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Life Cycle Analysis of Greenhouse Gas Emissions of Clean Fuels with the R&D GREET 2024 Model

Energy Systems and Infrastructure Analysis Division

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prepared by

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January 2025

1. Introduction

This document summarizes research on the life cycle greenhouse gas (GHG) emissions rates from the production and use of clean fuels to support a new version of the Research and Development Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (R&D GREET) model, R&D GREET 2024

In this effort, Argonne National Laboratory (ANL) focuses on clean fuel pathways that are readily available in the market or are emerging in the near term. The selected pathways represent clean fuel technologies that convert biomass- and/or waste-based feedstocks to liquid and/or gaseous fuels for the transportation sector and other potential uses. The pathways are configured in R&D GREET 2024 with up-to-date feedstock-to-fuel life cycle inventory (LCI) data. Additionally, a new tab has been added to R&D GREET 2024 called "Clean Fuels" which allows the user to easily change inputs and access LCA results.

Argonne does not warrant that the results presented in this report are consistent with the requirements of any particular regulatory or incentive program. Users interested in specific programs that reference GREET are encouraged to review guidance specific to those programs if and when it is available to determine appropriate means of compliance and contact the relevant responsible agencies for those specific policies or programs.

The clean fuel pathways reported here include:

1. Ethanol via fermentation, with the following feedstocks:
    a. Corn grain
    b. Sorghum grain
    c. A mix of corn and sorghum grains
    d. Brazilian sugarcane
2. Biodiesel (BD) via transesterification with co-produced glycerin and free fatty acids (FFA) & heavy distillation bottoms, with the following feedstocks:
    a. Soybean oil
    b. Used cooking oil (UCO)
    c. Tallow
    d. Distiller corn oil (DCO)
    e. Spring canola oil
    f. Winter carinata oil (intermediate crop)
    g. Winter camelina oil (intermediate crop)
    h. Winter pennycress oil (intermediate crop)
    i. A mix of the above vegetable oils and waste oils
3. Renewable diesel (RD) and sustainable aviation fuel (SAF) with co-produced propane and naphtha via hydroprocessed esters and fatty acids (HEFA), with the following feedstocks:
    a. Soybean oil
    b. Used cooking oil (UCO)
    c. Tallow
    d. Distiller corn oil (DCO)
    e. Spring canola oil

   f. Winter carinata oil (intermediate crop)
   g. Winter camelina oil (intermediate crop)
   h. Winter pennycress oil (intermediate crop)
   i. A mix of the above vegetable oils and waste oils
4. Ethanol via enzymatic hydrolysis and fermentation, with the following cellulosic feedstocks:
   a. Corn stover
   b. Switchgrass
   c. Miscanthus
   d. Willow
   e. Poplar
   f. A mix of the above cellulosic feedstocks
5. SAF (with joint production of RD) via alcohol-to-jet processes, using ethanol produced from
   a. Corn grain
   b. Sorghum grain
   c. Cellulosic feedstocks
   d. Brazilian sugarcane
   e. A mix of the above feedstocks
6. RD and SAF via gasification and Fischer-Tropsch synthesis, with the following feedstocks:
   a. Corn stover
   b. Switchgrass
   c. Miscanthus
   d. Willow
   e. Poplar
7. Renewable natural gas (RNG) via anaerobic digestion and upgrading, with the following feedstocks:
   a. Landfill gas
   b. Animal manures
   c. Wastewater sludge
8. Hydrogen fuel for on-board hydrogen fuel cell vehicles
   a. The user can provide a well-to-gate carbon intensity for their hydrogen production and select a hydrogen delivery method, and R&D GREET will then calculate the well-to-wheels carbon intensity.

Key research efforts detailed here include 1) updating and expanding the process inputs and yields of the feedstock production and fuel production of the above clean fuel pathways; 2) addressing the effects of selected measures to mitigate GHG emissions at the fuel production facilities, such as use of RNG as a process fuel; and 3) estimating the induced land use change (ILUC) and indirect effects (I-Effects) associated with changes in non-feedstock crop production and livestock production due to crop-based clean fuel/SAF fuel production using dedicated feedstocks (i.e., corn, soybean, sorghum, spring canola, and Brazilian sugarcane). In parallel, Argonne expanded the Carbon Calculator for Land Use and Land Management Change from

Biofuels Production (CCLUB), an affiliated tool of R&D GREET 2024, to address the ILUC and I-Effects.

This report documents updates of key parameters that affect the life cycle analysis (LCA) results of the clean fuel pathways listed above in R&D GREET 2024, as well as life cycle GHG emissions results and the changes relative to those in R&D GREET 2023 Rev.1 due to the pathway updates. For the expansion of CCLUB for ILUC and I-Effects modeling, see details in Kwon et al. (2024).

2. Direct LCA of Clean Fuel Pathways using Default R&D GREET 2024 Inputs

In Table 1, we summarize the direct LCA (D-LCA) results, in g CO_2e/MJ, which represent life cycle GHG emissions associated with direct energy and material consumption during the biomass- and/or waste-to-clean fuel supply chain, for selected clean fuel pathways using default R&D GREET 2024 inputs. Note that these results are generated with the IPCC AR6 100-year GWPs for CH_4 and N_2O emissions. D-LCA results are further broken down into feedstock emissions, feedstock transportation emissions, fuel production emissions including CH_4 and N_2O emissions from fuel combustion, and fuel transportation emissions. These results are based on (1) default parameters in R&D GREET 2024; (2) fossil natural gas (NG) providing energy for heat generation in clean fuel plants if NG is required; (3) hydrogen from NG steam methane reforming (SMR) for clean fuel production if hydrogen is required; and (4) U.S. average electricity generation, among other parameters. The values reported here only apply to R&D GREET 2024 default inputs – any modification of inputs by the user may change the results.

Table 1. Direct LCA results for selected clean fuel pathways, including D-LCA results based on default inputs in R&D GREET 2024 (g CO_2e/MJ of fuel, based on lower heating value)

Pathway	Feedstock	Direct LCA Total	Feedstock	Feedstock Transportation	Fuel	Fuel Transportation
Ethanol via fermentation	**Corn**	43.8	25.7	1.0	16.1	1.0
	Sorghum	45.7	27.5	1.0	16.1	1.0
	Brazilian sugarcane	30.2	22.2	0.0[1]	1.8	6.2[2]
Ethanol via enzymatic hydrolysis and fermentation	**Corn stover**	10.9	3.7	1.8	4.4	1.0
	Switchgrass	17.6	10.7	1.5	4.4	1.0
	Miscanthus	16.7	9.8	1.5	4.5	1.0
	Willow	13.4	5.5	2.0	4.9	1.0

[1] Brazilian sugarcane transportation from field to ethanol plant is included in feedstock production stage due to aggregated data collected for sugarcane farming and transportation.

[2] The transportation of Brazilian sugarcane ethanol includes ethanol transportation from sugarcane plants to Brazilian ports and subsequent transportation to the U.S. ports.

Pathway	Feedstock	Direct LCA Total	Feedstock	Feedstock Transportation	Fuel	Fuel Transportation
	Poplar	16.6	8.6	2.0	5.0	1.0
BD via transesterification	**Soybean oil**	20.2	10.5	0.8	8.5	0.3
	Domestic UCO	18.9	4.6	2.0	12.0	0.3
	Imported UCO	25.2	4.6	8.2	12.0	0.3
	Tallow	19.3	6.6	0.4	12.0	0.3
	DCO	14.0	1.3	0.4	12.0	0.3
	Spring canola oil	34.3	24.8	0.7	8.5	0.3
	Winter carinata oil (intermediate crop)	28.3	18.8	0.7	8.5	0.3
	Winter camelina oil (intermediate crop)	41.2	31.7[3]	0.7	8.5	0.3
	Winter pennycress oil (intermediate crop)	28.2	18.6	0.7	8.5	0.3
RD via HEFA	**Soybean oil**	24.7	12.8	0.9	10.6	0.4
	Domestic UCO	17.5	4.5	2.0	10.6	0.4
	Imported UCO	23.7	4.5	8.1	10.6	0.4
	Tallow	17.9	6.5	0.3	10.6	0.4
	DCO	12.6	1.3	0.3	10.6	0.4
	Spring canola oil	37.1	25.3	0.7	10.6	0.4

[3] Compared to carinata and pennycress, the higher contribution from camelina farming is due primarily to its lower yield, resulting in relatively higher nitrogen fertilizer and glyphosate requirement per kg of oilseeds produced.

Pathway	Feedstock	Direct LCA Total	Feedstock	Feedstock Transportation	Fuel	Fuel Transportation
	Winter carinata oil (intermediate crop)	31.8	20.0	0.7	10.6	0.4
	Winter camelina oil (intermediate crop)	45.3	33.5*	0.8	10.6	0.4
	Winter pennycress oil (intermediate crop)	31.7	19.9	0.8	10.6	0.4
SAF via HEFA	**Soybean oil**	24.7	12.8	0.9	10.6[4]	0.4
	Domestic UCO	17.5	4.5	2.0	10.6	0.4
	Imported UCO	23.7	4.5	8.1	10.6	0.4
	Tallow	17.9	6.5	0.3	10.6	0.4
	DCO	12.6	1.3	0.3	10.6	0.4
	Spring canola oil	37.1	25.3	0.7	10.6	0.4
	Winter carinata oil (intermediate crop)	31.8	20.0	0.7	10.6	0.4
	Winter camelina oil (intermediate crop)	45.3	33.5	0.8	10.6	0.4

[4] A small amount of CH_4 and N_2O emissions from combustion of SAF are accounted for, using the same CH_4 and N_2O emission factors of RD combustion on a per MJ basis.

Pathway	Feedstock	Direct LCA Total	Feedstock	Feedstock Transportation	Fuel	Fuel Transportation
	Winter pennycress oil (intermediate crop)	31.7	19.9	0.8	10.6	0.4
SAF via alcohol-to-jet process with ethanol[5]	**Corn grain**	61.4	43.6	0.2	17.0	0.6
	Sorghum grain	63.2	45.4	0.2	17.0	0.6
	Brazilian sugarcane	47.7	28.6	1.5[6]	17.0	0.6
	Corn stover	28.2	10.3	0.2	17.0	0.6
	Switchgrass	34.9	17.0	0.2	17.0	0.6
	Miscanthus	34.0	16.2	0.2	17.0	0.6
	Willow	30.7	12.8	0.2	17.0	0.6
	Poplar	33.9	16.0	0.2	17.0	0.6
RD via gasification and Fischer-Tropsch	**Corn stover**	5.7	3.1	1.5	0.7	0.4
	Switchgrass	11.4	9.0	1.3	0.7	0.4
	Miscanthus	10.1	3.9	0.6	5.2	0.4
	Willow	7.1	4.4	1.6	0.7	0.4
	Poplar	9.2	6.6	1.5	0.7	0.4
SAF via gasification and Fischer-Tropsch	**Corn stover**	5.7	1.5	0.8	3.0	0.4
	Switchgrass	11.4	4.5	0.6	5.9	0.4
	Miscanthus	10.1	3.9	0.6	5.2	0.4
	Willow	7.1	2.2	0.8	3.7	0.4
	Poplar	9.2	3.3	0.8	4.8	0.4

[5] ATJ plants may produce a small amount of RD together with SAF

[6] For ATJ using Brazilian sugarcane ethanol, transportation of sugarcane ethanol is included in the feedstock transportation stage. The fuel transportation here includes SAF transportation from SAF plant to use site within the U.S.

Table 2 summarizes the ILUC and I-Effects of corn ethanol, sorghum ethanol, Brazilian sugarcane ethanol, soybean biodiesel, canola biodiesel, soybean RD/SAF, and canola RD/SAF. These results are modeled in CCLUB 2024 that has been expanded with new data and methodologies (Kwon et al., 2024).

Table 2. Induced land use change (ILUC) and indirect-effects (I-Effects) of clean fuel pathways modeled in R&D GREET 2024

Biofuel Pathways using 2017 GTAP database (volume shock)		Corn Ethanol (1.5 BG)	Sugarcane Ethanol (1.5 BG)	Soy Biodiesel (0.5 BG)	Soy RD/SAF (0.5 BG)	Canola Biodiesel (0.5 BG)	Canola RD/SAF (0.5 BG)	Sorghum Ethanol (0.2 BG)
EF model		DayCent & Winrock	AEZ-EF	DayCent & Winrock	DayCent & Winrock	AEZ-EF	AEZ-EF	DayCent & Winrock
Total	g CO_2e/MJ	4.99	3.87	10.16	11.53	16.68	18.41	4.76
ILUC		6.10	13.10	10.32	11.69	15.15	16.68	7.52
Indirect-Effects		-1.11	-9.23	-0.17	-0.16	1.54	1.74	-2.76
Domestic ILUC	Forest	-1.04	0.01	0.31	0.32	0.07	0.07	-0.91
	Grassland	0.09	0.02	0.11	0.12	0.03	0.04	0.09
	Cropland-pasture & Unused land	0.34	0.44	0.50	0.57	0.56	0.63	0.44
	Belowground Crop Biomass	0.00	0.02	0.00	0.00	0.10	0.10	0.00
International ILUC	Forest	-0.05	4.22	3.14	3.66	3.15	3.55	0.39
	Grassland	1.57	-0.15	1.51	1.67	2.04	2.28	1.77

Biofuel Pathways using 2017 GTAP database (volume shock)		Corn Ethanol (1.5 BG)	Sugarcane Ethanol (1.5 BG)	Soy Biodiesel (0.5 BG)	Soy RD/SAF (0.5 BG)	Canola Biodiesel (0.5 BG)	Canola RD/SAF (0.5 BG)	Sorghum Ethanol (0.2 BG)
EF model		DayCent & Winrock	AEZ-EF	DayCent & Winrock	DayCent & Winrock	AEZ-EF	AEZ-EF	DayCent & Winrock
	Cropland-pasture & Unused land	5.29	10.35	4.87	5.47	9.19	10.00	5.83
	Belowground Crop Biomass	-0.10	-1.81	-0.11	-0.12	0.01	0.01	-0.09
Domestic indirect-effects	Livestock	-0.50	0.00	-0.04	-0.04	0.29	0.33	-0.42
	Non-Feedstock Crops [7]	-3.63	0.15	-4.14	-4.65	-0.40	-0.43	-6.25
International indirect-effects	Livestock	-1.03	-5.92	-0.49	-0.48	-1.15	-1.20	-1.52

[7] Non-Feedstock Crops emissions include methane emissions from rice paddy fields.

Biofuel Pathways using 2017 GTAP database (volume shock)		Corn Ethanol (1.5 BG)	Sugarcane Ethanol (1.5 BG)	Soy Biodiesel (0.5 BG)	Soy RD/SAF (0.5 BG)	Canola Biodiesel (0.5 BG)	Canola RD/SAF (0.5 BG)	Sorghum Ethanol (0.2 BG)
EF model		**DayCent & Winrock**	**AEZ-EF**	**DayCent & Winrock**	**DayCent & Winrock**	**AEZ-EF**	**AEZ-EF**	**DayCent & Winrock**
	Non-Feedstock Crops [8]	4.05	-3.47	4.47	5.00	2.80	3.05	5.42

[8] Non-Feedstock Crops emissions include methane emissions from rice paddy fields.

The following subsections present updates of key parameters and data sources for major clean fuel pathways in Table 1. We also present the life cycle carbon intensity (CI) results reflecting the GHG emissions from feedstock production and transportation (i.e., Feedstock CI) and emissions from fuel production, transportation, and combustion (i.e., Conversion CI). Note that these results exclude ILUC and Indirect Effects for relevant pathways.

2. 1 Ethanol (EtOH) via Fermentation

2.1.1 Corn and Sorghum Ethanol Pathway

For corn farming and corn ethanol production, the LCI data in R&D GREET 2024 remains the same as those in R&D GREET 2023 Rev.1. The corn farming fertilizers and pesticides input data, and corn yield was based on 2021 data from the National Agricultural Statistics Service (NASS) of the U.S. Department of Agriculture (USDA). The corn farming energy use data were based on USDA Agricultural Resource Management Survey (ARMS) 2016. Meanwhile, the LCI data for ethanol production was collected from an industry survey (Lee et al., 2021).

For grain sorghum farming, we updated the sorghum yield with the latest 2019 survey data from the USDA NASS (USDA, 2024). For sorghum grain to ethanol conversion, we assumed that the life cycle inventory (LCI) data encompassing process energy and chemical uses, along with the co-product profiles for grain sorghum ethanol, are the same as those for corn ethanol, which were based on Lee et al. (2021), given the similarities in their starch compositions and the fact that both can be processed together. Table 3 and Table 4 summarize the updated LCI for sorghum ethanol production and the total displaced products from DDGS and sorghum oil co-products.

Table 3. Life cycle inventory data of sorghum ethanol production, per gallon of ethanol produced

	R&D GREET1 2023 Rev.1	**R&D GREET1 2024[1]**
Sorghum inputs (bushel)	0.36	0.35
Energy inputs (Btu)	18,328	24,578
Natural gas (%)	86.4	91.1
Coal (%)		0.4
Electricity (%)	13.6	8.5
Co-products		
DDGS (dry lb)	5.63	4.61
Sorghum oil (lb)		0.27
Chemical inputs (g)		
Alpha Amylase	2.6	2.5
Gluco Amylase	5.5	5.4
Yeast	2.8	2.7
Sulfuric acid	4.7	4.6
Ammonia	18.1	17.8
NaOH	22.7	22.3
CaO	10.8	10.6

[1] Based on the plant design of dry milling with sorghum oil extraction.

Table 4. Total displaced products from sorghum DDGS and oil co-products (unit: lb/gallon)

Total displaced products	**GREET1 2023 Rev.1**	**R&D GREET1 2024[1]**
Corn	4.40	3.60
Soybean meal	1.73	1.42
Urea	0.13	0.10
Soy oil		0.27

[1] Based on the plant design of dry milling with sorghum oil extraction.

Table 5 shows the impacts of the updated LCI on sorghum ethanol CI. We observe a higher CI with R&D GREET 2024, mainly due to higher energy use and less DDGS co-product in the ethanol fermentation step. For the feedstock stage, despite that the LCI data per bushel of sorghum produced remain the same, we observe a lower CI with R&D GREET 2024, mainly because: 1) we account for the CH_4 credit from cattle and cow fed with DDGS, the same as those for corn DDGS; and 2) the sorghum-to-ethanol yield is slightly higher than the previous assumption.

Table 5. Updated sorghum ethanol CI results (unit: g CO_2e/MJ)

Total direct CI		**Feedstock CI**		**Conversion CI**	
GREET2023 Rev.1	GREET2024	GREET2023 Rev.1	GREET2024	GREET2023 Rev.1	GREET2024
42.9	45.7	30.4	28.5	12.5	17.2

2.1.2 Brazilian Sugarcane Ethanol Pathway

For the pathway of sugarcane ethanol production in Brazil and use in the U.S. in GREET 2023 Rev.1, both sugarcane farming and ethanol production LCI data relied on the data collected through the Brazilian RenovaBio program (Liu et al., 2023). In 2024, Brazilian Agricultural Research Corporation released a report that includes the latest Brazilian sugarcane farming data (Ramos et al., 2024). We collected new LCI data from the report and verified the data with the authors of the report, which are used to update the Brazilian sugarcane ethanol pathway in R&D GREET1 2024.

Table 6 summarizes the key parameters regarding the open field burning of sugarcane straw. It shows that the share of burnt fields in total sugarcane fields has been significantly reduced from 29.8% to 9.9%.

Table 6. Key parameters regarding field burning of sugarcane straw

	GREET 2023 Rev.1	R&D GREET1 2024
Yield of sugarcane straw: dry tonne/tonne of sugarcane	0.14	0.14
Proportion of sugarcane fields with manual cane cutting and burned fields	29.8%	9.9%
Fraction of sugarcane straw left in unburnt fields	98.6%	73.6%*
Share of straw burnt in burnt fields	90.0%	100.0%

* This amount of straw is used to determine the amount of N in straw for potential N2O contribution. The difference of 26.4% of the straw is due to straw removal together with the sugarcane to sugarcane ethanol plants.

Table 7 summarizes the updated energy and fertilizer use for Brazilian sugarcane farming. The farming energy use and nitrogen fertilizer use have decreased significantly, by 14.6% and 13.2%, respectively. The farming fuel shares, nitrogen fertilizer shares, and P_2O_5 fertilizer shares were also updated and summarized in

Table 8, Table 9, and Table 10, respectively. It is noteworthy that Brazilian sugarcane farming consumes ethanol as fuel. In GREET1 2023 Rev.1, we assumed that the sugarcane mills used their own produced ethanol in farming and thus subtracted these uses from the anhydrous equivalent yield to calculate the net yield. In the updated version, we assumed that the ethanol consumed in sugarcane farming is sourced from Brazilian market, and consequently, we updated the mill's sugarcane to ethanol yield from 20.85 to 20.89 gallons/wet tonne.

Table 7. Energy and fertilizer use for sugarcane farming (unit: per tonne wet sugarcane harvested)

	GREET 2023 Rev.1	**R&D GREET1 2024**
Farming Energy Use: Btu	171,143[1]	146,225[2]
Fertilizer Use: grams		
Nitrogen	1,168.2	1,013.7
P_2O_5	510.8	605.3
K_2O	1,005.2	862.8
$CaCO_3$	10,450.8	11,801.3
Gypsum	4,264.5	4,841.8
Pesticide Use: grams		
Herbicide	45.0	13.0
Insecticide	2.5	0.55

[1] The farming energy use excludes sugarcane ethanol as an energy source;
2 The farming energy use includes sugarcane ethanol as an energy source.

Table 8. Shares of fuels for sugarcane farming

	GREET 2023 Rev.1	R&D GREET1 2024
Diesel fuel	89.4%	85.6%
Gasoline	0.05%	0.1%
Electricity	1.4%	1.3%
Biodiesel	9.2%	9.7%
Ethanol	-	3.3%

Table 9. Shares of nitrogen fertilizer types for sugarcane farming

	GREET 2023 Rev.1	R&D GREET1 2024
Ammonia (NH_3)	0.0%	0.3%
Urea (NH_2CONH_2)	66.7%	35.7%
Ammonium Nitrate (NH_4NO_3)	24.7%	39.7%
Monoammonium Phosphate	4.0%	9.9%
Diammonium Phosphate	0.0%	0.2%
Urea Ammonium Nitrate (UAN) Solution (per ton N product)	0.4%	6.2%
Ammonium Sulfate	4.2%	8.0%

Table 10. Shares of P_2O_5 fertilizer types for sugarcane farming

	GREET 2023 Rev.1	R&D GREET1 2024
Monoammonium Phosphate	46.5%	89.1%
Diammonium Phosphate	0.7%	1.2%
Single superphosphate (SSP)	52.4%	5.5%
Triple superphosphate (TSP)	0.4%	4.1%

Table 11 summarizes the organic amendment application rates to sugarcane farming and their respective nitrogen contents.

Table 11. Organic amendment application rates for sugarcane farming

	GREET 2023 Rev.1	R&D GREET1 2024
Filtercake (kg dry filtercake/tonne sugarcane)	10.1	10.5
Vinasse (L vinasse/tonne sugarcane)	1,059	833
N content of filtercake (g N/dry kg)	8.16	8.14
N content of vinasse (g N/L)	0.30	0.39
Filtercake moisture content (wt%)	65%	65%

Table 12 shows the impacts of the updated LCI data on sugarcane ethanol CI. We observe an overall lower CI with R&D GREET 2024, mainly due to the less farming energy and nitrogen fertilizer use during farming. It is noteworthy that even though the ethanol fermentation LCI has not been updated (except for the sugarcane to ethanol yield as mentioned above), we still observe a lower conversion stage CI, mainly because of the ocean tanker cargo payload update in R&D GREET 2024, and ocean tanker is required to transport ethanol produced in Brazil to be used in the U.S.

Table 12. Updated sugarcane ethanol CI results (unit: g CO_2e/MJ)

Total CI		**Feedstock CI**		**Conversion CI**	
GREET 2023 Rev.1	GREET 2024	GREET 2023 Rev.1	GREET 2024	GREET 2023 Rev.1	GREET 2024
35.2	30.2	26.5	22.2	8.8	8.0

2.2 Soybean Biodiesel Pathway

2.2.1 Soybean Farming Update

The survey data from the USDA NASS (2024) have been utilized to update the amount of nitrogen, phosphorous, and potassium fertilizers; herbicides; and insecticides required for soybean farming in the United States. This survey provides a comprehensive data source of the total usage of these materials, acres planted, and total soybean production across 19 states. The estimation of the uses of fertilizers, herbicides, and insecticides per bushel of soybean harvested was based on this information and the reported annual yield of soybean farming in the United States. To address the impacts of climate and farming fluctuations on the farming LCI data, three-year averages of LCI data were developed based on the USDA NASS survey data from 2018, 2020, and 2023. Table 13 presents the fertilizer, herbicide, and insecticide uses, soybean yield, and total annual production for the surveyed years, as well as the three-year average estimation.

Table 13. Fertilizers, herbicide, and insecticide uses, in grams per bushel of soybean harvested, and the soybean yield, in bushels per acre.

	2018	**2020**	**2023**	**Three-year average**
Fertilizer use: grams per bushel				
Nitrogen	43.9	52.8	60.3	52.2
P_2O_5	208.4	207.9	229.3	215.0
K_2O	340.1	348.7	369.1	352.4
Pesticide use: grams per bushel				
Herbicide	19.4	21.2	22.1	20.9

Insecticide	0.3	0.3	0.2	0.3
Yield: bushels per acre	50.6	51.0	50.6	50.7

The farming energy use in R&D GREET 2023 Rev.1 was adjusted by the three-year average yield. Table 14 provides a comparison between the soybean farming LCI data in R&D GREET 2023 rev 1 and R&D GREET 2024.

Table 14. LCI data for soybean farming (per bushel of soybean harvested)

	R&D GREET 2023 Rev.1	R&D GREET1 2024
Farming energy use: Btu	13,634	13,694
Diesel (%)	68.1	68.1
Gasoline (%)	15.0	15.0
LPG (%)	4.8	4.8
Electricity (%)	10.7	10.7
Natural gas (%)	1.3	1.3
Fertilizer use: grams		
Nitrogen	52.7	52.2
P_2O_5	207.9	215.0
K_2O	348.7	352.4
Pesticide use: grams		
Herbicide	21.2	20.9
Insecticide	0.3	0.3

2.2.2 Soybean Crushing and Solvent Oil Extraction Update

The National Oilseed Processors Association (NOPA) conducted a survey on 52 soybean solvent extraction plants. The results of the survey representing operations in 2023 were reported by $(S\&T)^2$ Consultants Inc. (2024). The survey collected data from plants employing the solvent extraction process. These facilities reported processing 60,073,422 tons of soybeans, representing about 50% of the US total soybean production.

The survey showed that crushing and solvent oil extraction operations have a lower loss factor of 0.1% compared to previous value of 1.9% in R&D GREET 2023 Rev.1. The survey also revealed lower soybean requirements and reduced energy requirements per pound of oil extracted, as well as lower production of soybean meals as a co-product. In the survey, the use of residual oil and biomass as energy sources in the crushing and solvent extraction operations was not observed. As the survey did not collect data for hexane consumption, the value from R&D GREET 2023 Rev.1 is used in R&D GREET 2024.

Table 15 summarizes the LCI data for soybean use, meal production, and energy requirements for R&D GREET 2024, compared to those in R&D GREET 2023 Rev.1.

Table 15. Soybean requirement and soybean meal production from the crushing and oil extraction process (per lb of oil extracted)

	R&D GREET 2023 Rev.1	**R&D GREET1 2024**
Soybean inputs: lb, as received[1]	4.47	4.39
Energy use: Btu	3,073	1,756
Residual oil (%)	0.9	-
Diesel (%)	0.4	0.001
Natural gas (%)	56.1	78.8
Coal (%)	27.6	4.5
Electricity (%)	12.1	13.5
Biomass (%)	0.9	-
Landfill gas (%)	0.4	0.5
Hexane (%)	1.6	2.7
Co-product: lb as produced		
Soybean meals	3.45	3.39

[1] The industry standard moisture content for soybeans is 13%.

2.2.3 Transesterification

Similar to R&D GREET 2023 Rev.1, the LCI data for transesterification to produce biodiesel are from the industrial survey data in Xu et al. (2022). However, the prices of biodiesel, crude glycerin, free fatty acids (FFA) and heavy distillation bottoms have been updated to estimate revised market-value allocation factors. The biodiesel price was obtained from the quarterly Clean Cities and Communities Alternative Fuel Price reports issued by the U.S. Department of Energy (2024), covering prices from January 2019 to July 2024. Prices from crude glycerin were collected from publicly available data from various sources including the Jacobsen publishing (Watts, 2023; Watts, 2024a; Watts,2024b), Argus media group (2024, 2022), Imarc group (2024), Oleoline (2021), Indexbox (2024), and scientific articles and reports (Attarbachi et al., 2023; da Silva Ruy et al., 2020) spanning multiple years from 2019 to 2024. The price of residual fuel oil was utilized as a surrogate for the price of FFA and heavy distillation bottoms, as both products are assumed to have similar properties. The price data for these products were collected from the U.S. Energy Information Administration (US EIA, 2024) and covered the period from January 2019 to March 2022. The reported prices were estimated from the arithmetic mean of the prices collected for each product during the time interval. Despite the increase of the price of biodiesel compared to the value in R&D GREET 2023 Rev.1, the market-value allocation factor for biodiesel shows a reduction attributed to the almost twofold increase in the price of glycerin.

Table 16 presents the price data and the updated estimates of the market values for biodiesel and glycerin, compared to those in R&D GREET 2023 Rev.1.

Table 16. Updated prices, in USD($) per lb, and market-value allocation factors for biodiesel, glycerin, and FFA and heavy distillation bottoms

Coproduct	**R&D GREET 2023 Rev.1**	**R&D GREET1 2024**
Prices: $/lb		
Biodiesel	0.494	0.562
Glycerin	0.100	0.180
FFA and Heavy distillation bottoms	0.245	0.183
Market-value allocation factors for biodiesel production (%)		
Biodiesel	97.8	96.8
Glycerin	1.9	3.0
FFA and Heavy distillation bottoms	0.3	0.2

2.2.4 Impacts of Soybean Farming and Crushing/Oil Extraction Updates on the Direct LCA GHG Emissions of Soybean-Based Biodiesel

Table 17 shows a comparison of the direct LCA (D-LCA) GHG emission results for soybean-based biodiesel in R&D GREET 2023 Rev.1 and R&D GREET 2024. The total D-LCA GHG emissions are 11% lower in R&D GREET 2024 compared to R&D GREET 2023 Rev.1. This reduction is primarily driven by a 41% decrease in GHG emissions associated with soybean crushing and oil extraction. In contrast, the D-LCA GHG emissions from soybean farming showed only a 1% reduction in R&D GREET 2024 compared to R&D GREET 2023 Rev.1.

Table 17. Updated soybean-based biodiesel CI results (unit: g CO_2e/MJ)

Total CI		**Feedstock CI**		**Conversion CI**		**Combustion CI**	
R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024
22.0	20.2	13.0	11.3	4.3	4.1	4.7	4.7

2.3 Spring Canola Biodiesel/Renewable Diesel Pathways

2.3.1 Spring Canola Farming Update

Spring canola is mainly produced in Canada and US Northern Plains.

Table 18 summarizes the LCI data for spring canola farming, obtained from $(S\&T)^2$ Consultants Inc. (2022). The original data were available at the Reconciliation Unit (RU) level for Canada, and were aggregated to the national average LCI, using production potential in each RU as weighting factors. Given the geographical proximity, we assumed that the spring canola farming LCI data in the U.S. Northern Plains are comparable to those of its Canadian counterparts.

Table 18. LCI data for spring canola farming (unit: per tonne canola, as received)

	R&D GREET 2023 Rev.1	R&D GREET1 2024[1]
Farming Energy Use: Btu	528,667	416,693
Diesel (%)	96.6	97.4
Natural gas (%)	1.7	1.1
Electricity (%)	1.6	1.5
Fertilizer Use: grams		
Nitrogen	51,648.0	51,637.6
P_2O_5	15,919.0	15,993.9
K_2O	4,163.0	5,746.7
Pesticide Use: grams		
Herbicide	417.0	589.5
Insecticide	39.0	13.6
Total N in above and below ground biomass: grams	24,280	42,639
N_2O emissions: N in N_2O as % of N in N fertilizer	1.040[2]	1.374
N_2O emissions: N in N_2O as % of N in biomass	0.940[2]	1.264

[1] $(S\&T)^2$ Consultants Inc. (2022); [2] $(S\&T)^2$ Consultants Inc. (2017).

Table 19 summarizes the nitrogen fertilizer shares for spring canola farming, also derived from $(S\&T)^2$ Consultants Inc. (2022).

Table 19. Shares of nitrogen fertilizers for spring canola farming

	R&D GREET 2023 Rev.1	R&D GREET 2024
Ammonia (NH_3)	31.0%	25.8%
Urea (NH_2CONH_2)	23.0%	55.9%
Ammonium Nitrate (NH_4NO_3)	2.0%	1.0%
Monoammonium Phosphate	4.0%	1.3%
Diammonium Phosphate	6.0%	0.0%
UAN Solution (per ton N product)	32.0%	9.2%
Ammonium Sulfate	2.0%	6.8%

Table 19 shows that there is a significant shift from UAN solution to urea fertilizer. The UAN solution has a CI of 2.9 ton CO_2e/ton N, while urea has a CI of 1.9 ton CO_2e/ton N. As a result, the CI of updated nitrogen fertilizer mix decreases from 2.7 ton CO_2e/ton N to 2.3 ton CO_2e/ton N, a 14.2% decrease.

It is worth noting that in GREET1 2023 Rev.1, the nitrogen fertilizer to N_2O conversion factors from synthetic nitrogen fertilizer application and nitrogen in canola biomass were 1.04% and 0.94%, respectively, which were taken from $(S\&T)^2$ Consultants Inc. (2017). To ensure consistency across all feedstocks, we updated the N_2O EFs for canola (and other crops and biomass) based on IPCC 2019 Tier 1 values: 1.374% for synthetic nitrogen and 1.264% for nitrogen in canola biomass residue (

Table 18).

To calculate the total nitrogen in aboveground and belowground canola biomass, we adopted the values from Thiagarajan et al. (2018), as summarized in Table 20.

Table 20. Nitrogen in aboveground and belowground canola biomass

	Aboveground biomass	Belowground biomass
Canola Crop Residues (kg dry/kg dry canola)	2.65	1.35
Canola Crop Residue Nitrogen Content (kg N/dry kg residue)	0.013	0.009
N in Crop Residue (g N/tonne canola*)	31,522	11,117

*As received, with a moisture content of 8.5%

The general crop pesticide application rate of 1.38 kg per hectare from Alberta Environment and Parks (2020) is used to estimate the pesticide application rate for canola. With a canola yield of 2.28 tonnes per hectare, this translates to a pesticide application rate of 603 grams per tonne. On a mass basis, herbicide application rate is 43 times higher than insecticide application rate (Alberta Environment and Parks, 2020), resulting in rates of 589.5 grams per tonne for herbicides and 13.6 grams per tonne for insecticides, respectively. Additionally, to calculate the upstream GHG emissions from herbicide application, we approximated the herbicide mix for canola using the soybean herbicide composition, due to the lack of canola-specific data.

2.3.2 Update of Canola Oil Extraction

The LCI data for canola oil extraction were obtained from a Canadian Oilseed Processors Association (COPA) survey, covering 11 facilities that represent all canola crushing facilities in Canada and averaged for the three-year period of 2021 to 2023 (Don O'Connor, personal communication, 24 Oct 2024).

Notably, the LCI data in Table 20 represent one pound of combined canola oil, comprising 69% refined and 31% crude oil. The available data do not allow us to distinguish the energy requirements for producing crude canola oil versus refined canola oil. Using these LCI data, the CI of canola-based BD would be overestimated, while the CI of canola-based RD or SAF would be underestimated. This difference arises because BD production via transesterification can use crude oil, whereas RD/SAF production requires refined oil.

Table 21. Energy and material LCI data for canola oil extraction

Material Inputs	**GREET1 2023 Rev.1**	**R&D GREET1 2024**
Canola seed (dry lb/lb oil)[1]	2.17	2.18
Total Energy Inputs (Btu/lb oil)	1,316	1,125
Natural Gas (%)	79.3	81.4
Electricity (%)	13.4	14.2
Hexane (%)	7.3	4.4
Co-product		
Canola meal (dry lb/lb oil)[2]	1.12	1.21

[1] The industry standard moisture content for canola seeds is 8.5%.

[2] The industry standard moisture for the meal is 12%.

Table 21 indicates that over time, energy use has decreased (with added cogeneration capacity), while natural gas consumption has remained relatively stable despite an increase in the percentage of oil refined. This is due to the improved energy efficiency with added new crushing facilities. COPA does not track hexane consumption by crushers, so we used the hexane usage value from soy oil extraction in R&D GREET, estimated at 49 Btu/lb oil.

Table 22 shows the impacts of the updated LCI data on the CI of canola oil-based pathways. Despite the lower energy use in canola farming in R&D GREET 2024, the overall CIs are higher in R&D GREET 2024 compared to those in R&D GREET 2023 Rev.1. Despite the slightly reduced emissions from nitrogen fertilizer application, this is mainly due to the higher amount of total estimated nitrogen in aboveground and belowground canola biomass, and the updated N_2O conversion factors (as shown in

Table 18) , which together contribute to 63.1% higher N_2O emissions from fertilizer application and canola biomass decomposition, compared to R&D GREET 2023 Rev1. This contributes to most of the increase in feedstock CI (by 3.7 g CO_2e/MJ) as shown in Table 22. The CI of the conversion stage, on the other hand, remains the same.

Table 22. Updated canola oil BD/RD/SAF CI results (unit: g CO_2e/MJ)

	Total CI		**Feedstock CI**[1]		**Conversion CI**	
	GREET2023 Rev.1	GREET2024	GREET2023 Rev.1	GREET2024	GREET2023 Rev.1	GREET2024
BD	30.8	34.3	21.8	25.5	9.0	8.8
RD/SAF	33.3	37.1	22.1	26.0	11.2	11.0

[1] The feedstock CI contains contributions from both farming and oil extraction/refining stages.

It is worth mentioning that the well-to-plant gate CI of RD and SAF are the same, since they are co-produced from the HEFA process, and the default allocation method in R&D GREET is energy allocation for the HEFA plants.

2.4 Winter Camelina/Carinata/Pennycress Biodiesel/Renewable Diesel Pathways

Intermediate winter oilseeds crops added to existing crop production are potential feedstocks for production of biodiesel, renewable diesel, and sustainable aviation fuels. When grown between regular planting cycles on land that would otherwise be left without production, they also provide other benefits (e.g., soil erosion and nutrient loss prevention, pollinator habitat, etc.), while their seeds can be harvested at maturity to generate additional revenue for growers.

We focused on three intermediate winter oilseed crops – camelina (Camelina sativa L. Crantz.), carinata (Brassica carinata), and pennycress (Thlaspi arvense L.). We collected the LCI data for their farming and subsequent oil extraction and refining for biofuel production in Liu et al. (2024), with key data summarized in Table 23 and Table 24.

The farming energy use, chemical use, and yield data in Table 23 were compiled from various sources: camelina from Berti et al. (2017) and Gesch et al. (2014), carinata from Alam et al. (2021), pennycress from Mousavi-Avval and Shah (2021) and Fan et al. (2013). The energy use and chemical use are dedicated to intermediate winter oilseed farming. Energy use includes dedicated tractor passes for planting and harvesting these crops.

Table 23. Life cycle inventory data for intermediate winter oilseed farming (per kg of oil seed)

	Camelina	**Carinata**	**Pennycress**
Energy use: Btu	666.7	952.9	583.5
Diesel (%)	96.8	51.0	81.0
Electricity (%)	3.2	49.0	19.0

Fertilizer/chemical use: grams			
Nitrogen (N)	59.4	31.8	35.7
P_2O_5	25.5	15.9	17.9
K_2O	13.0	31.8	13.2
Glyphosate	4.8	2.3	0.5
Insecticide	0.0	0.2	0.0
Yield: kg of oil seed per ha	1,178	2,800	2,036
Oil seed moisture content (%)	10	8	12
Oil seed oil content (%)	37	45	32
Total N in crop residue: g of N	32.0	14.1	22.9

The LCI data for camelina oil extraction were from Shonnard et al. (2010). For generating the LCI data of carinata and pennycress oil extraction, camelina was used as a reference. The energy inputs per kg of carinata and pennycress oil are adjusted based on the feedstock-specific oil contents relative to that of camelina. The typical oil extraction rate for hexane solvent extraction is 97.5% (Mousavi-Avval and Shah, 2021). The crude oil is further refined via an oil degumming process, which enhances the stability and quality of the oil, making it more suitable for further processing. The inputs for crude oil refining were obtained from Prussi et al. (2020), with a refining loss factor of 2.4%.

Table 24. LCI data for winter oilseed oil extraction and refining (per kg of refined oil)

	Camelina	**Carinata**	**Pennycress**
Oil seed inputs: kg, as received	2.6	2.1	2.9
Energy Inputs[1]: Btu	1,502	1,269	1,707
Natural Gas (%)	85.9	85.8	86
Electricity (%)	7.5	7.8	7.4
Hexane (%)	6.6	6.4	6.7

[1] Combined energy use for both extraction and refining steps.

Table 25. GHG results of biodiesel, renewable diesel, and sustainable aviation fuel from intermediate winter oilseed crops (unit: g CO_2e/MJ).

		Total CI	Feedstock CI[1]	Conversion CI
Biodiesel	Winter carinata oil	28.3	19.5	8.8
	Winter camelina oil	41.2	32.4	8.8
	Winter pennycress oil	28.2	19.4	8.8
Renewable Diesel/SAF	Winter carinata oil	31.8	20.8	11.0
	Winter camelina oil	45.3	34.3	11.0
	Winter pennycress oil	31.7	20.7	11.0

[1] The feedstock CI includes contributions from both farming and oil extraction/refining stages.

R&D GREET 2023 Rev.1 did not have these intermediate winter oilseeds-based pathways. Therefore, Table 25 only summarizes the newly generated results from R&D GREET 2024.

2.5 Used Cooking Oil (UCO), Tallow, and Distiller Corn Oil (DCO) Pathways

UCO, tallow, and DCO are by-products, so no emissions are associated with activities upstream of collection/processing of them. For tallow and UCO, rendering processes require energy inputs to separate the lipid portion. For DCO, the oil extraction process in corn ethanol facilities requires electricity. These activities contribute to the emissions of production of these feedstocks. It is noted that DCO has similar free fatty acids (FFA) content to UCO and tallow which is much higher than the FFA content of vegetable oils (Winkler-Moser et al., 2023). Therefore, DCO is modeled as waste oil in R&D GREET 2024.

Domestic UCO and tallow are modeled the same in R&D GREET 2024 as in R&D GREET 2023 Rev.1. Imported UCO, on the other hand, is assumed with a transportation distance of 14,440 km by ocean tanker (from Singapore to Los Angeles). The payload of ocean tankers is assumed to be 25,000 deadweight tonnage (27,558 short tons).

For the BD and RD/SAF conversion processes, the same fuel yields and process energy and chemical requirements from R&D GREET 2023 Rev.1 are retained in R&D GREET 2024.

Transesterification of waste oil has different LCI than vegetable oil due to different compositions (e.g., high FFA content in waste oil). Methanol usage in transesterification of waste oil is slightly lower than that of vegetable oil. Since the fossil carbon in methanol ends up in the biodiesel product, biodiesel produced from waste oils have slightly lower fossil carbon content than those produced from vegetable oil. As a result, waste oil-derived biodiesel generates less GHG emissions from fuel combustion than vegetable-derived biodiesel.

2.6 RD and SAF via HEFA Pathways

For HEFA pathways that co-produce RD and SAF, the LCI data from the R&D GREET 2023 Rev.1, which relies mainly on HEFA conversion process data from industry surveys (Xu et al., 2022), remain the same in R&D GREET 2024.

2.6.1 Soybean Oil Refining

The production of RD and SAF requires a refining process to decrease the phosphorus content of the crude soybean oil. A reduced content of phosphorous content prolongs the lifetime of the catalyst used in the conversion process. The survey from the NOPA collected energy and material use data from 26 refining facilities ($(S\&T)^2$ Consultants Inc., 2024). Based on the survey, a material loss of 3.6% was estimated for the refining process. This data has been incorporated into R&D GREET 2024 for modeling soybean-based RD and SAF. Table 26 provides the material and energy uses of the refining process.

Table 26. LCI data for soybean oil refining process (per lb of refined oil)

	Value
Crude soybean input: lb	1.04
Energy use: Btu	314.8
Natural gas (%)	65.0
Coal (%)	21.7
Electricity (%)	12.6
Landfill gas (%)	0.3
Material inputs: grams	
Bleaching earth	0.8
Sodium hydroxide	1.2

2.6.2 Impacts of Updated Soybean Farming and Crushing and Oil Extraction LCI Data on GHG Emissions of Soybean-Based RD/SAF

The comparison of GHG emissions of soybean-based RD/SAF between R&D GREET 2023 Rev.1 and R&D GREET 2024 are illustrated in

Table 27. As shown, the GHG emissions for both fuels increased by only 1% in R&D GREET 2024 compared to those in R&D GREET 2023 Rev.1. Updates of farming practices led to a 3% increase in GHG emissions for this stage relative to R&D GREET 2023 Rev.1. Although the GHG emissions from crushing decreased by 38% in R&D GREET 2024 compared to R&D GREET 2023 Rev.1, the inclusion of the refining stage offset this reduction to a large extent. Nonetheless, GHG emissions related to soy oil processing are still 2% lower in R&D GREET 2024 compared to R&D GREET 2023 Rev.1.

Table 27. Updated soybean-based RD/SAF CI results (unit: g CO_2e/MJ)

Total CI		**Feedstock CI**		**Conversion CI**		**Combustion CI**	
R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024
24.4	24.7	13.2	13.7	10.5	10.3	0.7	0.7

2.7 SAF via ATJ with Ethanol

The conversion rate, which is 1.01 MJ of ethanol per MJ of SAF (with small amount of RD), remains the same for SAF production via the alcohol-to-jet (ATJ) processes using ethanol as feedstock, and were adopted in R&D GREET 2023 Rev.1.

2.8 Cellulosic Ethanol via Hydrolysis and Fermentation

For willow and poplar, the nitrogen content of aboveground and belowground biomass has been updated based on the 2016 Billion Ton Study (US DOE, 2016), which remains the same in the more recent 2023 Billion Ton Study (US DOE, 2024). For willow and poplar, the nitrogen content of aboveground and belowground biomass is 2,449 and 3,629 g-N/dry ton, respectively, or 0.27% and 0.40%, respectively (see Table 28). The nitrogen content estimates are for the plant parts only those used for the fuel production application and are based on the Bioenergy Feedstock Library (INL, 2016). In addition, the harvest/collection rates for willow and poplar, which reflect the impact of dry matter losses during field handling, drying, harvest, and collection, have been revised to be 90%, which are the same as those of switchgrass and miscanthus. These updates improve the estimation of nitrous oxide (N_2O) and nitrogen dioxide (NO_2) emissions from aboveground and belowground biomass for production and harvest of willow and poplar as a feedstock for biofuel production. Compared to R&D GREET 2023 Rev.1, the updates to the aboveground and belowground nitrogen in willow and poplar feedstocks along with other upstream updates, the feedstock CI for willow and poplar pathways increased by 6% and 5% respectively. Improvements in the LCI data for fuel conversion along with other upstream updates have increased the fuel conversion stage CI by 95% and 92%, for willow and poplar pathways, respectively.

Table 28. Updates of aboveground and belowground nitrogen *(N)* content, inputs for feedstock

Aboveground and belowground N content	**R&D GREET 2024**
Willow	0.27%
Poplar	0.40%
Harvest/Collection rate	
Willow	90%
Poplar	90%

Table 29 summarizes the feedstock and fuel conversion CI for the pathways. The increase in fuel conversion stage for willow and poplar to ethanol pathways is due to addition of glucose in the conversion process.

Table 29. Comparison of LCA GHG emissions between the two GREET versions for the cellulosic ethanol via fermentation pathways (g CO_2e/MJ).

Cellulosic Feedstocks	Total CI		Feedstock CI		Conversion CI	
	R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024	R&D GREET 2023 Rev.1	R&D GREET 2024
Corn Stover	10.2	10.9	5.4	5.5	4.8	5.4
Switchgrass	16.8	17.6	12.0	12.2	4.8	5.4
Miscanthus	15.6	16.8	10.7	11.3	4.9	5.5
Willow	10.1	13.4	7.1	7.5	3.0	5.9
Poplar	13.2	16.6	10.1	10.6	3.1	6.0

2.9 RD and SAF via Gasification and FT

The gasification of cellulosic biomass and Fischer-Tropsch synthesis process use the same LCI data in R&D GREET 2023 Rev.1 and R&D GREET 2024. A literature review of various studies (Swanson et al., 2010; Xie et al., 2011; Suresh et al., 2018; Tan and Tao, 2019; Tan et al., 2021) was conducted this time to determine the current state of the energy conversion efficiencies of the processes. The review revealed that the energy conversion efficiency ranges from 45 to 57%. Therefore, the previously established energy conversion efficiency of 50% in R&D GREET 2023 Rev.1, is considered a good approximation for the process.

2.10 RNG Pathways

Argonne has recently investigated analytical issues that affect the CI of RNG pathways. The GHG emissions associated with counterfactual scenarios of diverting different waste streams, such as specific sources of animal wastes for RNG production are estimated (Gan et al., 2025). For animal wastes of different types, such as dairy cow manure and swine manure, a bottom-up approach is applied to estimate biogas production potential from common manure storage/treatment systems such as anaerobic lagoons and deep pits, the statistics of adopting such common storage systems, as well as the downstream biogas management practices that lead to fugitive or flared biogas.

Second, GHG emissions are generated during biogas upgrading to pipeline quality RNG. The amount of GHG emissions is influenced by the methane leakage and energy consumption of specific upgrading technologies, including pressure swing adsorption, water scrubbing, membrane separation, and chemical absorption (Lim et al., 2025). R&D GREET 2024 will allow users to select the specific upgrader technology employed with either 1) default performance as supported by ANL research (Lim et al., 2025) or 2) user-defined performance. The default upgrader technology is set to pressure swing adsorption (PSA) to reflect typical upgraders in the US (Lim et al., 2025).

RNG can be used as a process fuel in fuel production facilities, such as biofuel plants, and be converted to compressed natural gas (CNG) or liquefied natural gas as a transportation fuel in NG-powered vehicles. When RNG is used as a process fuel, it is assumed that RNG is transported to a fuel production facility by pipeline for 680 miles that is subject to pipeline leakage by 0.26%. When RNG is distributed to a refueling station via local distribution pipeline to produce CNG, an additional leakage of 0.09% is considered. The inlet pressure to the CNG compressor station is assumed to be 50 psia (coming out of the pipeline), and the discharge pressure at the outlet of the compressor is 4,800 pounds per square inch (psia) for on-board vehicle storage at 3,600 psia.

The outcome of the analyses has informed updates of key assumptions for RNG pathways to estimate emissions of counterfactual scenarios and of biogas upgrading, and therefore the life cycle GHG emissions of RNG production, transportation, and end uses as a process fuel or as a transportation fuel in R&D GREET 2024 (Wang et al., 2024).

2.11 Hydrogen Pathways

For hydrogen as a clean fuel used in vehicles that can be produced from various resources and conversion technologies, Argonne has implemented three hydrogen transportation modes to hydrogen refueling stations – pipeline for gaseous hydrogen, tube trailer for gaseous hydrogen, and liquid truck for liquid hydrogen. The emissions associated with transporting hydrogen from a hydrogen plant to a hydrogen refueling station for vehicle use are estimated for these three modes separately in R&D GREET 2024. For pipeline transportation, a default transportation distance of 680 miles is considered. The default payload for liquid hydrogen truck is 4 tons and for tube trailer is 1 ton. A default transportation distance of 100 miles is assumed for both tube trailer and liquid truck. The liquid hydrogen transportation is preceded by liquefaction and cryogenic storage while the tube trailer is loaded via compression from 300 psia to 7,500 psia.

Acknowledgements

This effort was supported by the Bioenergy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, under Contract DE-AC02-06CH11357. We are grateful to John Cabaniss of the Bioenergy Technologies Office and Michael Shell of Strategic Analysis Office of the Office of Energy Efficiency and Renewable Energy for their support and guidance. The authors are solely responsible for the content of this publication.

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