g	mmBtu	7.37
Diesel	Energy	CO	g	mmBtu	11.75
Diesel	Energy	NOx	g	mmBtu	17.86
Diesel	Energy	PM10	g	mmBtu	1.30
Diesel	Energy	PM2.5	g	mmBtu	1.11
Diesel	Energy	SOx	g	mmBtu	4.75
Diesel	Energy	BC	g	mmBtu	0.17
Diesel	Energy	OC	g	mmBtu	0.30
Diesel	Energy	CH4	g	mmBtu	109.50
Diesel	Energy	N2O	g	mmBtu	0.22
Diesel	Energy	CO2	g	mmBtu	12,944
Diesel	Energy	CO2 (w/ C in VOC & CO)	g	mmBtu	12,986
Diesel	Energy	GHGs	g	mmBtu	16,330
Diesel	Energy	VOC: Urban	g	mmBtu	2.77
Diesel	Energy	CO: Urban	g	mmBtu	1.86
Diesel	Energy	NOx: Urban	g	mmBtu	2.85
Diesel	Energy	PM10: Urban	g	mmBtu	0.50
Diesel	Energy	PM2.5: Urban	g	mmBtu	0.43
Diesel	Energy	SOx: Urban	g	mmBtu	1.02
Diesel	Energy	BC: Urban	g	mmBtu	0.05
Diesel	Energy	OC: Urban	g	mmBtu	0.08

3.3.2. EFs

The LCProfile is used to consider all energy use and emissions to bring the item to the process. If this is an energy input (such as diesel or natural gas), on-site energy use and emissions should be accounted for. The emission factors (EFs) tab is to define the combustion characteristics of the energy inputs that are used in the LCI tab (Table 3). Since different technologies would lead to different emissions, the EFs tab specifies the EFs for each technology. For example, if 0.5 mmBtu of diesel fuel is combusted in a large gas turbine to produce 1 mmBtu of jet fuel, on-site CO₂ emissions are estimated at 39,093 gCO₂/mmBtu jet fuel (78,187 gCO₂/mmBtu diesel × 0.5 mmBtu diesel/mmBtu jet).

Table 3. The Data Structure of the EFs Tab. All Values Are Presented in Terms of mmBtu of Energy Use.

Energy	Technology	Metrics	Values
Diesel	Large Gas Turbine	Total energy	1,000,000
Diesel	Large Gas Turbine	Fossil fuels	1,000,000
Diesel	Large Gas Turbine	Coal	0
Diesel	Large Gas Turbine	Natural gas	0
Diesel	Large Gas Turbine	Petroleum	1,000,000
Diesel	Large Gas Turbine	VOC	0.26
Diesel	Large Gas Turbine	CO	1.56
Diesel	Large Gas Turbine	NOx	256.41
Diesel	Large Gas Turbine	PM10	25.94
Diesel	Large Gas Turbine	PM2.5	6.57
Diesel	Large Gas Turbine	SOx	0.54
Diesel	Large Gas Turbine	BC	0.66
Diesel	Large Gas Turbine	OC	1.64
Diesel	Large Gas Turbine	CH4	3.02
Diesel	Large Gas Turbine	N2O	0.60
Diesel	Large Gas Turbine	CO2	78,187

3.3.3. Payload

The payload tab is to support calculating transportation emissions (Table 4). The table includes the material, transportation mode, and payload (short ton). With the payload values and other information from GREET, energy intensity values are calculated.

Table 4. The Data Structure of the EFs Tab.

Material	Mode	Payload (short ton)
Crude Oil	Ocean Tanker	133,526
Crude Oil	Barge	22,500
Soybean	Barge	20,000
Soyoil	Barge	22,500
Crude Oil	Heavy-heavy Truck	25
Soybean	Heavy-heavy Truck	15
Soyoil	Heavy-heavy Truck	25
Soybean	Medium-heavy Truck	8

3.4. Results

The results tab is used to compile all the results at the process level. All impacts from the input energy/materials defined in the LCI are aggregated upstream and on-site. The module converts the units, accounts for the links between processes, and considers allocation factors at each process. All transportation impact is also aggregated, which are mainly from the transportation tab and the payload

tab. The combustion stage presents the combustion results; for SAFs, the module considers biogenic carbon credits, which leads to having approximately zero combustion emissions.

3.5. Export

To export the LCA results of multiple pathways, the Export tab can be used. Once the ‘Export Results’ button is clicked, the aggregated LCA results for the selected pathway are added to the table. Users may select a different pathway or change some parameters in the dashboard, and then clicking the ‘Export Results’ button would add the results to the table. The ‘Reset’ button would remove all the items on the table.

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