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REVIEW OF SELECTED MODELS USED FOR BIOFUELS GHG DETERMINATIONS AND COMPARISON OF RESULTS FOR TWO FUELS

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REVIEW OF SELECTED MODELS USED FOR BIOFUELS GHG DETERMINATIONS AND COMPARISON OF RESULTS FOR TWO FUELS

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1. EXECUTIVE SUMMARY

Lifecycle analysis (LCA) is widely used by government agencies, academic institutions, and other organizations to determine the level of greenhouse gas (GHG) emissions associated with the production, distribution, and use of biofuels in the transportation sector. LCA of biofuels used in the transportation sector is generally performed on what is known as a "well-to-wheels (WTW)" basis so that GHG emissions associated with all aspects of feedstock production, fuel production, and use of the fuel are taken into account. The GHG emissions associated with the WTW lifecycle of a biofuel are generally referred to as the carbon intensity (CI) of the fuel, which is usually reported in units of grams of carbon dioxide equivalent emissions per megajoule of fuel energy (gCO_2e/MJ).

Although there are numerous regulatory programs developed around the world that seek to reduce the CI of transportation fuels through the substitution of lower CI biofuels for higher CI conventional fuels, the incorporated LCA methodologies used to determine CI can vary considerably in terms of system boundaries, assumptions, and input data, which in turn creates the potential for a high degree of variability in the assessment of the CI of any particular biofuel.

Given this, the goal of this study was to perform a detailed review and comparison of the LCA methodologies associated with the eight selected regulatory frameworks intended to reduce the CI of transportation fuels and to identify differences in each that can lead to differences in the estimated CI value of a given fuel. These regulatory frameworks and the associated LCA methodologies were:

1. U.S. EPA Renewable Fuel Standard (RFS) Program → EPA Fuel Pathway Analyses
2. California Low Carbon Fuel Standards (LCFS) → CARB Look Up Tables and Tier 1 Calculators
3. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) → Roundtable on Sustainable Biofuels (RSB) Tool and Custom Calculator
4. Canadian Clean Fuel Regulation (Canadian CFR) → OpenLCA
5. European Union (EU) Renewable Energy Directive (EU RED) → RSB Tool and Custom Calculator
6. British Columbia Low Carbon Fuel Standard (BC LCFS) → GHGenius
7. RenovaBio, the Brazilian national biofuels policy → RenovaCalc
8. The U.S. Inflation Reduction Act (IRA) → GREET[1]

Furthermore, in order to provide specific insights into the sources of difference between the methodologies, CI values for two biofuel pathways – 1) ethanol produced from corn via dry milling and 2) renewable diesel fuel from hydrotreating of soybean oil – were computed using each regulatory framework methodology and subjected to a detailed comparison.

The results of the review indicated that the choice of system boundaries in terms of the consideration of land use change (LUC) plays an essential role as it determines the universe of greenhouse gases associated with the fuel. Likewise, employing different allocation methods in an LCA methodology, such as economic or mass-based approaches, can lead to varied GHG emissions estimates for co-products, which impact the resulting biofuel CI values. Temporal factors like location-specific emission factors and technology lifespans introduce additional variability in the results from different LCA methodologies. Further differences arise from varying approaches to quantifying GHG emissions within fuel production pathways, as well as reliance on diverse databases for input data, some of which are proprietary.

[1] The IRS has indicated that revised verisions of GREET will be release with revised parameters for IRA calculations.

Overall, it was found that even when estimating emissions from the same biofuel production pathway, there are substantial variations in LCA results observed from the different LCA methodologies examined in this study. To put the magnitude of these variations into perspective, CI values for dry mill corn ethanol, derived using default LCA inputs for those methodologies where they are available, ranged from about 53 to 75 grams of CO_2 equivalent emissions per megajoule of fuel energy (gCO_2e/MJ). Using GREET1_2022 inputs for dry mill corn ethanol, the CI values obtained from the different LCA methodologies ranged from about 38 to 71 gCO_2e/MJ, as shown in Figure 1-1. Similar results were observed for the soybean oil-based renewable diesel pathway, where the range of CI values observed using default values was about 22 to 66 gCO_2e/MJ, while the use of GREET1_2022 inputs resulted in CI values of about 18 to 57 gCO_2e/MJ, as shown in Figure 1-2.

Figure 1-1. GHG Emissions from Corn Ethanol Pathways – Baseline Values

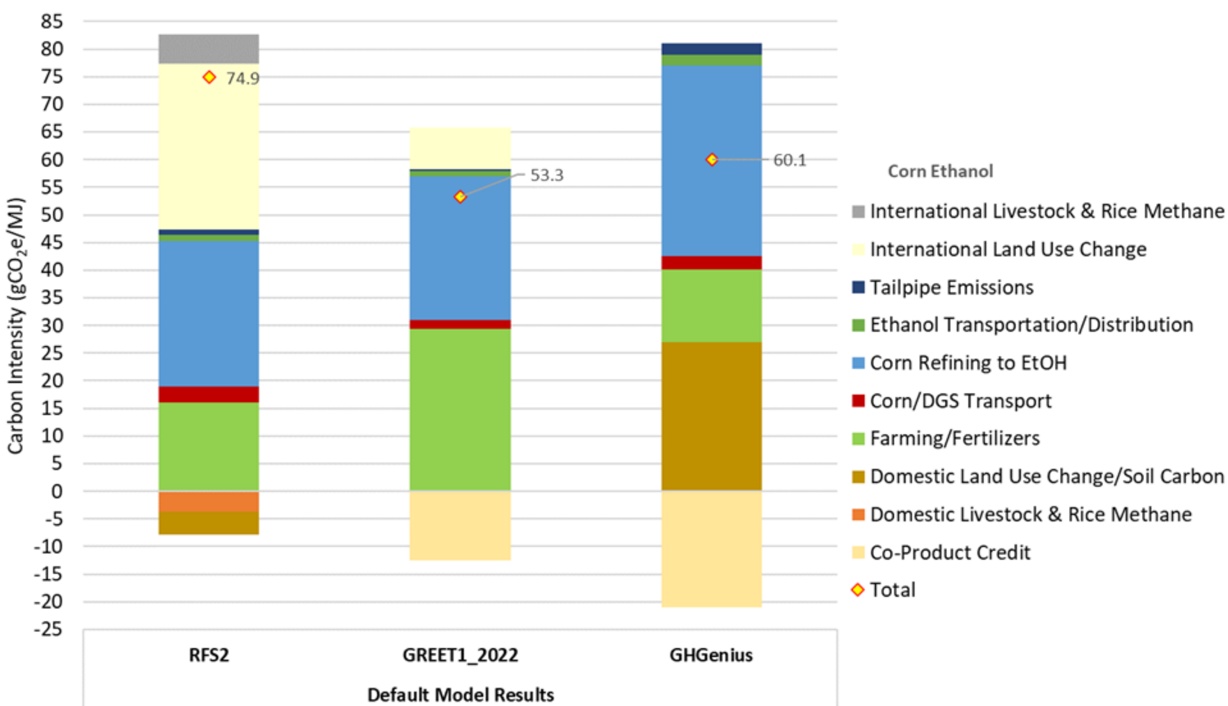
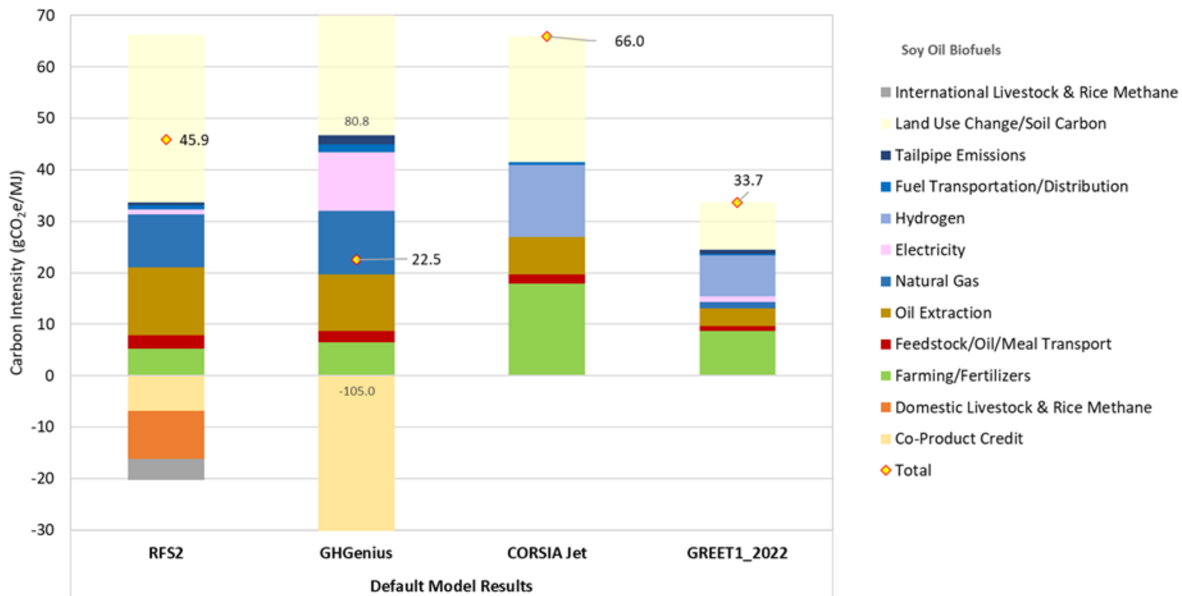


Figure 1-2. GHG Emissions from Soy Oil Pathways – Baseline Values



Although the assessment of the implications of these types of variations in CI values for the same fuels across the various regulatory programs and associated LCA methodologies was outside the scope this study, the observed level of variability clearly highlights the need for more consistent, more transparent, and more thoroughly documented LCA methodologies. Based on this, it is recommended that future studies in this area focus on achieving consensus on how LCA methodologies are structured, as well as on the assumptions and input data, so that they can be embraced by all of the regulatory bodies seeking to reduce GHG emissions associated with transportation fuels.

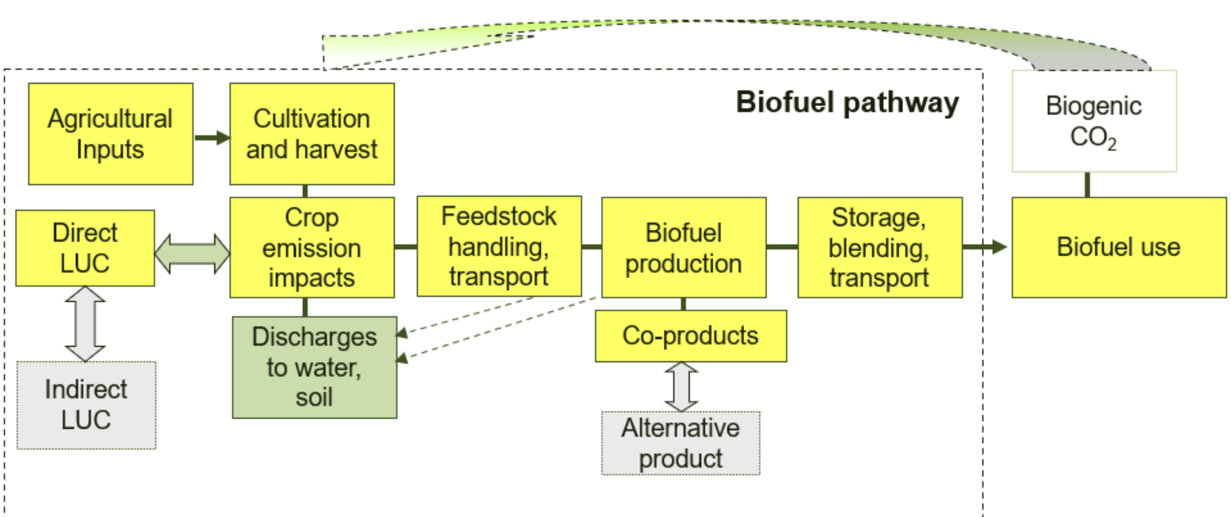
2. INTRODUCTION

2.1 Lifecycle Analysis Overview

Lifecycle analysis (LCA) is widely used by government agencies, academic institutions, and other organizations to determine the level of greenhouse gas (GHG) emissions associated with the production, distribution, and use of biofuels in the transportation sector. LCA of biofuels used in the transportation sector is generally performed on what is known as a "well-to-wheels (WTW)" basis so that GHG emissions associated with all aspects of feedstock production, fuel production, and use of the fuel are taken into account.

Figure 2-1 illustrates the system boundaries of a WTW LCA analysis for a biofuel used in the transportation sector. Feedstock production includes all agricultural inputs required to grow the crop, including fertilizers, pesticides, and herbicides. Cultivating and harvesting the crop would include emissions from farm equipment (e.g., diesel tractors), energy needed for irrigation, and other farming-related inputs. Emissions associated with transporting the bio-feedstock to the biofuel production facility could include diesel trucks used to move the crop from the field to a grain elevator, then potentially rail transport to the fuel production facility. The next steps in the LCA process require accounting for GHG emissions associated with producing the biofuel, as well as addressing the impact of co-products and waste products. Emissions are distributed between co-products which have useful value, while the burden of processing and transporting waste is also considered in the analysis. The final steps are related to the distribution and use of the finished biofuel. However, most of the actual GHG emissions associated with the combustion of the fuel in a vehicle are omitted as the CO_2 released is assumed to be taken up by the next round of biofuel crop that is produced. This is commonly referred to as "biogenic" or "short cycle" carbon.

Figure 2-1. Steps in the Lifecycle GHG Analysis of Biofuels



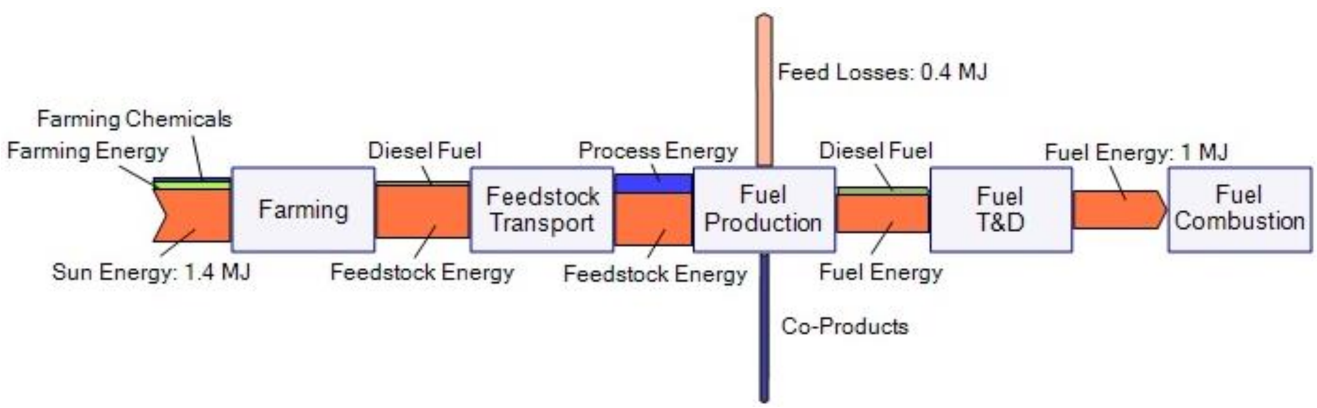
Also shown on the left side of Figure 2-1 are direct and indirect land use changes (LUC). Direct land use change (dLUC) occurs when biofuel feedstock cultivation displaces a former land use, such as soybeans grown on acreage that was previously grassland. This changes the amount of carbon stored in vegetation and soil. Indirect Land Use Change (ILUC), also referred to as induced land use change, is the unintended consequence of releasing carbon emissions due to land use changes around the world by the expansion of croplands in response to increased demand for biofuels and the need to maintain global food supply. For example, reduced exports of soybeans from the U.S. as a result of biofuel production could induce clearing of native forest for crop cultivation in Brazil to make up for the loss of U.S. exports.[2]

At a high level, the basic approach to LCA is fairly straightforward, with the GHG accounting process performed using one of a number of different models following the steps illustrated in Figure 2-2. As shown, the LCA GHG accounting process begins with GHG emissions associated with farming and feedstock production, followed by those associated with feedstock transportation, fuel production, fuel distribution, and finally fuel combustion. The "core LCA" GHG emissions are identified as part of an attributional LCA, while indirect and induced emissions including land use (LUC) conversion are included in a consequential LCA. The former can be measured and verified; the latter cannot be measured nor verified. If LUC emissions are included in an analysis, they are either applied as an "adder" to the total process-based fuel cycle emissions or all of the GHG emissions are treated as indirect impacts.

Accounting at each step in the process requires energy inputs and includes losses at each step in the pathway as a result of process inefficiency. Losses in either feedstock or fuel affect the overall production efficiency. Another factor is whether process energy inputs are evaluated on the basis of the higher (HHV) or lower heating value (LHV) of the fuel being produced and consumed. Use of HHV leads to lower numerical values of GHG emissions per unit energy associated with combustion of a given fuel relative to the LHV. However, LHV is often used in transportation because exhaust gases are not cooled before discharge. Overall, emissions data related to factors other than LUC is commonly referred to as "Lifecycle Inventory" (LCI) data and represent the "inputs" that are required to perform an LCA. These inputs are described in more detail in the following section along with LUC inputs.

The final result of an LCA is an estimate of the GHG emissions required to produce a unit of biofuel, known as the carbon intensity (CI) of that fuel usually specified in grams of CO_2 equivalent emissions (gCO_2e) emissions per megajoule (MJ) of delivered fuel energy from the specified production process or "pathway."

Figure 2-2. Fuel LCA Calculations Track Process Inputs Throughout the Fuel Cycle



[2] The emissions impact of ILUC associated with biofuel production remains a contentious issue. The concept was first introduced nearly 20 years ago, and there is still no consensus on the appropriate models and methods with which to estimate GHG emissions associated with ILUC. Additionally, some researchers have argued that large ILUC effects are not supported by available data that show significantly increased crop yields and little change in crop exports in the U.S. over the past 20 years.

2.2 Review of LCA Inputs

This section discusses the various LCA inputs shown in Figure 2-2, as well as other inputs and assumptions that are required for LCA.

2.2.1 Upstream Farming Emissions

LCA inputs for upstream farming GHG emissions account for the GHG emissions associated with the production and use of fertilizer, pesticides, energy, seeds, and other resources used in farming. The upstream farming cycle data that is used in an LCA can be a source of differences in LCA results, and the CI impact depends on specific assumptions and analytical approaches. For example, the GHG emissions associated with the use of fossil natural gas for fertilizer production are a key factor in upstream farming data (and other LCA inputs) and can vary considerably across LCA models and modeling platforms.

2.2.2 Production of Nitrous Oxide (N_2O) from Fertilizers used in Farming

Nitrogen in fertilizers decomposes due to nitrification and denitrification processes in the soil, which result in the production of nitrous oxide (N_2O), a powerful greenhouse gas. In addition to the decomposition of fertilizer in the soil, N_2O is also produced from fertilizer associated with agricultural runoff and through the decomposition of residual biofuel crop residues. Nitrogen associated with the fixation of atmospheric air by soybean nodules is included in these emissions.

2.2.3 Production of CO_2 from Soil Amendments and Fertilizers used in Farming

Emissions of CO_2 can result from the use of limestone, which is applied as a soil amendment to agricultural land to reduce acidity. The reaction of limestone and acidic soils produces CO_2, which is released to the atmosphere. The amount of CO_2 released depends upon factors such as the amount of limestone applied, the acidity of the soil, and soil conditions such as moisture content and composition. The use of urea fertilizers is another source of CO_2. CO_2 emissions from urea application depend on factors such as the amount of urea applied, the timing of applications, soil type, and ambient conditions. As with other LCA inputs, different data are used in different modeling methodologies, leading to somewhat different results.

2.2.4 Direct Farming and Feedstock Transport Emissions

Direct GHG emissions from farming operations arise from fossil fuel-powered agricultural equipment, such as tractors, combines, and other machinery, as well as trucks, trains, and other means of transporting biofuel feedstocks from the fields in which they are grown to the facilities at which they are processed. Combustion emissions data and assumptions can again vary between modeling methodologies for a number of reasons, including differences in non-CO_2 emissions accounting. These other pollutants include methane, nitrous oxide, and in some cases, carbon monoxide (CO) and volatile organic compounds, which are ultimately transformed into CO_2 by atmospheric reactions.

2.2.5 Power Generation Emissions

GHG emissions from electric power production include the direct emissions from power plants and upstream lifecycle emissions associated with the production of fuels that are inputs to the power plant. In general, this requires that the mix of power generation sources is known with a relatively high degree of accuracy. The generation source mix is combined with power production efficiency input data to determine overall power generation and overall upstream emissions after also taking into account power losses during transmission. Alternatively, directly reported GHG emissions and power output for power production facilities can be used in lieu of efficiency data.

2.2.6 Feedstock Processing and Biofuel Production

LCA inputs related to feedstock processing and biofuel production are mainly associated with process energy and non-combustion GHG emissions such as CO_2 emissions from fermentation. In addition to direct GHG emissions associated with the use of fossil fuels like natural gas, upstream emissions associated with the production and transport of various inputs are also accounted for. As with other LCA inputs, different modeling methodologies may use a variety of data sources for process energy emission factors, leading to somewhat different results.

2.2.7 Co-product Accounting

Many fuel production processes produce co-products beyond the main biofuel product. Modeling platforms can vary significantly in the handling of these co-products. The two most common methodologies for treating co-products are allocation and displacement. Allocation proportionally assigns emissions to products and co-products based on product energy, mass, or economic value. Displacement, substitution, or system expansion, on the other hand, gives credit based on the emissions that would typically occur if the co-product was produced conventionally. For example, fuel gas produced during biofuel production may displace natural gas that would otherwise be required, and credit would be assigned based on the amount of natural gas energy displaced. Allocation methods can significantly impact lifecycle results.

2.2.8 GHG Emission Credits

In addition to the allocation of GHG emissions to account for co-products, LCA methodologies often also provide credits for factors involved in biofuel feedstock growing and fuel production that significantly reduce GHG emissions. These may include carbon capture and sequestration (CCS), avoided methane impacts from sources such as landfills and diary digesters, use of renewable fuels for process energy, and climate smart agriculture (CSA).

2.2.9 Global Warming Potential (GWP)

Global warming potential (GWP) is used to account for the global warming potential of non-CO_2 GHGs relative to CO_2. GWP is formally defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of the reference gas, which is CO_2 (IPCC, 2018). After application of GWP values to the emissions of GHGs other than CO_2 from a source, total source GHG emissions are added and reported in terms of CO_2e.

The Intergovernmental Panel on Climate Change (IPCC)[3], an international body founded by the United Nations, has published 100-year and 20-year time horizons for the main GHGs in its Assessment Reports (AR). The current and past values developed by the IPCC are shown in Table 2-1, with the AR6 values being the most recent and the SAR values the oldest. Most LCA methodologies rely on one set of these IPCC values for determining GWP, which is the case for integrated system models such as GREET and GHGenius. However, calculator tools that rely on GWP-weighted LCI data from different sources and apply GWP values in their calculations may result in a mismatch of GWP factors. As the difference in the values shown in Table 2-1 indicate, the use of a different set of factors and the selection of 100-year or 20-year time horizons are important factors determining overall GHG emissions for a fuel pathway. Several species result in indirect GHG emissions. For example, carbon monoxide oxidizes in the atmosphere to form CO_2 and it has a secondary effect on other greenhouse gases. GREET counts the secondary formation of CO_2 but these

[3] https://www.ipcc.ch/

emissions are not part of the RED. The combination of GWP factor with pollutants is part of the "impacts assessment" of an LCA with the choice of factors described in Section 2.4.

2.2.10 Land Use Change (LUC)

In general, LUC for LCA is evaluated from the perspective of ILUC. ILUC inputs into LCAs account for the GHG emissions associated with the conversion of land, such as forests or existing agricultural land used to grow other crops that are "changed" to grow biofuel feedstocks. ILUC input data accounts for the GHG impacts of potential displacement of food and feed crops caused by the expansion of biofuel feedstock cultivation that may lead to additional land being converted elsewhere to compensate for the loss of food production. They also account for the net accumulation of carbon from both the carbon release from land conversion (e.g., clearing native vegetation by fire) and foregone carbon sequestration. ILUC emissions are difficult to quantify, relying on agro-economic models to estimate the quantity, type, and location of land changed in response to a biofuel "shock," linked with emission factor databases reflecting differing vegetation and soil carbon estimates by land type across the globe.

Table 2-1. Global Warming Potential (GWP) of Selected GHGs

<table>
<tr><th>IPCC Assessment</th><th colspan="2">AR6[a]</th><th colspan="2">AR5[b]</th><th colspan="2">AR4[c]</th><th>SAR[d]</th></tr>
<tr><td>GWP Time Horizon</td><td>100</td><td>20</td><td>100</td><td>20</td><td>100</td><td>20</td><td>100</td></tr>
<tr><td>CO_2</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>$CH_{4,\ fossil}$</td><td>29.8</td><td>82.5</td><td rowspan="2">28</td><td rowspan="2">84</td><td rowspan="2">25</td><td rowspan="2">72</td><td rowspan="2">21</td></tr>
<tr><td>$CH_{4,non\text{-}fossil}$</td><td>27.2</td><td>80.8</td></tr>
<tr><td>N_2O</td><td>273</td><td>273</td><td>265</td><td>264</td><td>298</td><td>289</td><td>310</td></tr>
<tr><td>VOC + CO</td><td colspan="6">These pollutants are treated either with GWP's based on full oxidation to CO_2 or other assessment methods.</td><td></td></tr>
</table>

[a] IPCC Sixth Assessment Report (AR6) published in 2021 includes CH_4 GWP for both fossil and non-fossil origins.
[b] IPCC Fifth Assessment Report (AR5) published in 2014 includes GWP of 28 for biogenic CH_4
[c] IPCC Fourth Assessment (AR4) report published in 2007
[d] IPCC Second Assessment (SAR) report published in 1995

2.3 Types of LCA Assessment Tools

There are three general types of LCA assessment tools that have been developed over time that are used in conjunction with determining the CI of biofuels used in the transportation sector. These are generally referred to as:

1. Integrated System Model
2. Lifecycle Databases
3. Certification tools

The basic features of each type of tool are summarized below.

2.3.1 Integrated System Models

Prime examples of integrated system models include the "Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies" or GREET[4] model developed by Argonne National Laboratory, which focuses on

[4] https://greet.anl.gov/index.php

U.S.-based fuel production, and GHGenius[5] developed by S&T Squared, which focuses on LCA of transportation fuels in the Canadian context. These models are also sometimes referred to as supply-chain LCA models as they estimate the inputs and outputs of a particular product supply chain in detail.

The characteristics of Integrated System Models with respect to biofuel LCA include:

- Calculation of upstream GHG impacts internally and encompassing the entire lifecycle from raw material extraction to production.
- Use of a fixed set of global warming potential (GWP) values to account for emissions of GHGs other than CO_2.
- Use of LCI data inputs in simplified, or reduced forms, such as efficiency, energy content (Btu/ton), etc.

2.3.2 Lifecycle Data Bases

LCA tools in this category include EcoInvent[6], GaBi developed by Sphera[7], and OpenLCA.[8] The characteristics of lifecycle data bases include:

- LCI input data are calculated internally within the tool and then represented as a dataset for use.
- Comprehensive set of lifecycle criteria for assessment, covering a wide range of environmental factors and impacts.

2.3.3 LCA Certification Tools

LCA certification tools include those developed for the U.S. EPA for use in the Renewable Fuel Standard Program and by the California Air Resources Board (CARB) as part of that agency's Low Carbon Fuel Standard (LCFS) and RenovaCalc used in the Brazilian RenovaBio program. The characteristics of LCA certification tools include:

- Use of predefined and static emission factors from models like GREET or LCA databases for conducting assessments.
- Use of structured data inputs for entering data, ensuring consistency and standardization of data input.

2.4 Key Regulatory LCA Frameworks Focused on Reduction of the Carbon Intensity of Transportation Fuels

There are a large number of models and methodologies that have been developed for use in performing LCAs to determine the CI values for transportation biofuels, including those identified in the previous section. However, the most well-developed and significant of these are associated with government regulatory programs that target reductions in the CI values of conventional fuels by requiring the substitution of lower CI alternatives. Given that a comprehensive review of all such models was outside the scope of this project, the following regulatory programs and their associated LCA methods for assessing transportation fuel CI values were selected for detailed analysis in this study as they have had and continue to have a substantial impact on the assessment of the CI values and the development of biofuels for use in

[5] https://www.ghgenius.ca/

[6] https://ecoinvent.org/

[7] https://sphera.com/product-sustainability-software/

[8] https://www.openlca.org/

the transportation sector. The list below first identifies the regulatory program and the associated LCA modeling tool.

1. U.S. EPA Renewable Fuel Standard (RFS) Program → EPA Fuel Pathway Analyses[9]
2. California Low Carbon Fuel Standard (LCFS) → CARB Lookup Tables and Tier 1 Calculators[10]
3. Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[11] → Roundtable on Sustainable Biofuels (RSB)[12] Tool and Custom Calculator or ISCC verification system[13]
4. Canadian Clean Fuel Regulations (Canadian CFR) → OpenLCA[14]
5. European Union (EU) Renewable Energy Directive (EU RED) → RSB Tool and Custom Calculator[15]
6. British Columbia Low Carbon Fuel Standard (BC LCFS) → GHGenius[16]
7. RenovaBio, the Brazilian national biofuels policy → RenovaCalc[17]
8. The U.S. Inflation Reduction Act (IRA) → GREET or GREET-based calculators[18]

Each of these regulatory programs and the associated LCA tool are summarized briefly below.

2.4.1 U.S. EPA RFS2

Implemented by the U.S. EPA in 2010, the Renewable Fuel Standard (RFS2) sets annual renewable fuel volume requirements and is intended to promote the blending of lower CI renewable fuels into conventional transportation fuels to reduce overall transportation sector GHG emissions. LCA analysis was performed by the U.S. EPA using a modeling framework that involved eight different models for LCI and ILUC data to determine the direct and indirect emissions of renewable fuels. These models include GREET1.8c for LCI data in combination with the Forestry and Agricultural Sector Optimization Model (FASOM) and the Food and Agricultural Policy and Research Institute (FAPRI) model, which addresses LUC as well as changes in agricultural emissions.

2.4.2 California LCFS

The California Low Carbon Fuel Standard (LCFS) program imposes CI targets on transportation fuels that are expected to be met through the substitution of lower CI renewable fuels for higher CI conventional fuels and by technology substitution (e.g., battery electric vehicles displacing internal combustion engine vehicles). Currently, LCA analysis is mainly performed using CA-GREET3.0 and the Tier 1 Calculators. The LCI data in CA-GREET3.0 and the Tier 1 Calculators are derived from GREET1_2016, with LUC values

[9] https://www.epa.gov/renewable-fuel-standard-program/fuel-pathways-under-renewable-fuel-standard

[10] https://ww2.arb.ca.gov/resources/documents/lcfs-life-cycle-analysis-models-and-documentation

[11] https://www.icao.int/environmental-protection/CORSIA/pages/default.aspx

[12] https://rsb.org/certification/certification-schemes/rsb-corsia-certification/

[13] https://www.iscc-system.org/certification/iscc-certification-schemes/iscc-corsia/

[14] https://www.canada.ca/en/environment-climate-change/services/managing-pollution/fuel-life-cycle-assessment-model.html

[15] https://rsb.org/certification/ghg-calculator/

[16] https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/fuel-lifecycle-assessment/ghgenius

[17] https://www.gov.br/anp/pt-br/assuntos/renovabio/renovacalc

[18] https://greet.anl.gov/greet/versions.html

developed by CARB in 2015 based on the Global Trade Analysis Project (GTAP) model (with 2004 baseline data) and the Agro-ecological Zone Emission Factor (AEZ-EF) model[19].

2.4.3 CORSIA

The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a program established by the United Nations International Civil Aviation Organization (ICAO) to reduce GHG emissions from the aviation sector. The goal of this program is to achieve carbon-neutral growth from 2020 via the use of offset credits. CORSIA eligible fuels (CEFs) can help aircraft operators reduce their offsetting obligation. A CEF must meet certain sustainability requirements, which includes a CO_2e reduction of at least 10% relative to the petroleum jet fuel baseline, which has been set at 89 gCO_2e/MJ on a "well-to-wake" basis. Within the CEF category is sustainable aviation fuel (SAF), which is a drop-in replacement fuel for conventional jet fuel made from biomass or waste resources, as well as lower carbon aviation fuel (LCAF), which is derived from petroleum but meets the CEF sustainability criteria, including reducing lifecycle GHGs by 10% as noted above. LCA is performed using a tool developed by RSB[20] or a specialized calculator developed by ICAO which is called the CORSIA CO_2 Estimation and Reporting Tool (CERT).[21] The International Sustainability & Carbon Certification (ISCC) system provides a certification scheme with similar GHG calculations. LCI data may be drawn from one of a number of approved sources including GREET and LUC data that has been developed using the Global Trade Analysis Project (GTAP) and Global Biosphere Management Model (GLOBIOM) frameworks. It should be noted that the CORSIA LCA methodology can also be used under the IRA for purposes of assessing the CI of sustainable aviation fuels.[22]

2.4.4 Canadian CFR

The Canadian CFR is similar to the California LCFS program in that it seeks to reduce the CI of transportation fuels on a nationwide basis in Canada. LCA is performed using the OpenLCA tool in combination with LCI data developed by the Canadian government, which is known as the Fuel LCA Model database.[23] ILUC emissions are not directly considered under the Canadian CFR program as only specific biomass feedstocks are allowed to be used in the program.[24] In addition, land use and biodiversity (LUB) requirements intended to minimize ILUC emissions also apply.

2.4.5 EU RED

The EU has put in place the Renewable Energy Directive (RED) to promote and support the adoption of renewable energy sources. This set of regulations utilizes different strategies, such as free attribution, mass balance, and book and claim credits, to monitor and incentivize the use of renewable biofuels. The same RSB tool that can be used for CORSIA compliance is also used for LCA under EU RED, as well as LCI data

[19] https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/iluc_assessment/iluc_analysis.pdf

[20] https://rsb.org/wp-content/uploads/2020/12/RSB-STD-12-001-RSB-ICAO-CORSIA-version-1.3.pdf

[21] https://www.icao.int/environmental-protection/CORSIA/Pages/CERT.aspx

[22] https://www.irs.gov/credits-deductions/businesses/sustainable-aviation-fuel-credit

[23] https://www.canada.ca/en/environment-climate-change/services/managing-pollution/fuel-life-cycle-assessment-model.html

[24] See Section 46(1)(b) https://laws-lois.justice.gc.ca/eng/regulations/SOR-2022-140/index.html

from International Sustainability and Carbon Certification (ISCC) 205.[25] ILUC emissions are not considered under EU RED as only specific feedstocks are allowed[26], and LUB requirements also apply.

2.4.6 BC LCFS

The British Columbia Low Carbon Fuel Standard (BC LCFS) program is a provincial regulatory program intended to reduce the carbon intensity of transportation fuels and is similar to California's LCFS. LCA is performed using the GHGenius calculator, version 4.03c which is similar to GREET including upstream, plant, and downstream emissions for a large array of fuel types and technologies to provide a full well-to-wheels carbon intensity score. BC has announced a transition to a more up-to-date platform in the future[27], but this study focuses on version 4.03c rather than the forthcoming v5.02c. ILUC emissions are not considered under the BC LCFS program.

2.4.7 RenovaBio

RenovaBio is a Brazilian program that promotes the use of biofuels to reduce greenhouse gas emissions. It involves setting emissions reduction targets and encouraging biofuel production. The RenovaCalc tool is used for certification purposes as it allows for the comparison and certification of different biofuels based on their CI values, supporting the objectives of the RenovaBio program in promoting sustainable biofuel production and reducing carbon emissions. RenovaCalc utilizes LCI data from various sources, including the EcoInvent database.[28] The EcoInvent database is a widely recognized and comprehensive lifecycle inventory database that provides data on the environmental impacts of different processes and activities. RenovaCalc does not address LUC emissions.

2.4.8 IRA

The U.S. Inflation Reduction Act (IRA) includes substantial incentives for the production of a variety of transportation fuels with low CI/GHG emissions. The GREET model is the tool which is specified in the legislation for use in assessing the CI/GHG emissions associated with most renewable fuels for purposes of assessing the magnitude of the incentives that can be provided to a fuel producer. The current version, GREET1_2022[29], is a widely used LCA model for estimating emissions from transportation fuels. It considers various factors, including upstream emissions, to calculate the lifecycle greenhouse gas emissions associated with different stages of fuel production, distribution, and use. It uses its own LCI data and accounts for LUC emissions using the CCLUB and GTAP models. As noted above, the CORSIA LCA methodology is identified as an option for aviation fuels under the IRA, and 40BSAF-GREET was adopted after the completion of this analysis by the U.S. Department of the Treasury for use in assessing the relevant CI-based tax credits as well.[30]

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[25] https://www.iscc-system.org/wp-content/uploads/2022/05/ISCC_EU_205_Greenhouse-Gas-Emissions-v4.0.pdf

[26] https://www.transportenvironment.org/wp-content/uploads/2021/06/2020_05_REDII_and_advanced_biofuels_briefing.pdf

[27] https://www2.gov.bc.ca/gov/content/industry/electricity-alternative-energy/transportation-energies/renewable-low-carbon-fuels/fuel-lifecycle-assessment/ghgenius

[28] https://ecoinvent.org/

[29] After this analysis was completed, R&D GREET 2023rev1 was released. See https://greet.anl.gov/

[30] https://www.energy.gov/eere/greet

2.4.9 Summary of Selected Regulatory Frameworks

Table 2-2 provides a summary of the key elements of each of the eight regulatory frameworks selected for evaluation in this study.

Table 2-2. Key Elements of Selected Fuel Policy Frameworks

GHG Framework	RFS2	CA LCFS	CORSIA	Canada CFR	EU RED II	BC LCFS	RenovaBio	IRA
IPCC GWP	SAR/AR5	AR4	AR5	AR5	AR4	AR5	AR5	AR5
Heating Value Basis	LHV	LHV	LHV	LHV	LHV	HHV	LHV	LHV
LCI Data Source	GREET1.8c	GREET1_2016	Any Approved	Various	ISCC 205, RSB Tool	GHGenius 4.03	Eco-Invent	GREET
Year	2010	2016	Current	Current	2017	2018	2018	2024
Co-product Allocation	Consequential	Various	Energy	Energy	Energy	Substitution/ Consequential	Energy	Various
Land Use Change	FASOM/ FAPRI	GTAP 2011	GTAP & GLOBIOM	Limited to Specific Feedstocks	iLUC Risk	Internal Calculation	None	GTAP BIO Modified RFS
Soil Carbon Impacts[a]	In iLUC	In iLUC	In iLUC	None	Yes	In Land Use	None	TBD
Certification Option	EPA Standard Pathways or Petition	CARB Look Up Values or Tier 1 Calculator	Custom Calculator, RSB Tool	Open LCA	Custom Calculator, RSB Tool	GHGenius	RenovaCalc	GREET or GREET Tools

a. Impacts of changes in the carbon storage of soils are included in the core LCA or as an Indirect Land Use Change effect.

2.5 Study Objectives

Although each of the eight regulatory frameworks listed above targets reductions in the CI of transportation fuels, each uses its own methodology for performing the LCAs needed to estimate the CI of a specific biofuel produced using a specific production pathway. As a result, the CI value of a specific biofuel produced using a specific pathway can differ depending on which regulatory framework's LCA methodology is applied.

The LCA methodologies embodied in these frameworks can differ in terms of the boundaries of the LCA, the underlying data used in the LCA, as well as in key assumptions. As a result, the different LCA methodologies in the different regulatory frameworks can produce different estimates of the WTW GHG emissions (i.e., CI values) associated with a specific biofuel.

Given this, the goal of this study was to perform a detailed review and comparison of the LCA methodologies associated with the eight selected regulatory frameworks to identify differences in each that can lead to differences in the estimated CI value of a given fuel.[31] Further, in order to provide specific insights into the sources of difference between the methodologies, CI values for two biofuel pathways – 1) ethanol produced from corn via dry milling and 2) renewable diesel fuel from hydrotreating of soybean oil – were computed using each regulatory framework methodology and subjected to a detailed comparison.

[31] It should also be noted that the purpose of this study was not to perform detailed assessments of any of the LCA methodologies although a number of them have been subjected to such detailed assessments in the past.

Section 3 of this report addresses the potential sources of variability in the LCI data and treatment of LUC associated with the LCA methodologies that can generally contribute to differences in CI results for a given biofuel between LCA methodologies. The results of the corn ethanol and renewable soy biodiesel comparison are presented in Section 4. The results presented in Section 4 begin with a comparison of the CI results obtained for the two biofuels using the default inputs for each LCA methodology. In addition, in order to provide insight into the magnitude of the differences created by input data versus assumptions and methodological differences, CI values for these two biofuels were also determined using each LCA methodology with the default input values from GREET1_2022.

3. REVIEW OF LCI DATA INPUTS AND ILUC METHODOLOGIES

This section presents a review of the potential for differences in LCI and ILUC approaches and data to create differences in LCA results for a given biofuel using different LCA methodologies. Although this review is not strictly focused on the eight methodologies selected for evaluation in this study, it is representative of them.

3.1 LCI Data Inputs

Several important LCI data inputs that are commonly used to perform a lifecycle analysis for biofuels are presented below. These include energy inputs such as natural gas, electricity, and hydrogen use rates. Natural gas is a particularly important input as it is a significant contributor to electricity and hydrogen GHG emissions. In addition, this section of the report includes a brief discussion of various credits that could be available to reduce the CI of biofuel pathways.

3.1.1 Process Energy – Natural Gas

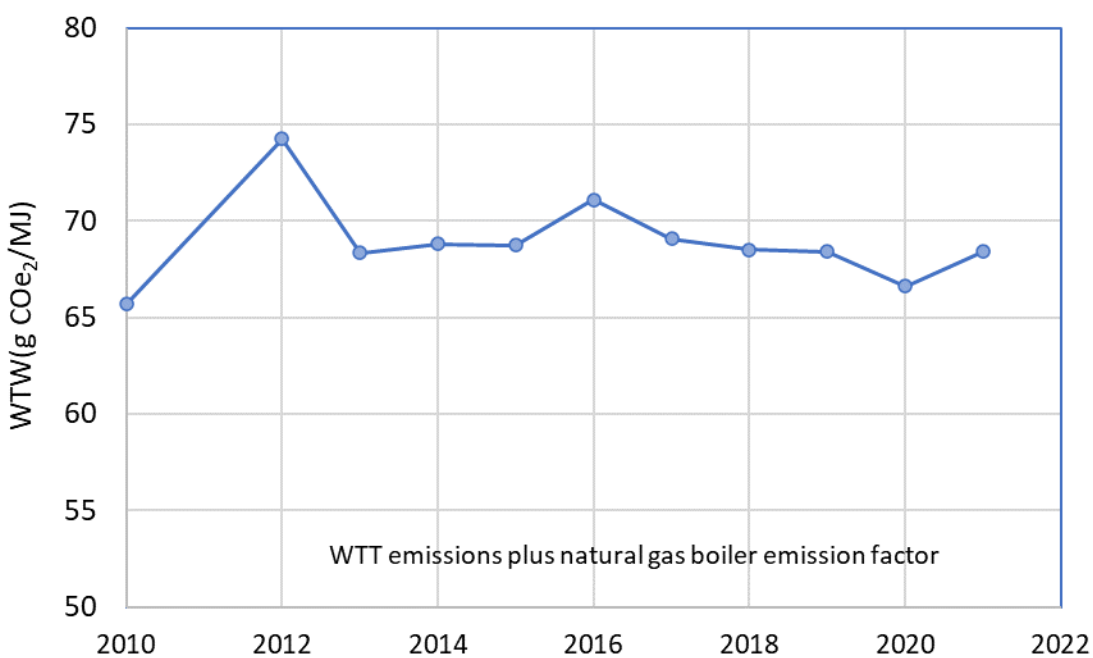
The GHG analysis frameworks include a wide variety of treatments for greenhouse gas emissions ranging from the GWP of pollutants (see Section 2-2) to emission factors and upstream lifecycle data. This can be seen in the data presented in Table 3-1, which shows direct fuel combustion emissions and upstream emissions associated with natural gas. Note that some modeling protocols include VOC and CO in the GHG total by assuming these compounds are oxidized to CO_2 in the atmosphere; however, this is generally a very small contribution to total CO_2e emissions. GHG emissions are calculated for the prevailing GWP factors for each methodology with AR6 used in GREET1_2022, AR4 for the CARB Tier 1 Calculators, and AR5 being used in the rest of the methodologies listed in Table 3-1. Note that the GHG emissions for some methodologies use a static GWP weighted factor with a single emission factor of CO_2e with no detail on the underlying CH_4 and N_2O GWP weighting factors. Nonetheless, all of the methodologies except RenovaCalc yield a total GHG emission value for fully combusted natural gas in an industrial boiler of about 69 gCO_2e/MJ. The RenovaCalc estimate is lower because it incorrectly calculates a relatively low upstream GHG footprint for natural gas. Combustion emissions are based largely on stoichiometry (i.e., $CH_4 + O_2 \rightarrow CO_2 + 2H_2O$) and therefore would not be expected to have much variability across models.

Figure 3-1 illustrates how the LCA of natural gas combustion has changed over time based on refinements of the data used in the GREET model from 2010 through 2021. Improved accounting for GHG emissions associated with natural gas extraction and transportation, particularly related to methane leakage, have resulted in an increase in the GHG intensity of natural gas process fuel since 2010 as discussed below.

Table 3-1. Direct and Upstream Emission Factors for Natural Gas Combustion (g/MJ)

Model	GREET 1_2022	CA-Tier 1 Calc	GHGenius	Canada CFR	ISCC 205	RenovaCalc
Version	2022	2016	4.03c			
IPCC GWP	AR6	AR4	AR5	AR5	AR5	AR5
Natural Gas Combustion in an Industrial Boiler						
VOC	0.002	0.002	0.04			
CO	0.024	0.024	0.04			
CH_4	0.001	0.001	0.001			0.005
N_2O	0.0003	0.0003	0.0006			0.0001
CO_2	56.3	56.3	56.0			56.1
CO_2e	56.4	56.4	56.4			56.3
Upstream Natural Gas Production and Transportation						
VOC	0.011	0.010				
CO	0.033	0.031				
CH_4	0.212	0.247				0.0001
N_2O	0.0013	0.0014				0.0000
CO_2	6.3	6.5				3.26
CO_2e	13.0	13.1	10.1		7	3.28
Total Lifecycle Emissions						
VOC	0.013	0.012		0		0
CO	0.057	0.054		0		0
CH_4	0.213	0.248		0.2		
N_2O	0.002	0.002		0.002		
CO_2	62.5	62.7		61.27		
CO_2e	**69.5**	**69.5**	**66.5**	**67.8**	**67.6**	**58.6**

Figure 3-1. WTW Carbon Intensity of Natural Gas plus Boiler Emission Factor in GREET



3.1.2 Process Energy – Electricity

Electricity is generated from a wide portfolio of feedstocks including coal, fuel oil, natural gas, nuclear sources, biomass, hydroelectric energy, and other renewables such as wind and solar. Fuel LCA models calculate GHG emissions for a mix of electricity generation resources. The models account for transmission losses and calculate upstream fuel cycle emissions in proportion to the fuel used for each production technology. Power plant emissions depend on fuel efficiency plus emission factors for CH_4 and N_2O.

Each of the models reviewed includes different feedstock mixes, based on the geographic region of interest. The CA GREET study includes regional consideration of more than six regions, and fuel pathway components are bundled into "feedstock" and "fuel" groups to determine the regional input parameters, including electricity mix. The electricity mix can be the average mix for a region, or the marginal mix associated with newly added generation capacity. The underlying data in both GREET and the California Tier 1 calculators is based on EPA's eGRID with different timeframes and regional groupings applied to the models.

GHGenius uses a unique electricity mix for many of the fuel pathway types; some fuel pathways are based on the U.S. average (or other country selected) electricity mix. Table 3-2 summarizes the treatment of electricity in the models and studies reviewed, along with assumed efficiencies for natural gas electricity generation (average and combined cycle gas turbine technology). The resource mixes are based on published statistics such as eGRID. The CI of power depends on the fraction of renewable sources, fossil fuel type, and efficiency for combustion power plants. Significant variations in renewable power occur in regions such as Washington, Brazil, and Quebec. Midwest power plants still include a significant fraction of coal generation.

Projections for power generation efficiency result in a significant variation among the model predictions, especially in future years. The projections for future improvements in generation efficiency vary considerably among models and are part of the modeling systems. For example, in GREET and GHGenius, the scenario year selection affects the CI of electric power and other energy resources. The scenario year is typically held constant when LCA models are used as certification tools. Estimates of fuel properties, as well as the upstream fuel cycle for natural gas and coal production, contribute to the difference. Another difference among models is the representation of marginal generation resources. For CA-GREET, the marginal resource mix varies by region. The impact of electricity mix is apparent when comparing ethanol plants operating in California to those in the Midwest. The difference in CI is about 3 g/MJ. The default GREET model and the EPA RFS2 analysis do not reflect these regional differences.

Renewable feedstocks contain biogenic carbon; therefore, only the combustion methane and nitrous oxide emissions are considered. The carbon-neutral assumption results in a much lower GHG estimate than for fossil fuel-derived electricity. Most biomass power is produced from residue, which is the basis for calculation in the GREET model.

Table 3-2. Efficiency Inputs for Power Generation

Model/Study	Electricity Generation Summary	Natural Gas Generation Efficiency	
		Average	CCGT[a]
GREET 1.8c	► Electricity calculated for resource mix for U.S., CA, U.S. Northeast, and user defined resource mix. ► U.S. average electricity mix used for biofuel production and co-product power in the U.S.	40.1%	53%
GREET1_2022	► 12 eGRID regions ► U.S. average electricity mix used for biofuel production and co-product power in the U.S.	47.3%	51.6%
CA-GREET/ Tier 1 Calculator	► Fuel pathways under LCFS use 27 eGRID regions for fuel production. Feedstock production power based on U.S. average or average for primary region where feedstock is produced. ► CA average based on updated data on California power generation in addition to eGRID sources.	45.87%	50.6%
ISCC 205 (EU RED)	► EU electricity mix for feedstock and fuel production in Europe. ► Energy efficiency for GEMIS database shown here. ► Certification requires regional electricity mix such as eGRID[b].	35.4%	51%
RenovaCalc	► EcoInvent basis for fuel pathway contributions[c] ► Certification required reginal electricity mix such as eGRID.		NF[d]
GHGenius	► Average Canada resource mix based on Statistics Canada data from the National Energy Board.	36%	51%

a. Combined Cycle Gas Turbine.
b. Regional or state-wide utility mix data may also be used for pathway certification.
c. Average is 31.3% in 1970, 35.6% in 2010.
d. NF=not found in documentation or model.

Even the calculation of average GHG emissions is not straightforward. For example, direct GHG emissions from electric power generation are well-documented as part of emission inventory efforts. Emission inventories in the U.S. are collected through EPA's eGRID database with measurements based on direct CO_2 emissions or fuel using IPCC GHG calculation methods. The average emissions from power generation are estimated from reported power sales and GHG emissions. In contrast, fuel LCA models are sometimes populated with estimates of generation efficiency, which are then used to calculate GHG emissions which can lead to differences in GHG emissions relative to emission inventory-based estimates. However, in the case of GREET, the average GHG emissions for power generation are tied to EPA and EIA power plant reporting.

As discussed in Section 2-2 and above with respect to natural gas, the GWP used in the LCA methodology is another factor that can impact GHG emission estimates between LCA methodologies. The impact of the selection of GWP values on GHG emissions associated with power generation is small.

3.1.3 Process Inputs – Hydrogen

Hydrogen is a component of many fuel production pathways and is also a potential fuel for transportation applications. Biofuel LCA methodologies calculate the energy inputs and emissions for both existing hydrogen technologies and future low GHG hydrogen technologies. For industrial applications, hydrogen is primarily produced via steam methane reforming (SMR) of North American natural gas in the U.S. SMR-based hydrogen production is a component of hydrogen vehicle pathways and also serves as an input to oil sands upgrading, oil refining, vegetable oil hydrotreating, and other fuel processing steps[32]. Hydrogen is used for fuel processing steps such as sulfur removal and cracking the fuel into components with a higher hydrogen-to-carbon ratio. In the case of vegetable oil processing, hydrogen input is about 3.7% of the mass of the feedstock oil[33], which translates into 0.08 kg/gal of fuel. Hydrogen input reflects about 10% of the primary energy in this case.

For natural gas SMR systems, the feedstock is recovered and transported to a hydrogen plant (either at a central location or hydrogen fueling station). There, high temperature steam is reacted with methane and higher hydrocarbons in the natural gas to produce carbon monoxide (CO) and hydrogen; this process is highly endothermic and requires a significant amount of energy, typically provided via natural gas combustion. The CO further reacts with water in the exothermic water-gas shift reaction to yield more hydrogen and carbon dioxide.

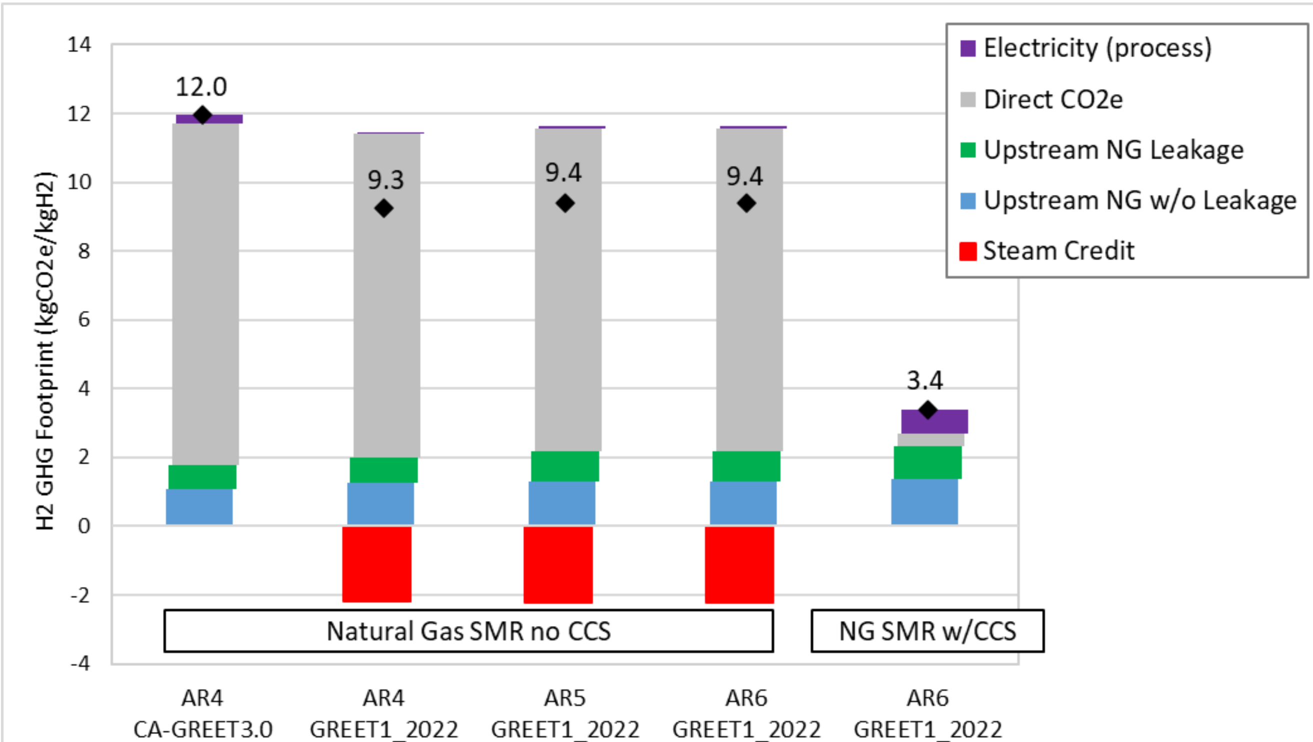
Figure 3-2 shows the GHG emissions associated with the different aspects of hydrogen production, as well as the total using the SMR based on GREET1_2022 and Tier 1 calculators. As shown, the GREET1_2022 GHG emission value is about 20% lower than that from the Tier 1 calculators, primarily as a result of a steam credit applied to the GREET1_2022 estimates. The primary input to the hydrogen pathways is the amount of natural gas and power used in the process. These values are input as efficiency and fuel shares in GREET and then converted to Btu/MMBtu of hydrogen. The GREET model distinguishes between feedstock, which is converted to CO_2 in the reformer, and natural gas/tail gas, which is burned as process fuel by assigning non-combustion emissions to the reformer feed, which is assumed to be 69.3% of the total natural gas input. The difference in emissions between natural gas that is directly burned versus processed in the reformer is about 1 g CO_2e/MJ natural gas.

The steam credit for hydrogen is based on modeling from Argonne National Laboratories (ANL), which shows that waste heat from SMRs is available for other industrial processes such as co-located oil refineries. Also shown in Figure 3-2. Effect of GWP on the GHG Footprint of Hydrogen is the impact of the GWP values used, which are again minimal. Finally, the impact of CCS is shown in the figure, which reduces GHG emissions by about 60%. No steam credit is assigned in this case as the excess heat from the SMR furnaces is assumed to be used for amine regeneration in the CO_2 capture process. The higher electricity footprint in the CCS case is primarily related to compressing the CO_2 to a pipeline pressure of ~2200 psi.

[32] Fuel LCA models typically use the calculation for uncompressed hydrogen as the input for other fuel processing steps.

[33] GREET default for renewable diesel II pathway.

Figure 3-2. Effect of GWP on the GHG Footprint of Hydrogen



3.1.4 Credits and Attribution of Emissions

The availability of GHG credits can result in a significant impact on GHG emissions among fuel pathways and LCA methodologies. Key parameters that result in CI reductions include CCS, avoided methane emissions, climate smart agriculture (CSA), and the use of low CI natural gas (e.g., renewable natural gas) and power (e.g., solar or wind) via book and claim. The types of credits available as part of the different LCA methodologies under review here are presented in Table 3-3.

The modeling frameworks result in different treatments of both co-products and end use products. The key co-product differences include substitution versus allocation, as well as the choice between energy and mass allocation. The most notable effect with substitution occurs with low input processes. For example, a corn ethanol plant that uses only renewable heat and power would receive the same substitution credit as an ethanol plant using natural gas or even coal as process fuel. However, in the case of energy allocation, used in CORSIA, the emissions associated with corn farming, as well as process energy inputs, are all reduced by an allocation factor.

GHG models typically treat fuel pathways as single feedstock systems. Multiple feedstocks and products become more a matter of implementation and volume reporting. LCA frameworks also affect the assignment of feedstocks to end products which range from free attribution to energy allocation. Examples of free attribution include assigning ethanol gallons to wet DGS processing and preferentially selling those gallons to a low carbon fuel market. The reporting of fuel volumes is also affected by the framework rules where a free attribution system allows assignment of multiple feedstocks to products. Examples include assigning sorghum gallons to sorghum ethanol for a facility that processes both corn and ethanol (allowed under RFS, LCFS, and other frameworks).

Table 3-3. Treatment of Credits and Low CI Emission Options

GHG Policy	RFS	GREET	Tier 1 Calculator	CORSIA	EU RED II	BC LCFS	RenovaBio
CO_2 Storage	Requires Rulemaking	CCS in Corn EtOH	CCS Protocol	Separate Offset	Yes	Requires Rulemaking	No
Climate Smart Agriculture	Part of Reg. Impact Analysis, no additional credit	In FD-CIC	No	Separate Offset	Yes, with detailed data	With model inputs	No
Off-site renewable Power	N/A	Not specified	For EV charging, Hydrogen by electrolysis	Yes, potential time of day matching	Yes	Not specified	Yes
Free Attribution to fuel products	N/A	Not specified	No	No	Yes	Not specified	No
RNG for fuel	CNG Book and Claim	Yes		Mass Balance	Mass Balance/ Free Attribution	Yes	Mass Balance
Avoided CH_4 from waste feedstocks	Not part of general pathways	Yes		Separate Offset	Yes	Yes	No

Avoided CH4 is not part of the CORSIA or RED CI but can be used as a separate offset to generate credits under the program. Free attribution is the ability to assign feedstocks within a process to products (usually by energy allocation). For example, tallow feedstock could be assigned to SAF under CORSIA rules but with LCFS, the fuel producer would need a CARB-approved methodology.

3.2 ILUC Methodologies

As noted previously, ILUC accounts for the GHG emissions related to the conversion of land, such as forests or grassland, that occurs indirectly as a result of biofuel production. It also takes into account the potential displacement of food and feed crops caused by the expansion of biofuel feedstock cultivation, which may lead to additional land being converted to compensate for the loss of food production. The general concept is as follows:

> Diverting crops for fuel production reduces exports and increases prices, resulting in increased production globally, potentially causing the conversion of native forest/grasslands to crop production (e.g., increased soybean production in Brazil, differences in grain exports from Europe, conversion from grassland to pasture, and shifts in food use patterns, which affect the demand for crops). The carbon stored in above-ground biomass and in the soil is released to the atmosphere, resulting in an increase in CO2 emissions relative to business-as-usual. There is also a loss of ongoing carbon sequestration in the vegetation that has been removed.

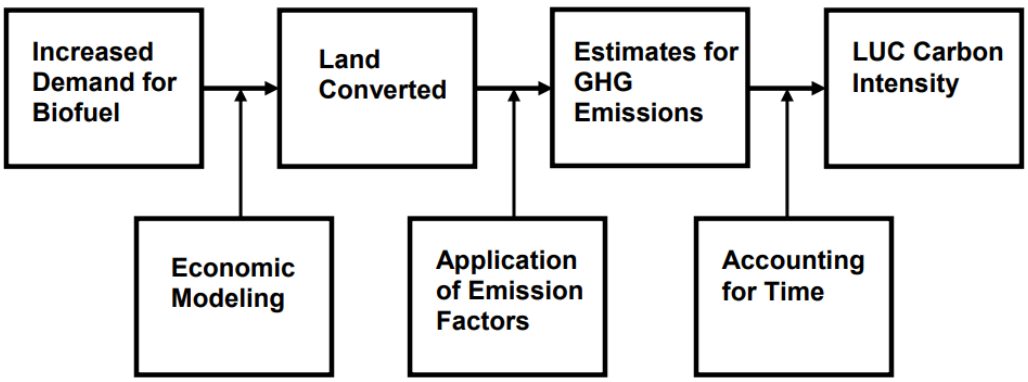
This section of the report first presents background information on modeling of ILUC, which is followed by details of the ILUC models used in the LCA methodologies evaluated in this project.

3.2.1 ILUC Modeling Background

Estimating ILUC emissions requires many assumptions as compared to direct emissions and can differ widely between models and modeling systems. According to Zhao et al.[34]: *Induced land use change includes both direct and indirect land use change, as the two cannot be distinguished given the complexity of the market-mediated responses*.

Figure 3-3 summarizes the general approach to calculating the carbon intensity of ILUC. A biofuel "shock" (i.e., increased demand) is modeled via agro-economic models to determine how much and what kind of land is converted as a result of the increased biofuel demand. Emission factors (above-ground and below-ground carbon) are applied to the converted land to determine the GHG impact of changing the land from, for example, native vegetation to crop production. Emissions are then allocated over a certain time period (usually 30 years in U.S. policy) assumed to be consistent with the length of the fuel program. RED-II does not include ILUC, and CORSIA considers a 25-year time horizon.

Figure 3-3. Simplified Block Flow Diagram of ILUC Modeling (CARB, 2015)[35]

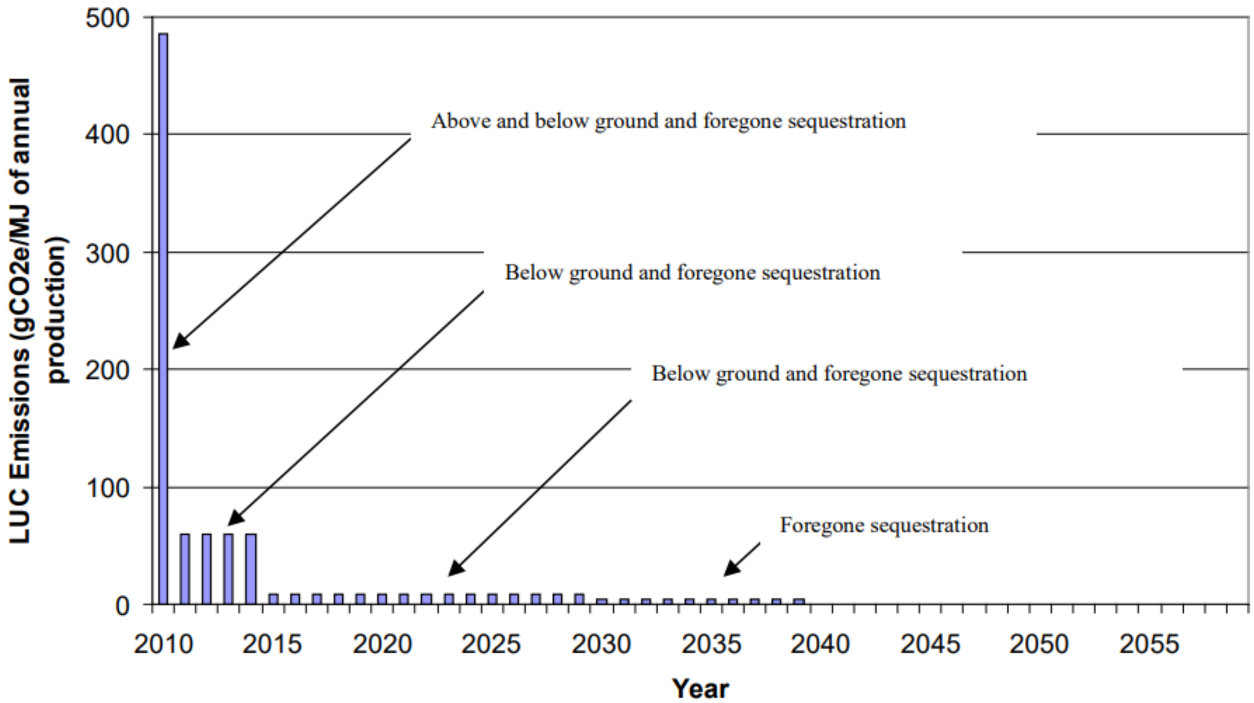


A typical land use change emissions profile is shown in Figure 3-4. Year 1 has the highest emissions as a result of land clearing and burning of the native vegetation. Most of the below-ground carbon (e.g., from roots and organic material) is released in years 1 to 5, with a slower release in years 6 to 20. Finally, foregone sequestration occurs during the entire project period, which, as noted above, is typically assumed to be 30 years.

[34] Zhao, X., Taheripour, F., Malina, R., Staples, M. D., & Tyner, W. E. (2021). Estimating induced land use change emissions for sustainable aviation biofuel pathways. Science of the Total Environment, 779, 146238.

[35] California Air Resources Board (CARB). (2015). Calculating carbon intensity values from Indirect Land Use Change and crop based biofuels. Appendix I: Detailed analysis for indirect land use change. Available at: https://www.arb.ca.gov/fuels/lcfs/iluc_assessment/iluc_analysis.pdf.

Figure 3-4. Emissions Profile of ILUC (CARB, 2015)



3.2.1.1 ILUC Modeling Historical Perspective

Figure 3-5 summarizes ILUC directives in the U.S. and some early ILUC GHG estimates through the 2000s. The 2007 Energy Independence and Security Act (EISA) directed EPA to include significant indirect effects, including land use change, in its lifecycle GHG estimates for renewable fuels in the RFS2 regulations. In EPA's analysis for RFS1[36], estimates for domestic land use change were included, and international land use change was cited as a concern, noting that data and model limitations at the time precluded such an analysis for RFS1. Finally, in their initial report on the development of a low carbon fuel standard for California as directed by Governor Schwarzenegger's Executive Order 01-07, Ferrell et al.[37] noted: *Among the most important market-mediated effects is land use change*.

[36] https://www.epa.gov/renewable-fuel-standard-program/renewable-fuel-standard-program-rfs1-final-rule-additional

[37] Ferrel et al. (2007). "A Low-Carbon Fuel Standard for California Part 1: Technical Analysis," Project Directors: Alexander E. Farrell, UC Berkeley and Daniel Sperling, UC Davis. Contributors: S.M. Arons, A.R. Brandt, M.A. Delucchi, A. Eggert, A.E. Farrell, B.K. Haya, J. Hughes, B.M. Jenkins, A.D. Jones, D.M. Kammen, S.R. Kaffka, C.R. Knittel, D.M. Lemoine, E.W. Martin, M.W. Melaina, J.M. Ogden, R.J. Plevin, D. Sperling, B.T. Turner, R.B. Williams, C. Yang, Report No. UCB-ITS-TSRC-RR-2007-2, May 2007.

Figure 3-5. Early ILUC Directives and ILUC Estimates for Corn Ethanol

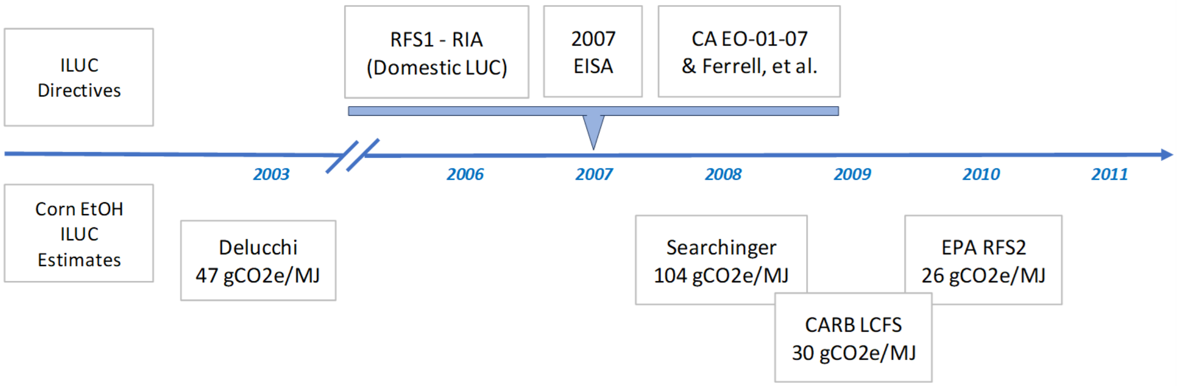


Figure 3-5 above also shows some early ILUC estimates for corn ethanol. The first numerical estimate that we are aware of was prepared by Mark Delucchi for his Lifecycle Emissions Model (LEM).[38] It is interesting to note that the Delucchi ILUC estimate was primarily associated with soil carbon impacts, whereas later analyses predicted a much greater impact from clearing above-ground vegetation. The paper prepared by Searchinger et al.[39] was widely read and received considerable attention. Over time, ILUC estimates have come down as models and model inputs have been refined. However, there is still considerable uncertainty associated with ILUC estimates as they cannot be directly measured and instead rely on various economic models to determine the quantity and location of land converted to crop production and emission factor datasets to assign carbon emissions per hectare of land converted.

3.2.1.2 Factors Impacting ILUC Modeling

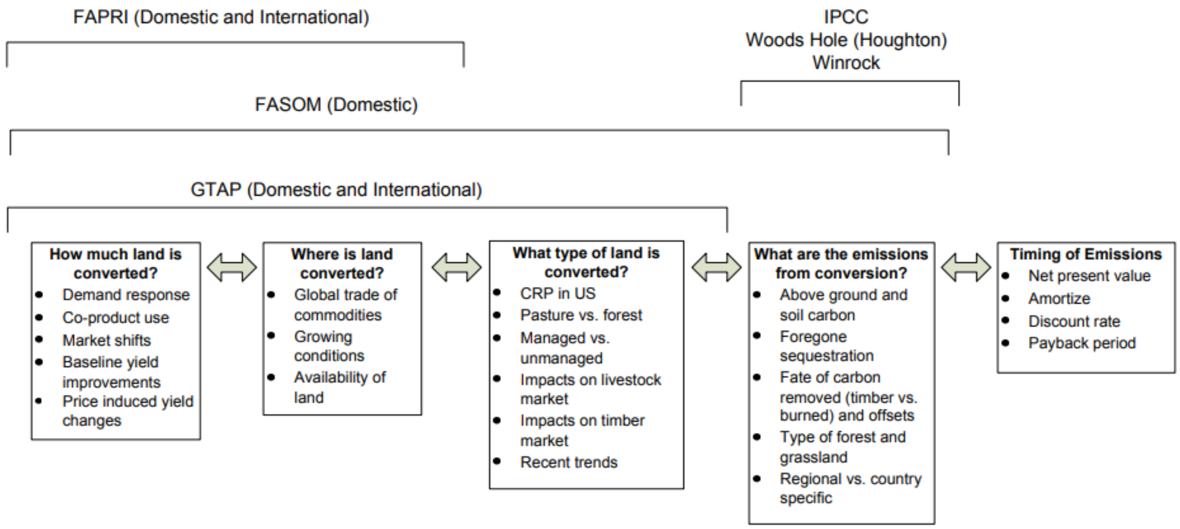
As shown in Table 2-2, the LCA methodologies selected for review use several different modeling systems to address ILUC emissions. These include GTAP (used in LCFS, CORSIA), FASOM and FAPRI (used in RFS2), GLOBIOM (used in CORSIA), and CCLUB (built into GREET).

Figure 3-6 shows a simplified breakdown of the factors that affect LUC estimates modeled in GTAP, as well as in FASOM and FAPRI. The significant differences between the GTAP modeling and the FASOM/FAPRI modeling include the carbon stock factors for released carbon and the regional detail for crop shifting. GTAP, for example, takes into account prior trade history between countries. All agro-economic models solve for prices that result in a supply and demand equilibrium. GTAP is a general equilibrium model that includes all sectors of the economy. FASOM and FAPRI are models including only agriculture and, in the case of FASOM, forestry. Those models are more detailed on individual agricultural commodities. All of the models project changes in land cover and predict changes in carbon stock through different carbon accounting mechanisms and carbon stock datasets.

[38] Delucchi, M. (2003). A lifecycle emissions model (LEM): Lifecycle emissions from transportation fuels, motor vehicles, transportation modes, electricity use, heating and cooking fuels, and materials. Institute of Transportation Studies, University of California, Davis.

[39] Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., ... & Yu, T. H. (2008). Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, 319(5867), 1238-1240.

Figure 3-6. Approaches to LUC Modeling (CARB, 2018)[40]



All modeling systems need to allocate emissions over time as they are predicting an initial "shock" of biofuel demand that is distributed over a period of biofuel production, typically assumed to be 30 years. Although the modeling represents the inputs to the GTAP system, the basic principles are the same for all LUC models. Improving crop yields, production of co-products, and high carbon stocks for converted lands reduce LUC emissions, and changes in key factors over time can impact estimates of ILUC values. For example, recent key findings for ILUC corn ethanol which impact ILUC values generated over time with GTAP include:

- Low conversion of land in the U.S.
- Crop-switching and multi-cropping
- Increase in soil carbon storage due to corn farming practices
- Overall decline in deforestation rates globally
- High substitute value of distillers' grain and solubles (DGS) as animal feed
- Increased cattle stocking rate with pasture intensification
- Corn oil co-product used to produce biodiesel and renewable diesel increases overall fuel output

Similar factors and the potential for other differences in changes in ILUC values over time also exist for other biofuels. One of the challenges in addressing multi-cropping and changes in soil organic carbon (SOC) is the understanding of the baseline conditions. Some degree of multi-cropping is included in the baseline ILUC model. So, expanding feedstock production with additional multi-cropping is difficult to reconcile. The same challenge applies to improvements in SOC. ILUC models include improvements in SOC due to no-till practices; so, attempts to credit such practices to individual batches of crops creates a potential for double counting.

3.2.2 GTAP, GLOBIOM, CCLUB

Prominent computational ILUC models, such as GTAP and GLOBIOM, are widely used to analyze the environmental and economic impacts associated with agriculture, forestry, and bioenergy sectors. These models specifically focus on the production of biofuels and land use changes.

[40] https://ww2.arb.ca.gov/rulemaking/2018/low-carbon-fuel-standard-and-alternative-diesel-fuels-regulation-2018

GTAP is a multi-sector multi-region Computable General Equilibrium (CGE) model that utilizes the comprehensive GTAP database. This extensive database includes Social Accounting Matrices (SAM) for 140 countries/regions across 57 economic sectors. In order to incorporate biofuel sectors into this framework, additional data regarding land cover, crop production, energy production, emissions, and trade from reliable sources was integrated into a separate modeling system, GTAP-BIO. The model employs various mechanisms including production functions and demand equations to determine supply-demand dynamics for all goods and services within the system. Moreover, GTAP incorporates nesting structures allowing it to effectively capture demands related to animal feed items. Furthermore, the model also accounts for observed land use changes by tuning its parameters accordingly. It takes multiple cropping practices into consideration while allocating unused cropland towards productive activities. GTAP depends on IPCC factors for land conversion to assess the release of CO_2 due to land conversion, which are processed to estimate GHG emissions using the AEZ-EF model.

In contrast to GTAP, GLOBIOM adopts a partial equilibrium constrained optimization approach which focuses primarily on agricultural, forestry, and bioenergy sectors as opposed to all global economic activity. The underlying methodology involves utilizing grid cell information in conjunction with specific activity models, such as EPIC (for crops) and G4M (for forestry). These activity-based models estimate productivity levels and environmental indicators using diverse inputs. GLOBIOM emphasizes optimizing resource allocation in terms of lands or other resources, to maximize consumer surplus. Producer surplus is also considered through evaluating factors like production, demand, and international trade. However, for the non-land-based sectors (e.g., energy industry, services), prices remain fixed throughout the analysis process.

When comparing GTAP and GLOBIOM it becomes evident that they share similarities but differ significantly in their approaches. Firstly, the commonality lies in their consideration of biofuel production and land use changes. However, the methodologies employed by GTAP-BIO and GLOBIOM differ considerably.

The latest version of GTAP-BIO employs a comparative static approach that utilizes 2014 as its base year to determine land use changes associated with each biofuel pathway. It isolates the impacts solely attributed to the expansion of biofuel production from other factors influencing the global economy. In contrast, GLOBIOM uses a recursive-dynamic methodology calibrated against baseline data for 2000 to assess impacts over several time periods. The model progressively increases intensity of shocks related to biofuels between 2010 and 2020 in order to assess resulting impacts.

The GTAP and GLOBIOM models serve as tools in understanding the intricate dynamics between biofuel production, land use, and the environment-economy interface. These models employ different analytical approaches and now provide the basis for ILUC determinations under CORSIA. While there are discrepancies between these two models regarding data sources, model structures, and methods of scenario implementation, they both adhere to a similar accounting convention when estimating ILUC emissions. Initially, the impact on land use is calculated for each expansion in biofuel production. Subsequently, these impacts are transformed into ILUC emissions.

The Carbon Calculator for Land Use Change from Biofuels Production (CCLUB) is a static module incorporated into GREET to account for both direct and Indirect Land Use Change emissions. The CCLUB module does not independently model land use change but rather relies on outputs from other models. It is primarily based on a set of GTAP-estimated induced land use change scenarios for various biofuel pathways. CCLUB then incorporates emission factors obtained from a parametrized CENTURY model into the GTAP modeled scenarios. This ecological model simulates carbon, nitrogen, phosphorus, and sulfur cycles in the context of land use changes. CCLUB also incorporates emission factors for international feedstocks from the Winrock and Woods Hole datasets.

The outputs generated by these models provide valuable insights into the potential emissions tied to ILUC, specifically concerning distinct scenarios associated with biofuel generation. These findings prove useful for policymakers, researchers, and stakeholders alike as they facilitate a better understanding of potential environmental consequences stemming from biofuel production activities.

3.2.2.1 GREET 40B

ANL provided a GREET calculations tool in support of Section 40B of the IRA which includes sample inputs and GHG results for SAF pathways that are currently in production. Indirect effects include ILUC from GTAP-BIO plus rice and livestock methane and other indirect effects that track the analysis in the RFS[41]. In contrast to the representation in the GREET model, ILUC emissions are proportional to the feedstock to fuel yield.

3.2.3 FASOM and FAPRI

In performing the LCA associated with the RFS2 regulatory program, US EPA developed a methodology for assessing ILUC and other "significant indirect emissions" as required by EISA using the FASOM and FAPRI models, which account for the incremental change of diverting crops to biofuel production. The US EPA methodology takes into account the direct farming emissions in the U.S. and internationally, as well as the effect on rice and livestock methane emissions due to shifts in the production of agricultural products. Emissions occurring in the U.S. are estimated with the FASOM model while those with international crop production are estimated using the FAPRI model in combination with emission factors for land cover change and agricultural inputs.

FASOM, the Forestry and Agricultural Sector Optimization Model developed by Texas A&M University and others, estimates the changes in crop area resulting from increased biofuel production. FASOM is a partial equilibrium model of the forest, agriculture, and livestock sectors for the United States. The model tracks U.S. cropland by county and estimates emissions associated with the conversion to cropland (i.e., domestic land use change). Within the model, the linked agricultural and forestry sectors compete for a portion of the land within the U.S. Prices for agricultural and forest sector commodities, as well as land, are endogenously determined based on demand functions and supply processes. The FASOM model maximizes the net present value of the sum of consumers' and producers' surpluses (for each sector) with producers' surplus estimated as the net returns from forest and agricultural sector activities. The GHG calculations are based on available data on inputs from crop budgets coupled with estimates from EPA, the IPCC, and the DAYCENT model developed by Colorado State University. The FASOM model also estimates the energy consumption, as well as fertilizer use, for crop production.

Since FASOM is only applicable for modeling the land use change within the U.S., EPA employed FAPRI, the integrated Food and Agricultural Policy and Research Institute international models, as maintained by the Center for Agricultural and Rural Development at Iowa State University, to estimate the changes in crop acres and livestock production by type and by country globally (international LUC). While FAPRI models how much cropland will change, it does not predict what type of lands, such as forest or pasture, will be converted. Therefore, EPA used Winrock International's data to estimate what land types are converted into cropland in each country. EPA also exercised the GTAP model and confirmed that the GTAP results were

[41] ANL (2024). Development of R&D GREET 2023 Rev1 to Estimate Greenhouse Gas Emissions of Sustainable Aviation Fuels for 40B Provision of the Inflation Reduction Act. Argonne National Laboratory ANL/ESIA-24/9.

consistent with outputs from the FASOM and FAPRI models. Since then, the GTAP model has undergone several revisions, but EPA has not compared its findings for the RFS2 rulemaking with the new results from the GTAP model.

3.2.4 Other Land Use Factors

As discussed previously, nitrogen in fertilizers decomposes due to nitrification and denitrification processes and results in incidental production of N_2O. Several different modeling systems are available for determining N_2O emissions including the IPCC methodology models such as GNOC and DAYCENT. The accounting of N_2O emissions varies among the modeling systems considered here and evolutions of GREET. Key factors include the conversion of chemical fertilizer to N_2O, N_2O caused by agricultural runoff, and the release of N_2O from decomposing crops and soybean nodules. Table 3-4 presents N_2O conversion factors for different groups that are incorporated into some of the LCA methodologies selected for evaluation in this study. All of the modeling systems provide a version of the IPCC approach for N_2O calculations based on applied nitrogen fertilizer and nitrogen in crop residue.

Table 3-4. N_2O Conversion Factors[42]

Emission Factor	GREET1_2022	GHGenius	BioGrace[a]	EcoInvent
Direct N_2O emissions				
Sugarcane	1.0%	1.25%	1.0%	1.0%
Corn	1.0%	1.25%	1.0%	
Soybean	1.0%	1.0%	1.0%	
Indirect N_2O emissions				
Volatilization N to NH_3	11%[b]	10%	10%	30.0%
Volatilization to N_2O	1.0%	1.0%	1.0%	
Leaching/Run Off	24%%	30%	30%	
Nitrate to N_2O	1.1%%	0.75%	0.75%	
Total N_2O emissions				
Sugarcane	1.264%	1.575%	1.325%	1.46%
Corn	1.264%	1.575%	1.325%	
Soybean	1.374%	1.325%	1.320%	

a BioGrace = model formerly used for RED certification

b Ammonia volatilization contribution is zero for corn and sugarcane.

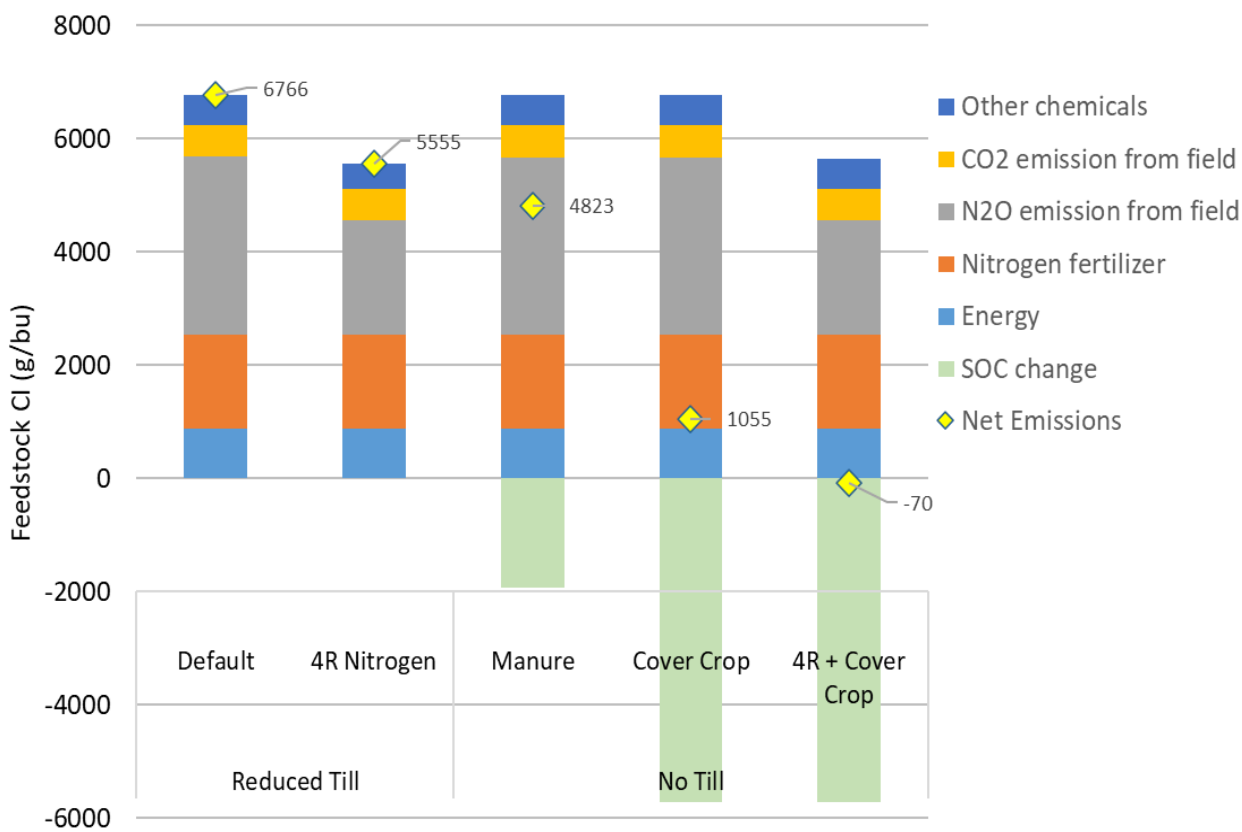
Table 3-5 and Figure 3-7 illustrate the effect that different farming practices have on SOC and overall GHG emissions from corn production based on Argonne's Feedstock Carbon Intensity Calculator (FD-CIC). As observed in the figure, reduced-till practices can reduce field-level N_2O emissions, while no-till practices can have a very beneficial effect on SOC build-up. Planting of cover crops, coupled with no-till practices, can result in a large reduction in GHG emissions from corn production.

[42] GREET values are taken directly from the model. Also Pereira, L. G., Cavalett, O., Bonomi, A., Zhang, Y., Warner, E., & Chum, H. L. (2019). Comparison of biofuel life-cycle GHG emissions assessment tools: The case studies of ethanol produced from sugarcane, corn, and wheat. Renewable and Sustainable Energy Reviews, 110, 1-12.

Table 3-5. Carbon Intensity of Corn Farming from the FD-CIC Model

Category	Reduced Till	4R Nitrogen	No Till Default	Cover Crop	4R + Cover Crop
Energy	877	877	877	877	877
Nitrogen fertilizer	1664	1664	1664	1664	1664
N_2O emission from field	3134	2010	3134	3134	2010
CO_2 emission from field	563	563	563	563	563
Other chemicals	524	437	524	524	524
SOC change	4	4	-743	-5708	-5708
Net Emissions	6766	5555	6019	1055	-70

Figure 3-7. Carbon Intensity of Corn Farming from the FD-CIC Model



4. COMPARISON OF MODELING SYSTEM RESULTS FOR SELECTED BIOFUELS

4.1 Basis for Model Comparison

Modeling systems with an identical set of inputs and analysis methods yield similar results. However, among the LCA methodologies reviewed here, differences in the inputs and analysis methods result in a wide range of GHG/CI outcomes for the same biofuels produced using the same pathways. In order to identify these differences in the selected LCA methodologies, dry mill corn ethanol and hydrotreated soy oil renewable diesel/jet cases were examined. First, the inputs and CI results obtained using default inputs for those LCA methodologies where they are available were reviewed and compared. Next, CI results from all of the selected LCA methodologies using default GREET1_2022 inputs were analyzed and compared.

The GREET defaults are based on the production of feedstock in the Midwest with a biorefinery located within 50 miles for the case of corn ethanol and within 500 miles for soybean oil renewable diesel and renewable jet. The values for model comparison are shown in Table 4-1. The electricity mix for illustration purposes is the U.S. average and the fuel transportation distance by rail is 1,600 miles, which is consistent with delivery to California from the Gulf Coast and allows for the comparison of the CARB Tier 1 Calculator (which does not include a barge delivery mode) with GREET. The GREET default includes a mix of rail, pipeline, barge, and truck delivery. Local fuel delivery distances are also consistent with delivery in California, therefore, the GREET model inputs are aligned with the Tier 1 Calculator inputs, allowing for one consistent set of transportation distances and electricity parameters. The same sets of assumptions are then applied to the soy oil jet pathway in GREET as, well as the pathways in GHGenius, RenovaCalc, and RED. Note that for GHGenius, the same transport distance was assumed. In the RenovaCalc and the RED cases, delivery was assumed by marine vessel to Brazil and the EU, respectively. This section of the report presents a comparison of LCA model results for corn ethanol and soybean oil (SBO) hydrotreated vegetable oil (HVO) for the following modeling systems:

- EPA's modeling approach developed for the RFS2 regulations in 2010
- GHGenius model as used in the British Columbia LCFS
- CORSIA aviation fuel analysis
- Argonne's GREET1_2022 model
- California Tier 1 Calculators
- Canada CFR model
- EU RED methodology
- RenovaCalc

The comparisons in this section start with model results in the various models' "baseline" configurations. For example, EPA established 2022 as the target year for analysis in the RFS2 regulations, and while calendar year is a user-input variable in GREET1_2022, the model populates this field to 2021 when opened. For GHGenius, 2016 is the standard year for analysis, and the California Tier 1 Calculators are based on the GREET1_2016 model. Presenting results in this fashion helps to address the question, "Why can different LCA models give such different results for the same fuel pathways?"

The subsections below present information first on corn ethanol, followed by soy HVO. For each fuel pathway, model inputs are presented for the following:

- Agricultural inputs

- Fuel production
- Fuel transportation and distribution
- Fuel combustion

Baseline analyses are available for the RFS2, CORSIA, GHGenius, and GREET. Sources of information for the RFS2 modeling of fuels are included as a combination of the Regulatory Impact Analysis[43] prepared for the final rule and associated spreadsheets downloaded from the docket for the RFS2 rulemaking. In addition, a technical report on the FASOM model was used to extract data on agricultural inputs for both corn and soybean farming. Input values for GREET1_2022 and GHGenius 4.03c were extracted directly from the models.

The bases for the inputs are compared and discussed. Afterwards, the inputs for GREET are evaluated within the California Tier 1 Calculator, GHGenius, Canada CFR, EU RED, and RenovaCalc models. Except for EU RED and RenovaCalc (with non-U.S. transport destinations), the models are run with identical fuel delivery distances. Table 4-1 shows the comparison basis for the fuels examined here. Each of the modeling systems requires different units. For example, fertilizer application may be represented per bushel or per hectare. Appendix A summarizes the model inputs.

Table 4-1. Basis for Fuel Pathway Comparison

Pathway	Corn Ethanol	Soy Renewable Diesel	Soy Renewable Jet
Technology	Dry Mill	Hydrotreating	Hydrotreating
GREET Worksheet	EtOH	BioOil	Aviation WTP
Process Inputs	Natural Gas	Hydrogen, Natural Gas	Hydrogen, Natural Gas
Co-Products	DGS, Corn Oil	Renewable Naphtha	Renewable Diesel, Renewable Naphtha
Electricity Mix	U.S. Average	U.S. Average	U.S. Average
Feedstock collection 10 mi MD Truck			
Feedstock to refinery	40 mi Truck	500 mi Rail	500 mi Rail
Transport to California or Canada			
Fuel	1600 mi Rail	1600 mi Rail	mix
Delivery	90 mi Truck	50 mi Truck	pipeline
Transport to EU			
Fuel to Port	500 mi	100 mi Rail	Not analyzed
Fuel to Market	6200 mi marine	6200 mi marine	
Delivery	90 mi Truck	50 mi Truck	

[43] U.S. Environmental Protection Agency. (2010, February). Renewable fuel standard program (RFS2) regulatory impact analysis (EPA-420-R-10-006).

4.2 Corn Ethanol

Ethanol, primarily made from corn, is an important blending component of the U.S. gasoline pool, making up about 10% by volume of typical gasoline sold in the U.S. (i.e., as E10). In addition to qualifying as a renewable biofuel under EPA's RFS2 standards, its high octane contributes to its properties as a gasoline blendstock. While higher ethanol blend percentages are available in the market – E85 for flex-fuel vehicles and potentially E15 for newer vehicles – consumption of those blends is negligible. In 2022, 910,000 barrels per day of fuel ethanol were blended into motor gasoline (14.0 billion gallons)[44].

The majority of U.S. ethanol production is located in the Midwest and Upper Midwest States, where ethanol plants are close to a consistent supply of corn, water, and have ample livestock production nearby as a market for co-products.

Ethanol is produced from corn grain by hydrolysis and fermentation. Inputs to LCI for corn production include farming energy, fertilizer production, changes in soil carbon, and N_2O emissions from fertilizer application. Ethanol is fermented from corn grain starch. Milling and distilling, which require electricity and heat, are the most energetically expensive parts of the pathway. The main co-products of corn ethanol production are distillers' grains and solubles (DGS), corn oil, and corn syrup.

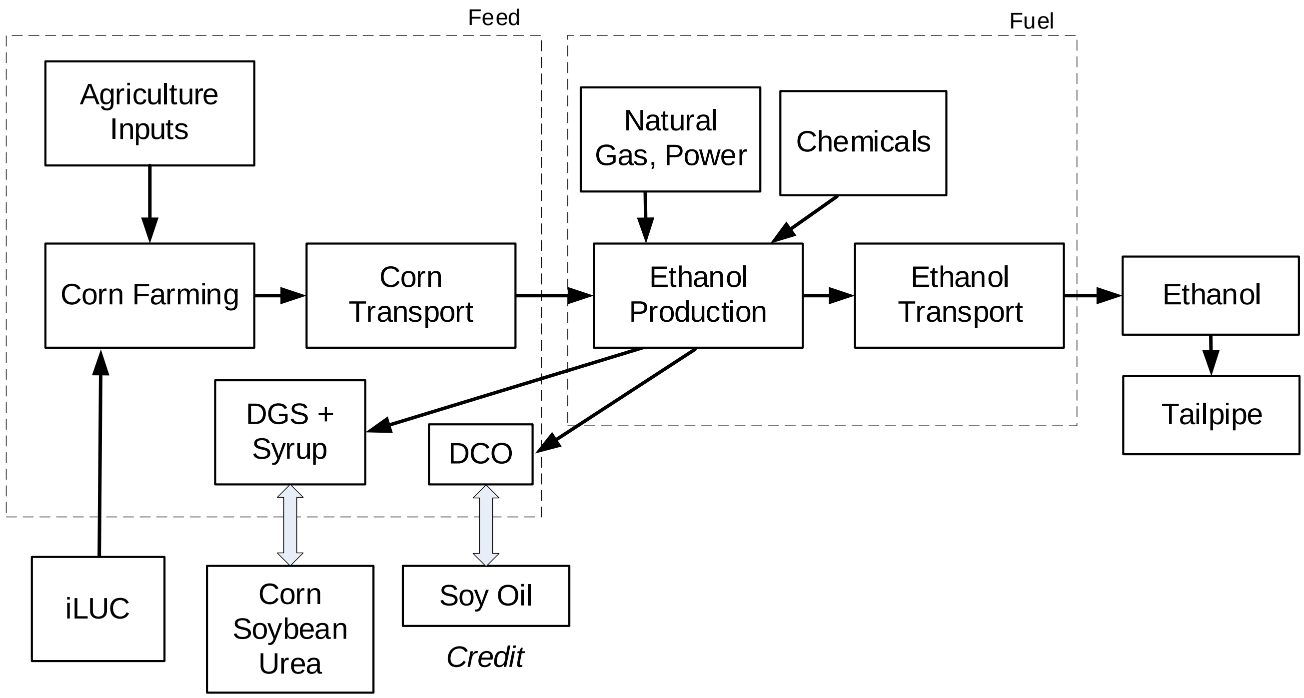
The steps for the conversion of corn biomass to ethanol are shown in Figure 4-1. Corn is harvested, collected, and transported to a bio-refinery. Harvesting involves establishing the crop, applying fertilizer inputs, and collecting biomass with harvesting equipment. Fuel processing includes pretreatment and conversion to ethanol. Finished fuel is transported to fueling stations for blending and/or vehicle operation.

Co-products from corn ethanol production include DGS, syrup, and distillers corn oil (DCO). Corn syrup is either sprayed on the DGS following fermentation or sold as a stand-alone product. If corn oil is extracted, then it is added to the DGS following fermentation, sold as an animal feed supplement, or used as a biodiesel feedstock. The treatment of co-products varies with the LCA modeling framework. Figure 4-1 shows the GREET groupings of the feedstock and fuel phase of the lifecycle. The GREET configuration uses the displacement method to calculate energy and emission credits based on co-product displacement ratios. The co-product credit is grouped in the feedstock production phase in GREET as the production of DGS displaces the production of other agricultural products. These displacement ratios affect the value of the co-product credit for the substitution method. The energy content of co-products on a dry matter basis provides the basis for energy allocation. The co-product treatment differs among the LCA frameworks examined here with the following approaches applied:

- GREET: Multiple allocation options, displacement of DGS and corn oil for substitute products is the default, credit for avoided enteric fermentation
- CA Tier1 SFE: displacement credit for DGS and corn oil for substitute products (no special treatment for corn oil, no enteric fermentation credit)
- RED, RenovaBio, Canada CFR: Energy Allocation

[44] https://ethanolrfa.org/media-and-news/category/news-releases/article/2023/02/eia-data-indicate-ethanol-blend-rate-hit-a-record-high-in-2022#:~:text=U.S.%20ethanol%20production%20rose%20two,of%2010.79%20percent%20in%20October

Figure 4-1. GREET System Boundary Diagram for Dry Mill Corn Ethanol



Corn farming requires fuel for farming equipment, agricultural chemicals (fertilizers, pesticides), as well as electric power and fuel from grain drying. The lifecycle emissions from grain ethanol production systems depend on the process inputs used to produce the fuel. Corn farming inputs are default values from GREET, presented in terms of Btu/bu and g/bu, and are documented in CARB and ANL corn ethanol pathway descriptions. Farming inputs are combined with emission factors for direct and upstream fuel cycle emission factors to determine GHG emissions on a lifecycle basis.

GREET includes ILUC based on Argonne's GTAP-based CCLUB model and applies the substitution method to provide a credit for DGS and corn oil. The model also includes a credit for avoided emissions from enteric fermentation due to the use of DGS as animal feed. Each of the other modeling system results in somewhat different approaches, as discussed in Section 4.2.4.

The California GREET model represented in the Tier 1 Calculator applies a similar approach except DCO is treated as DGS mass rather than corn oil, and the calculator provides no credit for avoided enteric fermentation. With the consequential analysis applied under the RFS, agricultural inputs reflect the inputs required to grow crops that replace corn used in ethanol production after the displacement effect of DGS is considered. Additional agricultural effects include indirect land use and changes in methane from rice and cattle. The USDA's update of the RFS reexamines the RFS analysis with updated modeling results, the most significant of which was the use of GTAP to estimate LUC effects rather than the FASOM and FAPRI models.[45]

[45] Rosenfeld, J., Lewandrowski, J., Hendrickson, T., Jaglo, K., Moffroid, K., & Pape, D. (2018). A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol. Report prepared by ICF under USDA Contract No. AG-3142-D-17-0161.

Energy allocation is utilized with the Canada CFR, RED, and RenovaCalc modeling protocols. The models do not apply a co-product credit for DGS and DCO but instead calculate an allocation factor based on the energy content of ethanol, DGS, and DCO on a dry matter basis. None of these modeling systems apply ILUC while the RED system, in principle, allows for user-defined data on soil carbon storage. The GREET modeling system includes a credit for soy oil displacing DCO while the CA Tier1 SFE calculator treats DCO and DGS mass with an assumed 1% moisture content.

4.2.1 Corn Farming Inputs

This section includes new data on corn yield and crop inputs. This section also reviews recent data on farming and makes a comparison to the estimates in the 2010 RFS2 RIA and the current GREET model. Table 4-2 shows the default model inputs for RFS2, GREET, and GHGenius. GHGenius was configured to model U.S. Corn/Ethanol production using the "USA Avg" option. Note that the RFS calculates farming emissions on a consequential basis; so, corn farming inputs are only part of the impact of corn consumption. Key differences in the default values include nitrogen and limestone application rates. Nitrogen application rates result in upstream emissions for fertilizer production, as well as field N_2O emissions. The agricultural data are derived from USDA sources, with the primary differences associated with the year the data were collected.

The following conclusions can be reached based on review of the data presented in Table 4-2:

> *Corn Yields* are very consistent across models which supply a yield, ranging from 178 to 181 bushels per acre.
>
> *Fuel Consumption* in Btu/bu is highest for RFS2 and GHGenius. This input is driven by relatively high energy input values for LPG (RFS2) and natural gas (GHGenius) used for grain drying.
>
> *Fertilizer* use is generally lower for RFS2 and GHGenius. This is an important difference, particularly for nitrogen fertilizer, which contributes substantially to GHG emissions. RFS2 values are projections while GREET data are updated annually from USDA data.
>
> *Herbicides & Pesticides* are typically small contributors to GHG emissions associated with agricultural activities. Gram-per-bushel values across modeling platforms are reasonably close. GHGenius only has one input for this which covers both herbicides and pesticides.
>
> *Corn Transport to Ethanol Plants* is identical between RFS2 and GREET1_2022. This assumption is higher for GHGenius but does not significantly impact the final CI value.

Table 4-2. Agricultural Inputs for Domestic Corn Farming – Baseline Values

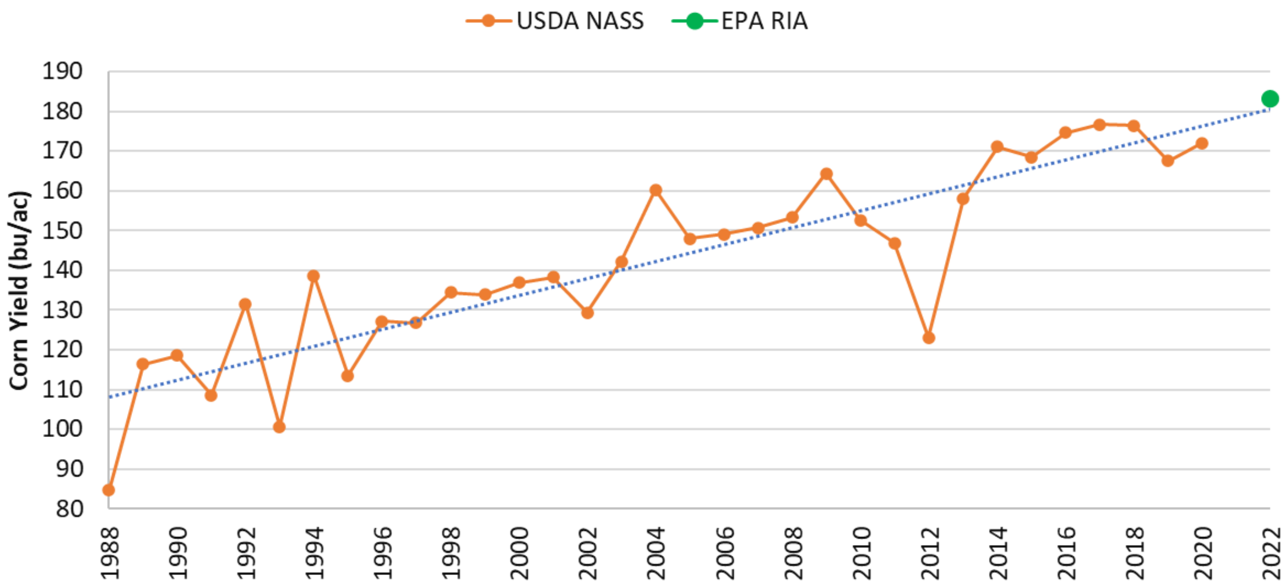
Model Inputs	RFS 2	GREET1_2022	GHGenius
Domestic Corn Farming Agricultural Inputs			
Corn Yield (bu/acre)	181.2	178.4	Not explicit
Corn Farming Fuel Consumption (Btu/bu)			
Diesel	7,374	5,200	6,654
Gasoline	--	802	--
Natural Gas	--	479	8,190
LPG	6,894	1,026	3,026
Electricity	1,437	1,326	--
Fertilizer Inputs (g/bu)			
Nitrogen	316	401	294
P_2O_5	77	151	125
K_2O	--	152	172
Limestone ($CaCO_3$)	273	1,457	--
Herbicide & Pesticide Inputs (g/bu)			
Herbicides	6.6	5.9	--
Pesticides	1.5	0.7	7.9
Corn Transport to EtOH Plant (mi)			
Medium-Duty Diesel Truck	10	10	--
Heavy-Duty Diesel Truck	40	40	92

The consumption of farming inputs such as fertilizers, pesticides, and energy (such as diesel and LPG) affect the GHG intensity of corn or crops that are grown to make up for corn used for biofuel production. Crop yields affect both the land required for crop production and LUC.

Historical data on corn yield indicate that the yield has increased steadily over time, from 85 bu/ac in 1988 to 172 bu/ac in 2020, as shown in Figure 4-2. The adoption of double-cross hybrid corn, continued improvement in crop genetics, adoption of N fertilizer and pesticides, and agricultural mechanization resulted in a steady increase of corn yield in the U.S.[46] Aside from the steady increase in corn yield, the harvested area of corn has increased over time. Due to the continuous improvement of corn yield, the production quantity has an upward trend. The 2010 RFS2 RIA estimated the corn yield for 2022 as 185 bu/ac, based on past 30 years of corn yields from the USDA database. EPA's projection of corn yield for 2022 is consistent with the trendline of current data in Figure 4-2.

[46] Nielsen, R.L. (n.d.) Historical corn grain yields for the U.S. Accessed 02/08/2019. Available at: http://www.kingcorn.org/news/timeless/YieldTrends.html..

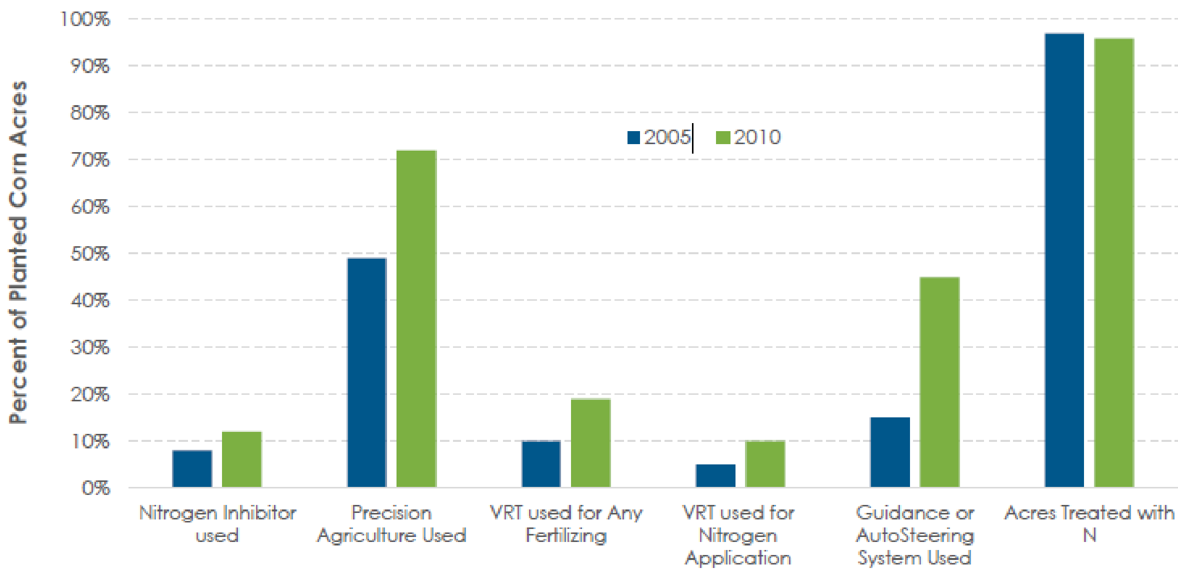
Figure 4-2. Corn Yield Over Time (USDA NASS, 2018)[47]



Management practices such as tillage and nitrogen application rates affect the GHG intensity of crops. In order to decrease the environmental footprint and lower the production costs, farmers have started using new technologies such as precision agriculture to manage their fertilizer consumption, as shown in Figure 4-3. Reduced tillage, which reduces soil carbon emissions, has also become a common practice across the U.S. Nitrogen inhibitors reduce the requirement for nitrogen and also reduce the formation of N_2O. Precision farming and guidance methods also allow for the more efficient application of nitrogen. The combination of all of these methods results in increased yield per acre and reduced nitrogen per bushel.

[47] USDA NASS (2018). United States Department of Agriculture, National Agricultural Statistics Service.

Figure 4-3. Changes in Corn Production Practices from 2005 to 2010 (Rosenfeld et al., 2018)[48]



4.2.1.1 Corn Farming – GREET Basis

Corn ethanol pathways were compared based on a consistent set of input values for GREET, Tier 1 Calculator, Canada CFR, EU RED, and RenovaBio. The GREET1_2022 model defaults from Table 4-2 were converted to the standard input basis for each model as shown in Appendix A. These provide a consistent basis for comparison in all modeling systems. The Tier 1 Calculator uses standard values for corn farming; so, these were not changed to align with GREET1_2022.

4.2.2 Ethanol Plant Operation

Corn ethanol production inputs are summarized in Table 4-3. Note that these inputs are based on the dry mill process using natural gas as process fuel. The corn to ethanol yield affects the upstream lifecycle emissions for corn farming. The yield also affects ILUC discussed in Section 3. DGS affects the displacement effect modeled under the RFS2 and GREET with displacement ratios that indicate the type of animal feed product that is replaced by a co-product. Natural gas use rates represent the process fuel used to produce and distill ethanol and dry DGS. The RFS2 and GREET values represent an assessment of the composite of U.S. ethanol plants and not 100% DGS drying. A small amount of coal process energy is assumed in the GREET baseline inputs and this value was converted to natural gas to provide a similar basis for comparison.

The following conclusions can be reached based on review of the data presented in Table 4-3:

> *Product and Co-Product Yields* are similar across models. GREET1_2022 has a lower yield of DGS than RFS, but the ethanol yield is slightly higher, and it is assumed that corn oil is extracted from the DGS.

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[48] Rosenfeld, J., Lewandrowski, J., Hendrickson, T., Jaglo, K., Moffroid, K., & Pape, D. (2018). A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol. Report prepared by ICF under USDA Contract No. AG-3142-D-17-0161.

DGS Displacement Ratios, which reflect how much feed corn and soybean meal are displaced by DGS, are also similar across models. Displaced product is shown on an as-received basis per pound of bone-dry DGS. GREET models DCO as a substitute for SBO.

Table 4-3. Corn Ethanol Production Baseline Inputs (Dry Mill – Natural Gas)

Model Inputs	RFS 2	GREET1_2022	GHGenius
Corn Ethanol Production			
Product & Co-Product Yields			
Ethanol, Dry Mill (gal/bu)	2.71	2.86	2.74
Dry DGS (lb/bu)	17	13.2	13.25
Corn Oil (lb/bu)		0.27	
DDGS Displacement (lb/lb DDGS)			
Feed corn	--	0.78	0.78
Soybean meal	--	0.31	0.31
N-urea	--	0.02	--
Beef & dairy (feed corn & SB meal)	1.196	--	--
Swine & poultry (feed corn & SB meal)	1	--	--
*Natural Gas Consumption (Btu/gal EtOH)**			
Dry DGS	23,616	22,480	27,603
Wet DGS	15,047	--	--
Natural Gas Emission Factor (gCO_2e/mmBtu), LHV			
Model Value	68,575	73,386	71,999
Electricity Consumption (BTU/gal EtOH)			
Dry DGS	3,251	2,098	1,820
Wet DGS	3,251		
Electricity Emission Factor			
Value in Common Units (gCO_2e/kWh)	**750.1**	**466.5**	**661.17**
Other Processing Inputs & Chemical Use (g/gal)			
Enzymes and Yeast	--	10.6	11.4
Sulfuric acid (H2SO4)	--	4.6	13.9
Ammonia (NH3)	--	17.8	27.8
NaOH	--	22.3	7.6
CaO	--	10.6	
DGS Transport to Feed Lot			
Rail (% by mode)	14%	DGS Transport Not Explicitly Modeled	DGS Transport Not Explicitly Modeled
Rail (miles)	800		
Barge (% by mode)	2%		
Barge (miles)	520		
Heavy-Duty Diesel Truck (% by mode)	86%		
Heavy-Duty Diesel Truck (miles)	50		

Natural Gas Consumption is similar between RFS2 and GREET1_2022 for dry DGS. Under the RFS2 modeling, wet DGS is also modeled (assumed to be 37% of dry mill corn ethanol production). Wet DGS, which has a short "shelf life," can be used when feedlots are relatively close to the ethanol production facility. If DGS is not dried, there is a large natural gas savings in the LCA modeling. GHGenius assumes a larger amount of natural gas usage and 100% dry DGS. RFS2 modeling assumed 63% dry DGS and 37% wet DGS. About 90% of U.S. ethanol plant capacity consists of dry mill plants with the mix of wet and dry DGS projected by EPA[49]. The balance of ethanol capacity is wet mills with 2/3 operating on natural gas fuel and the balance on coal.

Natural Gas Emission Factors, which represent both combustion and upstream GHG emissions, are higher for GREET1_2022, reflecting increased methane leakage in more recent estimates of natural gas production and pipeline transportation.

Electricity Consumption is higher for the RFS2 estimates. However, electricity is typically a relatively small contributor to LCA analyses of biofuels. The RFS2 emission factor for electricity is 60% higher than that of GREET1_2022, reflecting an increase in natural gas combined cycle power plants displacing coal and increased renewables that were not envisioned in the 2010 analysis performed for the RFS2 rulemaking.

Other Processing Inputs and Chemical Use, such as enzymes and yeast, acid, ammonia, etc., are explicitly accounted for in GREET1_2022 and GHGenius, whereas it does not appear that they were explicitly modeled for the RFS2 rulemaking.

Distillers' Grains and Solubles (DGS) Transport to Feed Lots is included in RFS2 as part of the displacement analysis, but it is not explicitly modeled in GREET1_2022 nor GHGenius.

4.2.3 Fuel Transportation/Distribution and Fuel Combustion

The final set of model inputs for corn ethanol includes transportation and distribution of the fuel and combustion in an engine. These inputs are listed in Table 4-4 and are summarized below.

Ethanol Transport and Distribution refers to the transportation of the fuel from the production facility to a blending facility, and then distribution to the fueling station. GHGenius does not separate transport and distribution distances. The RFS2 and GREET1_2022 inputs are very similar, which is not surprising given that the RFS2 inputs were based on an earlier version of GREET (GREET1.8c).

Tailpipe Methane (CH_4) and Nitrous Oxide (N_2O) Emissions are accounted for in all modeling systems. The modeling systems exclude biogenic CO_2 from the net GHG results. Although GREET includes a small amount of fugitive VOC emissions that are counted as fossil CO_2. However, GHGenius includes a factor for CO_2 from lube oil which is not considered to be biogenic. This additional consideration causes a higher CI impact for combustion within the GHGenius modeling. Note that the RFS2 estimates of CH_4 and N_2O are higher than those for GREET1_2022, but the overall impact of this component of the LCA is relatively small. Table 4-4 also shows the 100-year global warming potentials for CH_4 and N_2O, which changed between RFS2 (based on IPCC AR2 values) and GREET1_2022 (IPCC AR6 values). The RFS analysis is based on the implementation of the rule through the original 2022 timeframe.

[49] Unnasch. S., D. Parida, and B. D. Healy (2023). GHG Reductions from the RFS2 – A 2022 Update. Life Cycle Associates Report LCA. LCA.6145.238.2023 Prepared for Renewable Fuels Association.

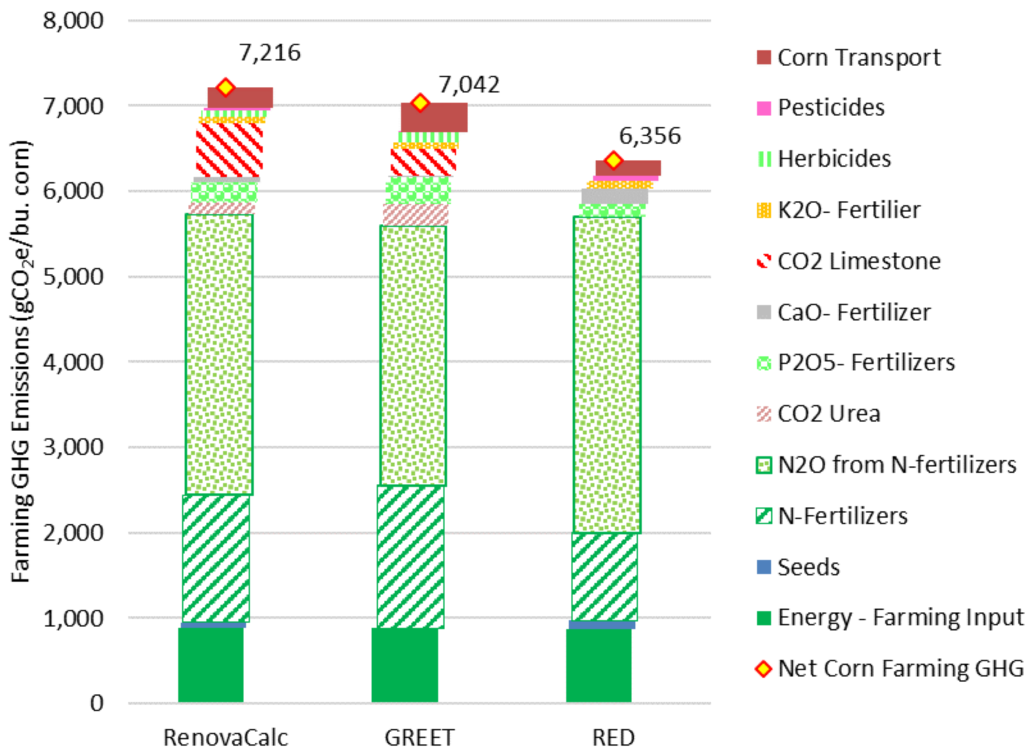
Table 4-4. Ethanol Transport & Distribution and Fuel Combustion

	RFS 2	GREET1_2022	GHGenius
Ethanol Transport & Distribution			
Rail (% by mode)	77%	79%	43%
Rail (miles)	629	800	436
Barge (% by mode)	12%	13%	0%
Barge (miles)	336	520	-
Heavy-Duty Diesel Truck (% by mode)	17%	7.9%	100.0%
Heavy-Duty Diesel Truck (miles)	68	80	114
Local HD Truck (% by mode)	83%	100%	Not Treated
Local HD Truck (miles)	6.5	30	Seperately
Tailpipe CH4 and N2O Emissions			
Emissions (g/MJ)			
CH4	0.012	0.0032	0.0114
N2O	0.002	0.0009	0.0031
CO2 from Lube Oil			0.8843
100-Year Global Warming Potential			
CH4	21	29.8	25
N2O	310	273	298
GHG Emissions (gCO2e/MJ)	**0.83**	**0.33**	**2.09**

4.2.3.1 CO_2 from Urea and Limestone and N_2O from Fertilizer

Urea contains carbon in its formulation when applied to the soil. The carbon molecules either dissociate in the soil and are consumed by biological organisms and remain in the soil, become part of the plant matter, or are liberated as field CO_2 emissions. Carbon from urea either remains as part of the soil carbon mass or is released to the atmosphere. GREET calculates 100% of the carbon in urea and 50% of carbon in limestone as emitted to the atmosphere. N_2O emissions depend on the fate of nitrogen in fertilizer and nitrogen in biomass. The results also differ slightly by modeling system. The lifecycle GHG emissions of corn on a per bushel basis for each of the modeling systems is shown in Figure 4-4 shows the disaggregated GWP weighted emissions.

Figure 4-4. GHG Emissions from Corn Farming



4.2.4 Corn Ethanol GHG Results and Discussion

The information and data summarized above were used in conjunction with the models assessed in this project to calculate lifecycle GHG emissions for corn ethanol. Section 4.2.4.1 below presents a comparison of RFS2, GREET1_2022, and GHGenius GHG results in their baseline configurations. Following that, Section 4.2.4.2 presents a comparison of GREET1_2022, CARB Tier 1 Calculator, GHGenius, Canada CFR LCA model, EU RED, and RenovaCalc GHG results using a standard set of inputs based on GREET1_2022. Presented in Section 4.2.4.3 is a comparison of the RFS2 results to an updated RFS2 analysis from 2018 sponsored by USDA.

4.2.4.1 GHG Results for Baseline Configurations of RFS2, GREET1_2022, and GHGenius

The inputs described in Table 4-2, Table 4-3, and Table 4-4 summarize the various defaults to modeling GHG emissions from corn ethanol in the RFS2, GREET1_2022, and GHGenius modeling platforms. The GHG results from these models are presented in Table 4-5, which shows a large difference in estimates across the methodologies, with the EPA RFS2 value of 74.9 gCO_2e/MJ on the high end and the GREET1_2022 estimate of 53.3 gCO_2e/MJ on the low end. A summary of the main components of the LCAs is presented below:

> *Feedstock Production and Transport* GHG emissions are much higher for GREET1_2022 than for RFS2, with much of that difference associated with field emissions and fertilizer use. However, as noted in the Co-Product Credits section of Table 4-2, both RFS2 estimates account for co-product credits in farming/field/fertilizer emissions. Subtracting the GREET1_2022 co-product credits from the farming/field/fertilizer emissions results in much better alignment between models. The

GHGenius feedstock production and transport emissions are much lower than both GREET1_2022 and the EPA RFS2. Another item to note is that the RFS2 methodology accounts for a projected increase in international livestock and methane emissions and a corresponding decrease in domestic livestock and methane emissions.

Table 4-5. Lifecycle GHG Emissions for Corn Ethanol – Baseline Model Results

Default Corn Ethanol Carbon Intensity (gCO_2e/MJ)			
Life Cycle Component	**EPA RFS2**	**GREET1_2022**	**GHGenius**
Corn Production			
Farming/Field Emissions	16.03	3.82	6.73
Fertilizers/Herbicides/Pesticides		25.58	6.46
Domestic Livestock & Rice Methane	-3.75	--	
International Livestock & Rice Methane	5.26	--	
Corn Transportation	2.25	1.54	2.32
DGS Transportation	0.60	--	
Total Feedstock Production/Transport	**20.40**	**30.95**	**15.51**
Land Use Change/ Soil Organic Carbon	**26.1**	**7.4**	**27.0**
Ethanol Production			
Electricity	8.91	3.56	4.88
Natural Gas/Fuel Gas	17.49	20.47	27.45
Other Processing Inputs	--	1.99	2.26
Total Corn Refining to EtOH	**26.40**	**26.02**	**34.59**
Co-Product Credits			
DGS Displacing Corn Feed	Included in Farming/ Field Emissions	-5.70	
DGS Displacing Soybean Meal		-3.84	
DGS Displacing Urea		-0.79	
CH_4 Reduction from Cattle Fed with DGS		-2.14	
Total Co-Product Credits		**-12.47**	-21.01
Ethanol Transportation/Distribution	**1.18**	**1.05**	**1.93**
Tailpipe Emissions	**0.83**	**0.33**	**2.09**
Total Carbon Intensity	**74.9**	**53.3**	**60.1**

Ethanol Production GHG emission estimates are very similar between the GREET1_2022, RFS2, and GHGenius. The RFS2 results represent a relatively large impact from electricity, while the GREET1_2022 natural gas numbers are higher.

Co-Product Credits are separately calculated in GREET1_2022 and GHGenius, while they are included in the corn production estimates for RFS2. As noted above, these credits appear to be relatively similar across models based on combining field/fertilizer emissions and co-product credits for GREET1_2022 and GHGenius, which should be expected given the similarities in DGS displacement ratios between the models.

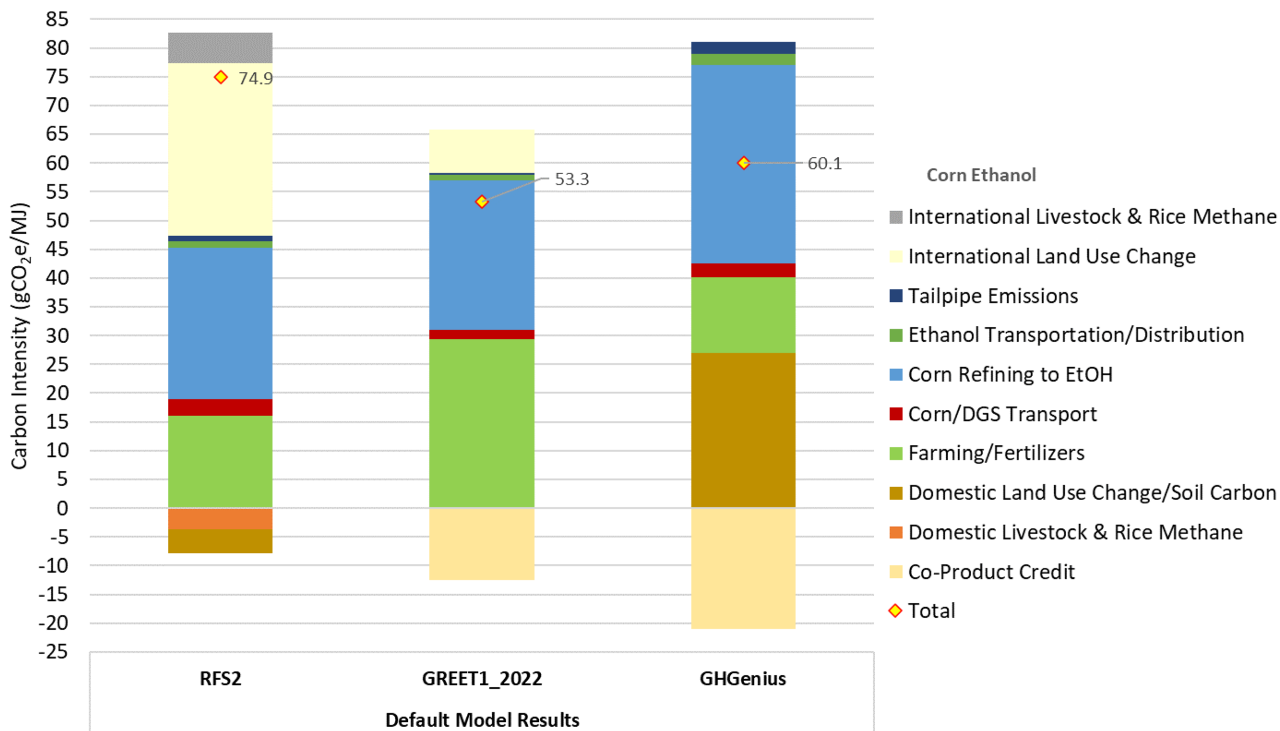
Ethanol Transportation/Distribution emissions are very similar between RFS2 and GREET1_2022. Again, this was not unexpected given the similarities in transport modes and distances between the models. GHGenius emissions are higher due to a higher assumed truck transport distance.

Tailpipe GHG Emissions are over double for RFS2 versus GREET1_2022. However, that component of LCA accounts for only about 1% of total GHG emissions. Tailpipe emissions are much higher for GHGenius since CO_2 from petroleum lube oil consumption is included. This contribution to total tailpipe GHG emissions is as high as the non-CO_2 species (CH_4 and N_2O).

Land Use Change estimates for the RFS2 are based on a consequential method that examines the interaction between crop farming, land conversion, and changes in animal feed. The net results are comparable to the value in the LCFS Tier 1 discussed in the following section. The GREET1_2022 model uses the ILUC value from CCLUB, which accounts for much of the difference between the two models. GHGenius does not consider ILUC however, it does include soil organic carbon (SOC) emissions associated with corn farming. The SOC impacts include those from farming and the displacement effect of co-products. This category is comparable to the domestic soil carbon parameter in GREET; however, the magnitude is much higher and the RFS shows negative domestic SOC. ILUC represents a net change in SOC and this value is either calculated as an indirect impact which includes the effect of corn farming, new crop activity and co-products or as the direct SOC impacts for a cropping activity which is the case under the RED.

Figure 4-5 compares the baseline values for three modeling studies which have relatively similar inputs for corn farming and ethanol production. Due to the complexity of each modeling system and the significant differences among the approaches, simply comparing the default results illustrates key differences in these analysis efforts. First, the RFS2 is largely a consequential approach, which assesses farming inputs as the additional farming required to make up for corn production that is diverted to ethanol. Some of the farming inputs include international production of other crops. The EPA analysis also predicts land use conversion and other indirect effects such as the impact on livestock and rice production. GHGenius and GREET1_2022 apply a substitution analysis in which DGS is treated as a co-product credit. The large SOC GHG footprint in GHGenius is offset by a larger co-product credit.

Figure 4-5. GHG Emissions from Corn Ethanol Pathways – Baseline Values



4.2.4.2 Corn Ethanol GHG Results Based on Common Inputs

The GREET inputs from Table 4-2 to Table 4-4 were used as inputs to the other modeling systems evaluated in this effort which require primary data. The conversion from GREET inputs to the generic model inputs is shown in Appendix A. The RFS was not reexamined as modifying the indirect farming and land use impacts was not possible within the context of this project. Process fuel use is represented as 100% natural gas rather than 4% coal which is the GREET default. The transport distances are all the same except for RED and RenovaCalc which involve inherently longer transport. The LCFS CI excludes the gasoline denaturant and the tailpipe CH_4 and N_2O from blended E10 combustion are shown here.

Table 4-6 compares the lifecycle GHG emissions for corn ethanol from these modeling systems, which range from a low of 38.2 g CO_2e/MJ for RenovaCalc even with longer transport distances to a high of 68.6 gCO_2e/MJ for the LCFS Tier 1 Calculator. Key similarities and differences across the modeling platforms are discussed below.

Feedstock Production/Transport – GREET1_2022 and the CA Tier 1 Calculator have similar and the highest GHG emissions for this step, while the other models are about one-third lower, which is related to co-product allocation methods as explained below. The similarity between GREET and the CA Tier 1 Calculator was not unexpected as the Tier 1 Calculators were based on an older version of GREET. Note that the Canada CFR model also uses default parameters for corn production as these cannot be changed within the model.

Land Use Change/Soil Organic Carbon – This element of the LCA represents an area of significant differences between models. The Canadian model, EU RED, and RenovaCalc do not include ILUC or SOC impacts, so this entry is zero for those models. The difference in ILUC between GREET1_2022 and the Tier 1 Calculator reflects most of the difference in total CI between the two models, with the Tier 1

Calculator being nearly three times that of GREET1_2022. Although both estimates use GTAP as the basis for the calculations, the Tier 1 Calculator ILUC estimate was based on a much older version of GTAP-BIO and corresponding inputs to the model. The key factor affecting the GHG differences is the source of carbon stock factors described in Section 3.2.

Farming, Fertilizer, and Field Emissions – The most significant component is emissions associated with fertilizer production, N_2O release from fields and conversion of carbon in fertilizer to CO_2.

Ethanol Production – GREET1_2022, the CA Tier 1 Calculator, and GHGenius GHG emissions for this step are nearly identical. The Canada CFR model, EU RED, and RenovaCalc models estimating lower values due to an energy allocation method rather than the displacement credit is used to account for co-products, with about 35% of corn and ethanol production assigned to DGS and corn oil products.

Co-Product Credits – GREET1_2022, the CA Tier 1 Calculator, and GHGenius all use a displacement method to account for co-products, while the Canadian model, EU RED, and RenovaCalc use energy allocation. As a result, co-product credits are not explicitly calculated in the latter three models, but the feedstock and ethanol production elements of the LCA are discounted by the energy embodied in the co-products.

Transportation/Distribution/Tailpipe Emissions – These elements of the LCA have a lesser impact on the overall CI for the different models, except for transportation, which is not insignificant for EU RED and RenovaCalc as fuel is assumed to be transported from Europe and Brazil, respectively.

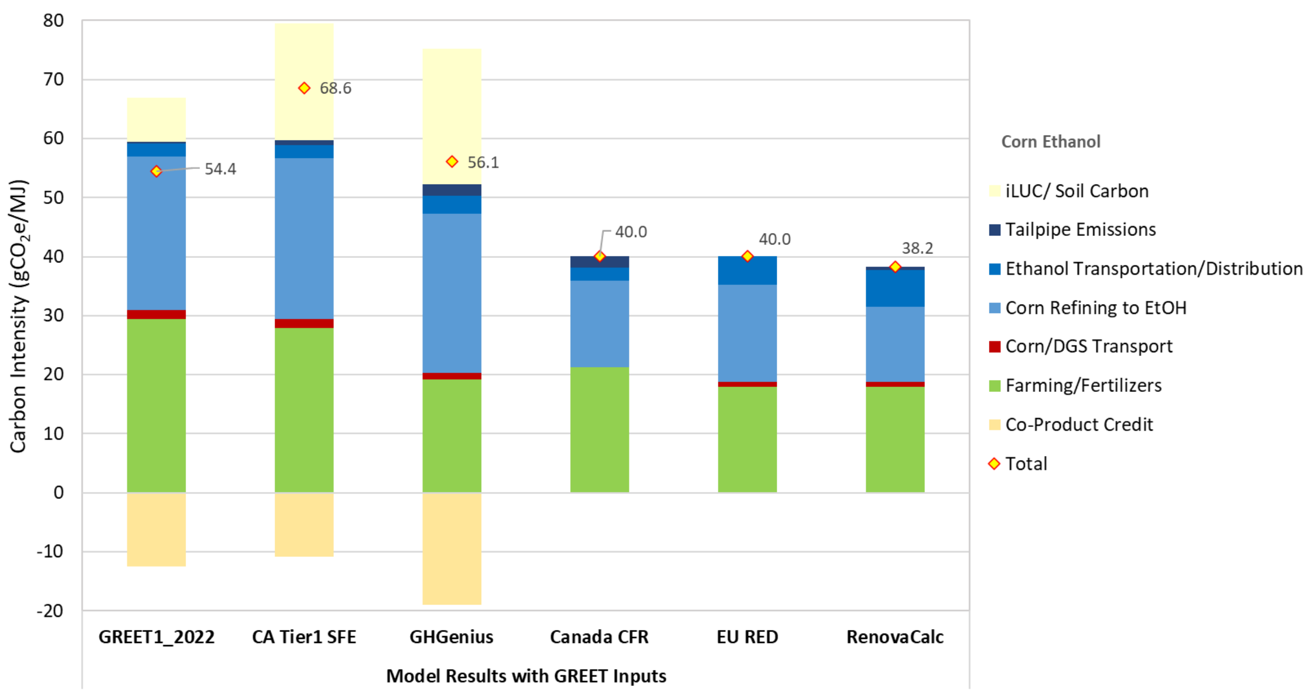
Table 4-6. Lifecycle GHG Emissions for Corn Ethanol Based on Common GREET1_2022 Inputs

	Corn Ethanol Carbon Intensity (gCO_2e/MJ), GREET Inputs					
Life Cycle Component	**GREET1_2022**	**CA Tier1 SFE**	**GHGenius**	**Canada CFR**	**EU RED**	**RenovaCalc**
Corn Production						
Farming/Field Emissions	19.87	16.78	7.00	Aggregated	13.62	12.91
Fertilizers/Herbicides/Pesticides	9.55	11.15	12.15		4.36	5.02
Corn Transportation	1.54	1.50	1.08		0.78	0.81
Total Feedstock Production/Transport	**30.96**	**29.43**	**20.23**	**21.31**	**18.75**	**18.75**
Land Use Change/ Soil Organic Carbon	**7.39**	**19.8**	**23.0**	**0.0**	**0.0**	**0.0**
Ethanol Production						
Electricity	3.56	4.66	4.76	2.39	2.35	3.46
Natural Gas/Fuel Gas	20.48	20.49	19.56	11.84	13.16	7.93
Other Processing Inputs	1.91	2.11	2.75	0.39	0.99	1.32
Total Corn Refining to EtOH	**25.95**	**27.26**	**27.07**	**14.62**	**16.50**	**12.71**
Co-Product Credits						
DGS Displacing Corn Feed	-5.70			Energy Allocation Reflected Above	Energy Allocation Reflected Above	Energy Allocation Reflected Above
DGS Displacing Soybean Meal	-3.84					
DGS Displacing Urea	-0.79					
CH_4 Reduction from Cattle Fed with DGS	-2.14					
Total Co-Product Credits	**-12.47**	-10.88	-19.01			
Ethanol Transportation/Distribution	**2.23**	**2.25**	**3.02**	**2.18**	**4.78**	**6.32**
Tailpipe Emissions	**0.33**	**0.76**	**1.87**	**1.94**	**0.00**	**0.44**
Total Carbon Intensity	**54.4**	**68.6**	**56.1**	**40.0**	**40.0**	**38.2**

Tier1 SFE does not include tailpipe, this is for gasoline in E10. Tier1 SFE includes denaturant in CI U.S. average electricity.

Figure 4-6 shows the GREET baseline values were then converted to inputs for the California, BC, Canada, European, and Brazilian programs. The California GREET result implemented in the Tier 1 Calculator is comparable to the GREET baseline model except for the omission of a credit for avoided methane emissions from cattle and a higher ILUC. The remaining three analysis frameworks use energy allocation for co-products, in which the DGS co-product is treated as an allocation factor that reduces the overall farming and ethanol plant emissions. Note that the transport emissions to the EU and Brazil are larger due to the longer distances. RenovaCalc includes a standard value for transport, which makes these emissions higher. Finally, the emissions from natural gas combustion under RenovaCalc are lower due to a unit conversion issue.

Figure 4-6. GHG Emissions from Corn Ethanol Pathways – GREET Inputs



4.2.4.3 USDA Update to RFS2 Corn Ethanol GHG Estimates

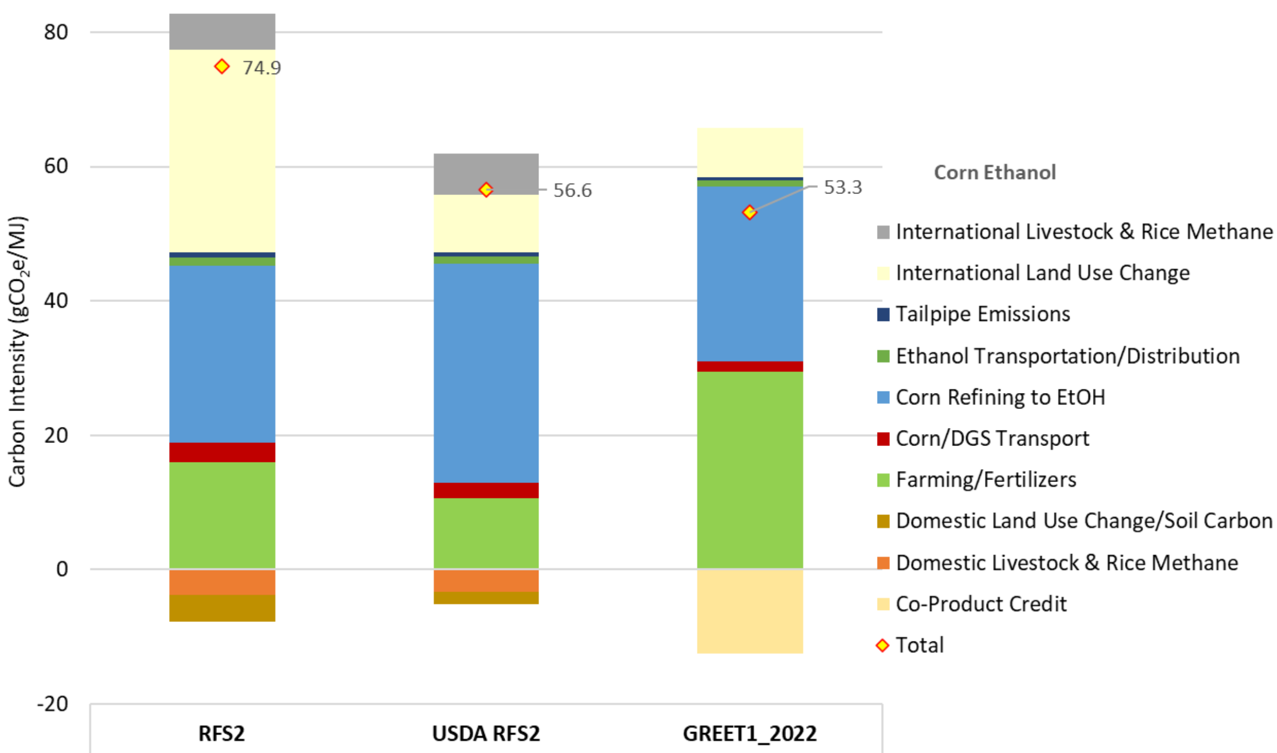
In 2018, the USDA sponsored an update to the corn ethanol GHG emissions calculated in the RFS2 rulemaking conducted by ICF.[50] That study reviewed every aspect of EPA's RFS2 analysis conducted in 2010 and made updates based on more recent data when available. Conducted by Figure 4-7 compares the corn ethanol lifecycle GHG results for RFS2, the USDA update to RFS2, and GREET1_2022.

The differences between the original and updated RFS2 results are primarily related to land use change and the indirect effects of corn use. As indicated in the development of the USDA RFS2 update of EPA's international LUC modeling for RFS2, one reason the RIA potentially over-estimated the global land use response to increasing U.S. corn ethanol production is that, except in Brazil where some increases in double cropping were allowed, world agriculture's response to increasing commodity prices was generally limited to the extensive margin (i.e., bringing new land into production). While commodity production data show that the world's farmers did respond to high global and domestic commodity prices during the period 2004-2012 by increasing production, Babcock, and Iqbal (2014) show that most of this increase was the result of the

[50] https://www.usda.gov/sites/default/files/documents/LCA_of_Corn_Ethanol_2018_Report.pdf

world's farmers making changes at the intensive margin (e.g., increasing the use of double and triple cropping, increasing irrigation, and reducing lands in idle uses). Multi-cropping effects are reflected differently in the modeling systems. USDA RFS2 is based on GTAP-BIO (similar to GREET1_2022), while EPA RFS2 is based on FAPRI-CARD.

Figure 4-7. USDA Update to RFS2 Corn Ethanol GHG Emissions



4.2.5 Ethanol-to-Jet GHG Estimates

This section of the report presents ethanol-to-jet GHG emissions for several different pathways. This is presented separately from the corn ethanol results above because they are different products with different inputs. Figure 4-8 shows the lifecycle GHG emissions for ethanol to jet based on the GREET1_2022 model and the effect of a range of emission reduction strategies including CCS, CSA, hydrogen based on book and claim of low CI RNG, as well as renewable heat and power. The analysis illustrates key differences between the GREET1_2022 and CORSIA analysis frameworks. While there are differences in calculation methods, the key factors include the inclusion and exclusion of emission reduction strategies within CORSIA.
Included in CORSIA are:

- Use of renewable natural gas by mass balance as opposed to book-and-claim[51]: This entails ensuring that an equivalent amount of renewable gas is used to offset any non-renewable consumption.
- Use of renewable power either on-site or with source-specified certification: By integrating such sustainable energy solutions into operations, organizations can significantly reduce their carbon footprint.

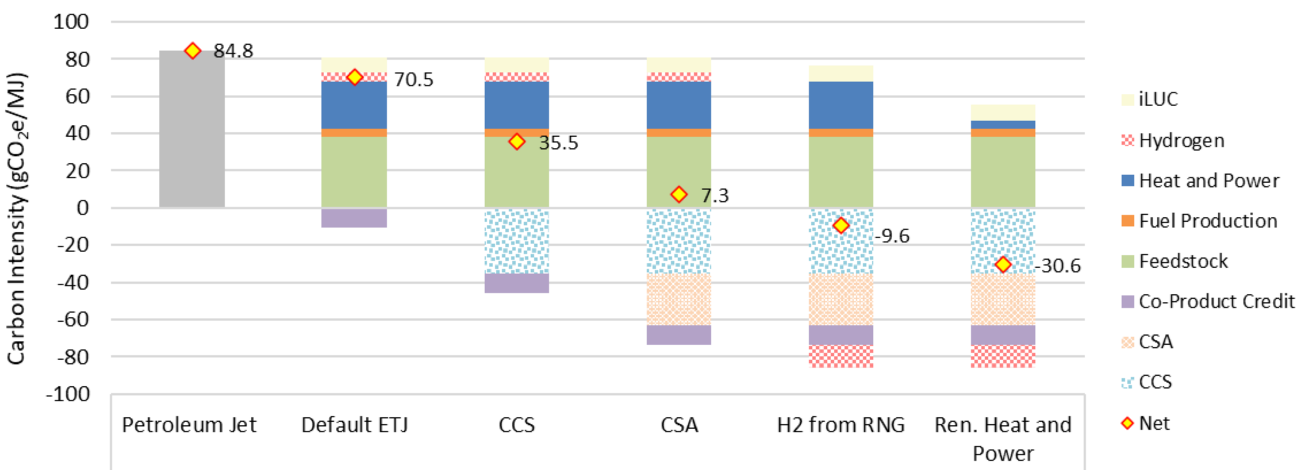
[51] Credits for avoided methane emissions are currently not part of CORSIA and would need to be included as a separate offset.

- Use of on-site renewable heat and power systems: These technologies enable businesses to generate clean energy directly at their facilities, further reducing reliance on traditional fossil fuel-based resources.

Although not included in the CORSIA initiative, there are additional offsets that can be pursued independently. These measures are implementable in GREET but are available under CORSIA only as offsets and not part of the fuel pathway. These include:

- Carbon Capture and Storage (CCS): A technology that involves capturing carbon dioxide emissions from industrial processes and storing them underground to prevent their release into the atmosphere.
- Soil carbon storage comparable to CSA: This refers to practices aimed at increasing soil organic matter content, which can help sequester carbon and improve soil health.
- Methane avoidance from manure management: Implementing measures such as anaerobic digestion or composting of livestock waste can reduce methane emissions, a potent greenhouse gas.

Figure 4-8. GHG Emissions from Corn Ethanol to Jet – GREET Inputs



4.3 Soy Renewable Diesel

Soybean oil (SBO) is a feedstock used in a variety of fuel pathways including biodiesel and renewable diesel and jet. Renewable diesel refers to an oil/lipid (triglyceride) that is hydrotreated to remove the oxygen (about 11% by weight in typical vegetable oils) and cleave the glycerin backbone from the three hydrocarbon chains resulting in hydrocarbons in the C16 to C18 range along with renewable naphtha and propane as co-products. The oxygen in the lipid is removed in the form of H_2O and CO_2. A hydrotreating project may also produce a jet cut, and the broad category of fuels is referred to as hydrotreated vegetable oils (HVO) and hydrogenated esters and fatty acids (HEFA). Renewable diesel is different than "biodiesel," in which an oil/lipid is combined with methanol in the presence of a catalyst (typically NaOH) to produce glycerin and fatty acid methyl esters (FAME). Importantly, renewable diesel does not contain oxygen, and its molecular structure is chemically the same as petroleum-based diesel so that it can be considered a "drop-in" fuel. EIA estimates a supply of approximately 195,000 barrels per day of renewable diesel in 2023[52] (3 billion gallons per year) and indicates that renewable diesel production now exceeds biodiesel production.

[52]https://www.eia.gov/todayinenergy/detail.php?id=60281

Consistent with the corn ethanol inputs, sources of information for the RFS2 modeling of soybean oil renewable diesel included a combination of the Regulatory Impact Analysis prepared for the RFS2 final rule and associated spreadsheets downloaded from the docket for the RFS2 rulemaking. The FASOM report cited previously was also used to extract data on agricultural inputs for soybean farming.[53] Input values for GREET1_2022 and GHGenius were extracted directly from the models.

GHGenius does not model soy-based renewable diesel by default, as renewable diesel was not envisioned as a main component of the BC LCFS Program.[54] Biodiesel is shown below for GHGenius CI results as the SBO renewable diesel results are not available, but the treatment of soybean meal co-products provides insight to the model structure. This comparison illustrates the effect of the SBO feedstock, but the results are somewhat skewed by biodiesel not requiring hydrogen and generally having a slightly higher yield. Because of the limits of this comparison, inputs are not shown and only CI results are presented.

Soybeans are a major crop throughout much of North America, South America, and Asia. Brazil produces approximately 41% of the world's soybeans, followed by the United States (28%)[55]. Soybeans contain 18 to 20% oil by weight and yield approximately 57 gallons of oil per acre (gal/ac). Soybean products include soy oil and soybean meal (SBM).

Soybeans are farmed predominantly in the Midwest, harvested, and transported to a crushing facility. Farming inputs include tractor fuel, fertilizers, and pesticides. Soybeans require relatively low nitrogen inputs because soybean nodules fix nitrogen from the atmosphere.

The renewable diesel production process, hydrotreating or hydro processing, requires vegetable oil or animal fat and hydrogen as primary inputs. Further process inputs are electric power, and natural gas. The hydro processing reaction makes hydrogen react with the triglyceride molecules via competing decarboxylation and hydrodeoxygenation reactions. The reaction steps produce either water, CO, or CO_2. The extent of the reactions and ultimate yield of renewable diesel depend on the catalyst used and the process conditions. The process yields a primary product in renewable diesel, which by virtue of the saturation of olefinic bonds, is a purely paraffinic product. The primary co-product derived from the three-carbon backbone is propane, suitable as a feedstock for LPG.

The system boundary diagram for soybean-based renewable diesel evaluated in the GREET model is shown in Figure 4-9. ILUC is analyzed based on the GTAP model as implemented in CCLUB. The GREET model is configured with a variety of allocation approaches. The process level allocation approach illustrated here is also used for the LCFS calculations. Soybean farming emissions are allocated to soy oil and renewable diesel/naphtha product based on the mass of SBO and SBM. The net effect is that the CI of SBO is almost identical to the CI of soybeans. Energy inputs for oil extraction are also allocated between SBO and SBM based on mass. Finally, the energy inputs for hydrotreating are allocated by energy content to diesel, jet, naphtha, and LPG. The LCFS Tier1 BDRD calculator follows this approach except that the final fuel products are allocated based on their energy content. The inputs to GREET for renewable diesel include a pre-processed energy and yield per pound of RD which already has naphtha production taken into account. This

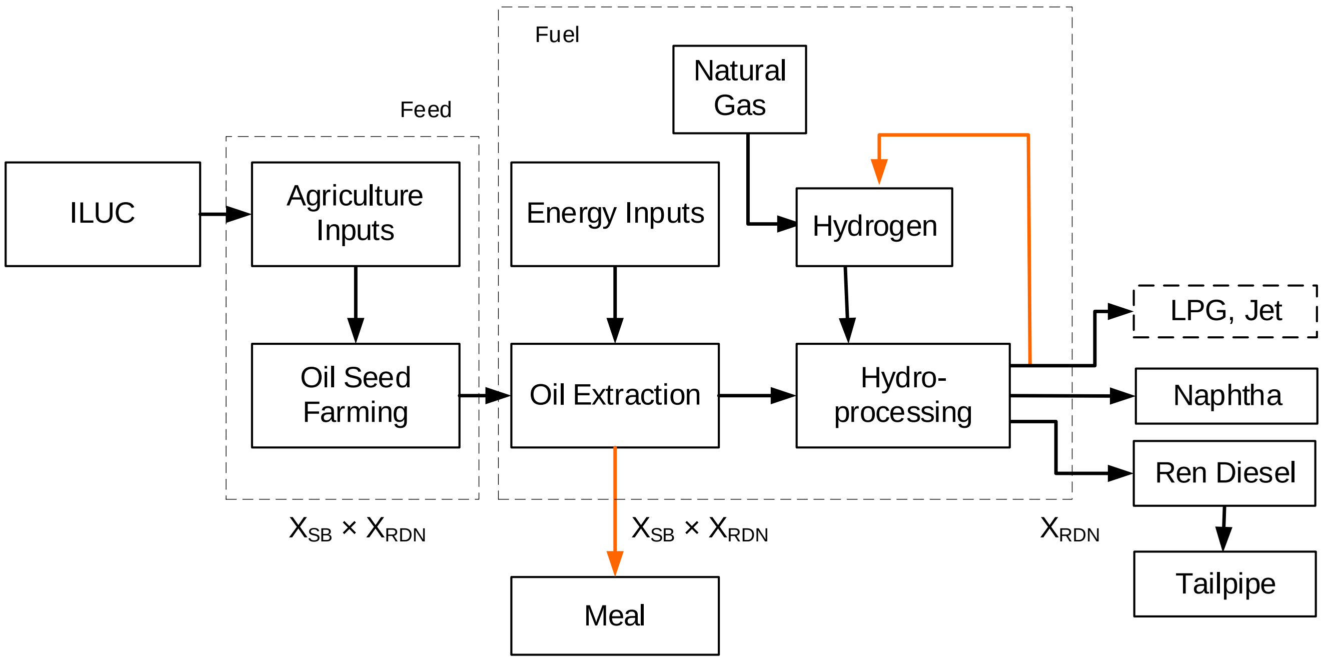
[53] Beach, R., & McCarl, B. (2010, January). U.S. agricultural and forestry impacts of the Energy Independence and Security Act: FASOM results and model description (Final Report). Prepared for the U.S. Environmental Protection Agency by Texas A&M, RTI International.

[54] The BC LCFS cites biodiesel as the primary renewable fuel replacement for diesel. As of 2023, there are a large number of RD pathways https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf012_-_approved_carbon_intensities_-_current_04aug2023.pdf

[55] https://ipad.fas.usda.gov/cropexplorer/cropview/commodityView.aspx?cropid=2222000

mass/energy allocation approach is comparable to energy allocation since naphtha and diesel have similar heating values on a mass basis and is referred to as subsystem mass allocation in GREET.

Figure 4-9. GREET System Boundary Diagram for Soy Renewable Diesel



4.3.1 Agricultural Inputs for Domestic Soybean Farming

Table 4-7 summarizes the agricultural inputs for soybean farming in the U.S. for the modeling systems analyzed in this section of the report, which include the RFS2, GREET1_2022, and CORSIA (U.S.) for jet fuel. As noted above, because GHGenius does not model renewable diesel, it was not included in summarizing model inputs, and the CORSIA SBO-based renewable jet was substituted for GHGenius. Farming inputs include fuel use per bushel of soybeans and the fraction of SBO extracted per bushel of soybeans. The agricultural emissions reflect the vintage of USDA data and are derived from different versions of GREET (1.8c for RFS2, 2016 for CORSIA, and GREET1_2022). Soy nodules are a significant source of N2O emissions56. The nitrogen application rate, which is proportionality lower for soy than other fuel pathways is also a source of N2O emissions.

[56] Cai, H., M. Wang, A. Elgowainy, and J. Han. (2015). Updated N_2O Emissions for Soybean Fields. Argonne National Laboratory.

Table 4-7. Baseline Agricultural Inputs and Processing for Domestic Soybean Farming

Model Inputs	RFS2	CORSIA, U.S.	GREET1_2022
Domestic Soybean Farming Agricultural Inputs			
Soybean Yield (bu/acre)	46		50.6
Soybean Oil Yield (lb SBO/dry bu)	11.2	11.2	11.2
Soybean Farming Fuel Consumption (Btu/bu)			
Diesel	22,609	12,985	9,353
Gasoline	7,375	2,902	2,065
Natural Gas	--	0	176
LPG	3,365	0	662
Electricity	1,176	886.6	1,468
Fertilizer Inputs (g/bu)			
Nitrogen	67	48	44
P2O5	90	187	208
K2O	--	299.1	330
Limestone (CaCO3)	1,089	0	0
Herbicide & Pesticide Inputs (g/bu)			
Herbicides	11.7	17.9	19.4
Pesticides	7.0	0.4	0.3
Soybean Transport to Crushing Plant (mi)			
Medium-Duty Diesel Truck	10	10	10
Heavy-Duty Diesel Truck	40	40	40
Crushing Plant Fuel Consumption, Unallocated (Btu/lb SBO)			
Residual oil	--	27	27
Diesel fuel	--	13.5	13.2
Natural gas	1,976	1,757	1,723
Coal	--	865	848
Electricity	387	312.8	372
n-Hexane (Petroleum-Based Solvent)	--	56.8	49.2
Biomass	--	27.0	26.7
Landfill Gas	--	13.5	13.2
SBO to RD Plant Transport Distance by Mode	Not Explicitly Modeled in the RD Spreadsheet		
Rail (% by mode)			20%
Rail (miles)			700
Barge (% by mode)			40%
Barge (miles)			520
Heavy-Duty Diesel Truck (% by mode)			40%
Heavy-Duty Diesel Truck (miles)			80

The following summarizes the similarities and differences observed in Table 4-7:

Soybean Yields are lower in the RFS2 modeling than in GREET1_2022. The soybean oil yield is identical between the models at 11.2 lb. SBO/dry bu.

Fuel Consumption in Btu/bu is much higher for RFS2, which is seen across all fuel types except for electricity.

Fertilizer use is mixed across models. RFS2 assumes greater use of nitrogen and limestone, while GREET1_2022 assumes greater use of P_2O_5 and K_2O.

Herbicides & Pesticides are typically small contributors to GHG emissions associated with agricultural activities. However, as observed in Table 4-7, there are substantial differences in these inputs across models.

Soybean Transport to Crushing Plants is identical between RFS2 and GREET1_2022.

Crushing Plant Emissions are greater for GREET1_2022 than in the RFS analysis, primarily driven by a fair amount of coal in the GREET default for process energy. The actual use of coal may be lower. The RFS analysis likely considered a scenario that phased out coal.

Soybean Oil Transport to RD Plants was not explicitly modeled in the RFS2 spreadsheets reviewed in this work, while GREET1_2022 assumes a fair amount of transport via rail and barge, with lesser distances of transport via heavy-duty diesel truck. When mileage is weighted across transport modes, GREET1_2022 assumes 37% by rail, 55% by barge, 8% by heavy-duty truck. Barge transport likely reflects SBO being routed from Midwest oil crushing plants via the Mississippi River to RD production facilities in the Gulf Coast.

4.3.2 Renewable Diesel Processing

Soybean oil renewable diesel production inputs are summarized in Table 4-8. Note that these inputs are based on hydrogen being produced from natural gas via steam methane reforming. Additionally, the RFS2 values are reported for hydrotreating in the "Max Diesel" mode.[57] A comparison of inputs across models is summarized below.

[57] The report upon which EPA's hydrotreating inputs were based modeled both "Max Diesel" and "Max Jet" modes. Slightly more hydrogen is used in the Max Jet mode as there is some cracking of the hydrocarbon chains to produce product in the jet range. See https://dspace.mit.edu/bitstream/handle/1721.1/65508/746766700-MIT.pdf;sequence=2

Table 4-8. Soybean Oil Hydrotreating Default Inputs (Natural Gas Based Hydrogen)

Model Inputs	RFS2	CORSIA	GREET1_2022
Product	Max Diesel	Max Jet	Max Diesel
Soybean Oil Hydrotreating			
Product Yields (lb/lb SBO or kg/kg SBO)			
Renewable Diesel	0.681		0.791
Jet Fuel	0.128		
Naphtha	0.018		
Propane/LPG	0.058		Captured in Fuel Gas
Hydrogen Consumption			
Native Units	lb H2/100 lb SBO	Btu/lb Jet	Btu/lb RD
Model Value	2.7	1,736	2,071
Value in Common Units (SCF H2/BBL SBO)	**1,647**	**2,280**	**1,918**
Hydrogen Emission Factor			
Native Units	N/A - H2 consumption included in natural gas		$kgCO_2e/kg$ H2
Model Value		9.40	9.40
Value in Common Units (gCO_2e/SCF H2)		22.7	**22.7**
Electricity Consumption			
Native Units	Btu/lb SBO	Btu/lb jet	Btu/lb RD
Model Value	68.24	87.70	185.2
Value in Common Units (kWh/bbl SBO)	**6.4**	**9.1**	**14.2**
Electricity Emission Factor			
Value in Common Units (gCO_2e/kWh)	**750.1**	**549.5**	**466.5**
Natural Gas/Fuel Gas Consumption			
Native Units	Btu/lb SBO	Btu/lb jet	Btu/lb RD
Model Value	2432	87.70	352
Value in Common Units (Btu NG/bbl SBO)	**781,626**	**31,094**	**101,977**
Natural Gas Emission Factor			
Value in Common Units (gCO_2e/mmBtu NG), LHV	**68,575**	**73,386**	**73,386**

Product and Co-Product Yields are for combined liquid products (renewable diesel, renewable jet, and renewable naphtha) and are similar across models with RFS2 at 0.827 lb/lb SBO, and GREET1_2022 at 0.791 lb/lb SBO. GREET1_2022 reports renewable diesel as the liquid product with the balance of LPG product treated as a co-product energy allocation factor (0.099 lb/lb RD or 0.125 lb LPG plus naphtha/lb SBO). RFS2 carries renewable propane as a distinct co-product, while GREET1_2022 captures this co-product as fuel gas. Treatment of co-products between the models results in important differences in the calculated GHG footprint of renewable diesel.

Hydrogen Consumption, which is the most carbon-intensive input to hydrotreating SBO, is about 14% lower for the RFS2 modeling at 1650 scf H2/BBL SBO versus 1920 SCF H2/bbl SBO for GREET1_2022.[58] The RFS2 modeling did not treat hydrogen as a separate input to the modeling. Instead, the input for the RFS analysis is total natural gas which includes the feedstock for hydrogen production as natural gas used as process heat.

Electricity Consumption is higher for the GREET1_2022 estimates. However, electricity is typically a relatively small contributor to LCA analyses of biofuels. The RFS2 emission factor for electricity is 60% higher than that of GREET1_2022, reflecting an increase in natural gas combined cycle power plants displacing coal and increased renewables that were not envisioned in the 2010 analysis performed for the RFS2 rulemaking.

Natural Gas Consumption is much higher in the RFS2 modeling than in GREET1_2022. That is a result of hydrogen production being a large part of the natural gas consumption under RFS2, while GREET1_2022 carries hydrogen as a separate input in its modeling of renewable diesel.

Natural Gas Emission Factors, which represent both combustion and upstream GHG emissions, are higher for GREET1_2022, reflecting increased methane leakage in more recent estimates of natural gas production and pipeline transportation.

Other Processing Inputs and Chemical Use is not included as part of the RFS2 and GREET1_2022 inputs. However, CARB's Tier 1 Calculator for renewable diesel assumes a small GHG footprint for chemical use, amounting to 0.03 gCO_2e/MJ.

4.3.3 Fuel Transportation/Distribution and Combustion

The final set of model inputs for SBO renewable diesel includes transportation and distribution of the fuel and combustion in an engine. These inputs are listed in Table 4-9 and are summarized below.

Renewable Diesel Transport and Distribution refers to the transportation of the fuel from the production facility to a blending facility, and then distribution to the fueling station. The GREET1_2022 inputs include transport by rail, barge, and heavy-duty truck. The precise distribution modes for renewable diesel in RFS2 were not clear from the materials available in the docket for this pathway (although values are available for biodiesel). The overall total of 0.76 gCO_2e/MJ is reported for RFS2, which is higher than that calculated for GREET1_2022, but still a relatively small component of the overall fuel pathway GHG emissions.

Tailpipe Methane (CH_4) and Nitrous Oxide (N_2O) Emissions are accounted for in all modeling systems. Because CO_2 emissions are biogenic, they do not contribute to GHG emissions in the lifecycle analysis.

[58] The different models use different units for hydrogen consumption, and therefore hydrogen consumption was converted to standard cubic feet per barrel of SBO (SCF H2/bbl SBO) as those units are commonly used by refiners.

The RFS2 estimates are slightly lower than for GREET1_2022, but the overall impact of this component of the LCA is relatively small. Table 4-9 also shows the 100-year global warming potentials for CH4 and N2O, which changed between RFS2 (based on IPCC AR2 values) and GREET1_2022 (IPCC AR6 values). The emission factors shown here for both the RFS and GREET are for light-duty passenger cars.

Table 4-9. Renewable Diesel Transport & Distribution and Fuel Combustion

Model Inputs	RFS2	CORSIA	GREET1_2022	GHGenius
Renewable Diesel Transport & Distribution				
Transport Distance (mi)	Unclear for RD; Values available for BD			
Rail (% by mode)			29%	
Rail (miles)			800	
Barge (% by mode)			8%	
Barge (miles)			520	
Heavy-Duty Diesel Truck (% by mode)			63%	
Heavy-Duty Diesel Truck (miles)			50	
Local HD Truck (% by mode)			100%	
Local HD Truck (miles)			30	
RFS2 Transport Emissions (gCO_2e/MJ)	0.76		--	
Tailpipe CH_4 and N_2O Emissions				
Emissions (g/MJ)				
CH_4	0.0005		0.024	
N_2O	0.0021		0.00018	
100-Year Global Warming Potential				
CH_4	21		29.8	
N_2O	310		273	
GHG Emissions (gCO_2e/MJ)	**0.66**		**0.78**	

4.3.4 SBO Renewable Diesel GHG Results and Discussion

4.3.4.1 GHG Results for Baseline Configurations of RFS2, CORSIA, GHGenius, and GREET1_2022

Table 4-10 compares the SBO fuel pathway lifecycle GHG results for the models analyzed in this section of the report, which include RFS2, CORSIA, GHGenius, and GREET1_2022. The GHGenius estimates are for SBO-based biodiesel and the CORSIA estimates are for SBO-based renewable jet. While the fuel conversion processes differ between biodiesel, renewable diesel, and renewable jet, the comparison still illustrates the key differences in the modeling systems. The differences across models are primarily related to differences in land use change and treatment of co-products. A summary of the main components in the modeling is below. GHGenius assigns 82,720 g CO_2e/GJ, HHV to the soybean meal co-product, which is the dominant factor in the fuel calculation.

Feedstock Production and Transport is nearly double for GREET1_2022 compared to RFS2 when looking at the overall numbers. However, there are many differences in the two modeling approaches, which give very different results. GREET1_2022 only accounts for soybean farming, oil extraction, and oil transport. On the other hand, RFS2 includes the impact that increased soybean use for fuel is expected to have on reducing livestock production and rice farming, both of which result in large decreases in methane emissions. There are also differences in how emissions are allocated between soybean oil (SBO) and soybean meal (SBM) in the models. For example, based on the SBO extraction (crushing plant) inputs in Table 4-7, one would expect higher GHG emissions associated with the GREET1_2022 modeling. However, the GREET1_2022 value is 74% lower than the RFS2 estimate. The mass-based approach allocates emissions between SBO and SBM in the GREET model. Because the mass split between the two is about 20% SBO and 80% SBM, GHG emissions are allocated with a 20/80 split. When that is accounted for, the extraction/processing emissions are much better aligned across the models.

The GHGenius modeling of this portion is fundamentally different from the two models discussed above, and at first glance appears much higher. Soybean co-products, such as soymeal, are treated within the feedstock portion of the model for RFS2 and GREET1_2022. GHGenius, on the other hand, accounts for soybean co-products, as well as any other co-products, at the back end of the calculation. This displacement method results in the default credits slightly exceeding the total feedstock production and transport emissions. This phenomenon is a key contributor to the much lower biodiesel/RD scores in GHGenius. As a direct result, certified values for these fuels are much lower in the BC LCFS program.[59]

Table 4-10. Lifecycle GHG Emissions for Soybean Oil Pathways – Baseline Values

	Default Soy Bean Oil Fuel Carbon Intensity (gCO_2e/MJ)			
Lifecycle Component	**EPA RFS2 Max Diesel**	**GREET1_2022**	**CORSIA Jet**	**GHGenius**
Fuel	**Diesel**	**Diesel**	**Jet**	**Biodiesel**
SBO Production				
Farming/Field Emissions	5.29	1.52	17.90	
Fertilizers/Herbicides/Pesticides		7.21		6.49
Soybean Transportation	--	0.42	1.10	
Extraction/Processing	13.21	3.45	7.30	10.98
Soy Oil Transport	--	0.47	0.70	2.14
Domestic Livestock/Rice Methane	-9.46	--		
International Livestock/Rice Methane	-4.09	--		
Feedstock & Co-Product Transport	2.55	--		
Total Feedstock Production/Transport	**7.50**	**13.07**	**27.00**	**19.61**
Land Use Change/ Soil Carbon	**32.5**	**9.20**	**24.5**	**80.8**
Soybean Oil Hydrotreating				
Hydrogen	--	7.91	14.00	
Electricity	0.93	1.16		11.42
Natural Gas/Fuel Gas	10.33	1.18		12.41
Other Processing Inputs	--	--		0.00
Total SBO Refining to RD	**11.25**	**10.24**	**14.00**	**23.83**
Co-Product Credits				
Renewable Propane/LPG	-4.68	Hybrid Mass Allocation	Energy Allocation	
Renewable Naphtha	-2.10			
Total Co-Product Credits	**-6.78**			**-105.04**
RD Transportation/Distribution	**0.76**	**0.39**	**0.50**	**1.45**
Tailpipe Emissions	**0.66**	**0.78**	**0.00**	**1.86**
Total Carbon Intensity	**45.9**	**33.7**	**66.0**	**22.5**

GHGenius does not model soy-based RD by default, and biodiesel is shown. Biodiesel uses methanol as an input instead of hydrogen.

Renewable Diesel Production: A comparison of renewable diesel production estimates reveals that the RFS2 and GREET1_2022 models yield similar results. The RFS2 model predicts a value of 11.25 gCO_2e/MJ, while the GREET1_2022 model estimates it to be slightly lower at 10.24 gCO_2e/MJ.

[59] See https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/transportation/renewable-low-carbon-fuels/rlcf012_-_approved_carbon_intensities_-_current_04aug2023.pdf for current scores.

Interestingly, both models converge on an electricity consumption estimate of approximately 1 gCO_2e/MJ. However, when it comes to combined hydrogen and natural gas emissions, the RFS2 projections surpass those of GREET1_2020 by around 1 gCO_2e/MJ, which corresponds to about 8% of the renewable diesel processing facility emissions. This disparity indicates that there may be additional factors influencing these emission levels in each respective model.

Co-Product Credits for renewable naphtha and renewable propane are treated with a displacement method in RFS2 (i.e., renewable naphtha is assumed to displace fossil gasoline and renewable propane is assumed to displace fossil natural gas). This results in a fairly sizable credit for these co-products, which could lead to a gearing situation if larger amounts of naphtha are co-produced. Gearing occurs when a large quantity of co-products drive the carbon intensity lower. A classic example is a waste biomass to ethanol facility, which burns lignin for process heat and co-produces electric power. In an LCA system that provides a substitution credit for the export power, the CI can become negative as less ethanol is produced while the kWh export power increases. Gearing is a concern among regulators for fuel pathways that have not been examined extensively. GREET1_2022 allocates these co-products outside of the GREET model in a data aggregation step. However, in effect, they are treated with energy allocation as the renewable naphtha energy is captured in renewable diesel, and renewable propane is treated as the co-product. CH_4 and N_2O emissions from fuel gas combustion are not explicitly part of the GREET calculations.

The GHGenius modeling of this portion is fundamentally different from the two models as discussed above. GHGenius includes both fuel production co-products and soybean co-products as co-product credits. These credits are very large and cause the overall GHGenius results to be much lower for soy-based fuels.

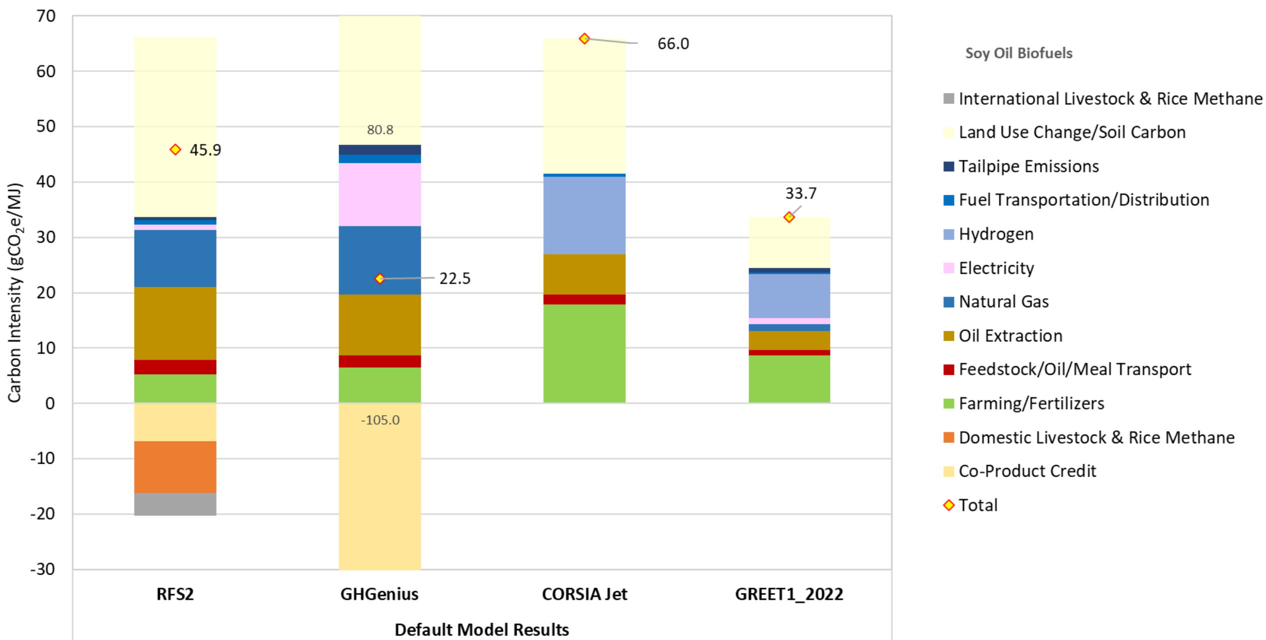
Renewable Diesel Transportation/Distribution: According to the RFS2 estimates, there is a significant increase in emissions from Renewable Diesel Transportation/Distribution compared to GREET1_2022. Nevertheless, it should be noted that the impact of this particular aspect on the total lifecycle greenhouse gas (GHG) emissions remains relatively minor.

Tailpipe GHG Emissions: According to the RFS documentation, there is a similarity in tailpipe greenhouse gas (GHG) emissions between RFS2 and GREET1_2022. However, these specific aspects of lifecycle modeling only make a minor contribution to the overall GHG emissions for this particular fuel pathway.

Land Use Change estimates are much higher for RFS2, which is based on FASOM and FAPRI, than for GREET1_2022, which is derived from the CCLUB factors with GTAP. GHGenius does not consider indirect land use change, but soil carbon loss is a significant source of emissions, which is offset by the co-product credit for displaced soybean meal.

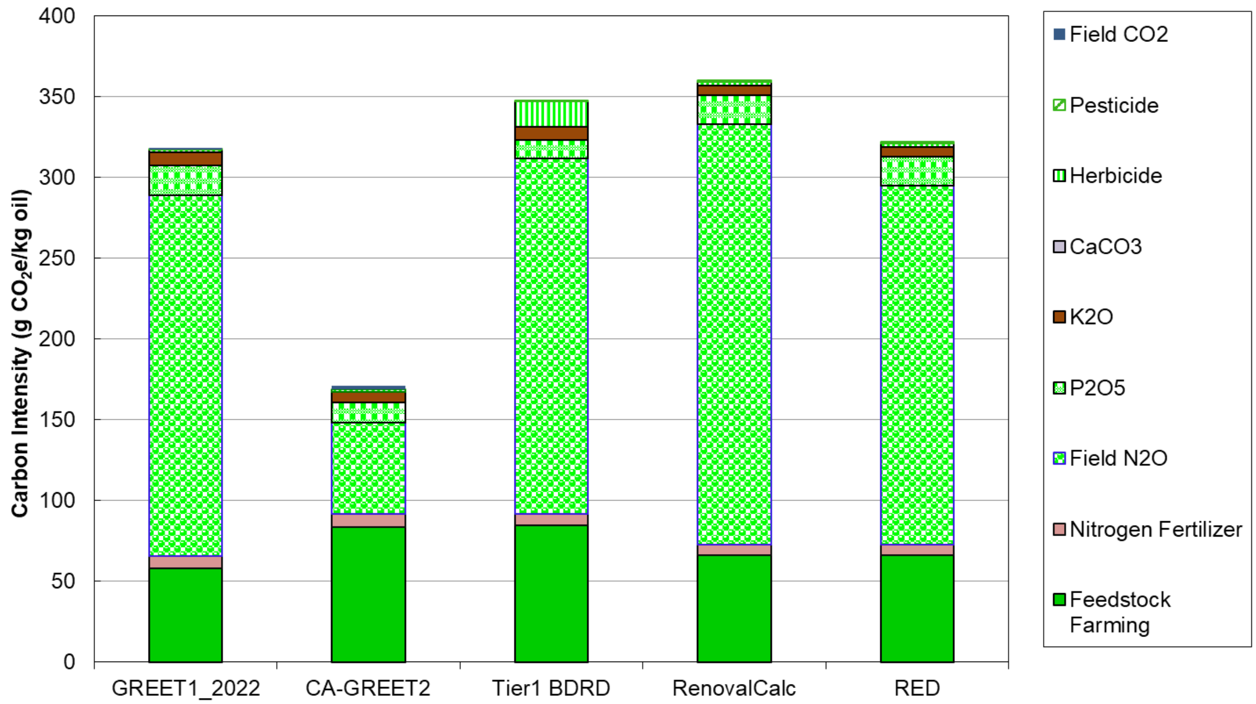
Figure 4-10 shows the baseline values for each of the SBO modeling systems with their baseline inputs. The figure shows the key differences in the analysis. The indirect effects and soil carbon impacts in the RFS, GHGenius, and CORSIA analyses result in substantial soil carbon release due to farming or the indirect effects of farming. These emissions are somewhat offset with co-product impacts in the RFS2 and GHGenius. The indirect effects are combined into a single ILUC value for CORSIA and GREET. The ILUC values are lower for GREET. The RFS approach assigns all farming emissions to renewable diesel with a credit for the displaced products. Therefore, all of the oil extraction emissions are assigned to the fuel product, in contrast to the CORSIA and GREET approach, where these emissions are allocated to renewable diesel and soybean meal.

Figure 4-10. GHG Emissions for Soy Oil Pathways – Baseline Values



The modeling systems result in somewhat different emissions for soybean farming based primarily on fertilizer inputs and the treatment of field emissions of N2O and CO2 from fertlizer as shown in Figure 4-11. Most notably, the N2O emissions applied in earlier versions of GREET and CA-GREET2.0 did not include N2O from the soybean nodules as these were of biogenic origin. However, the emissions are related to crop production and have been included in subsequent versions of GREET and other LCA models. The higher GHG emissions in other modeling systems correspond to nitrogen in biomass, which includes the soybean nodules. This change is reflected in GREET1_2016, which is the basis for emission factors in the CARB Tier1 SFE calculator. Other differences in LCA models include variations in upstream lifecycle emission factors for fertilizers and CO2 release factors for carbon in urea. The RFS predicts effects such as changes in rice methane, which are primarily due to predicted changes in rice cultivation.

Figure 4-11. GHG Emissions for Soybean Farming



4.3.4.2 SBO-Based Renewable Diesel GHG Results Based on Common GREET Inputs

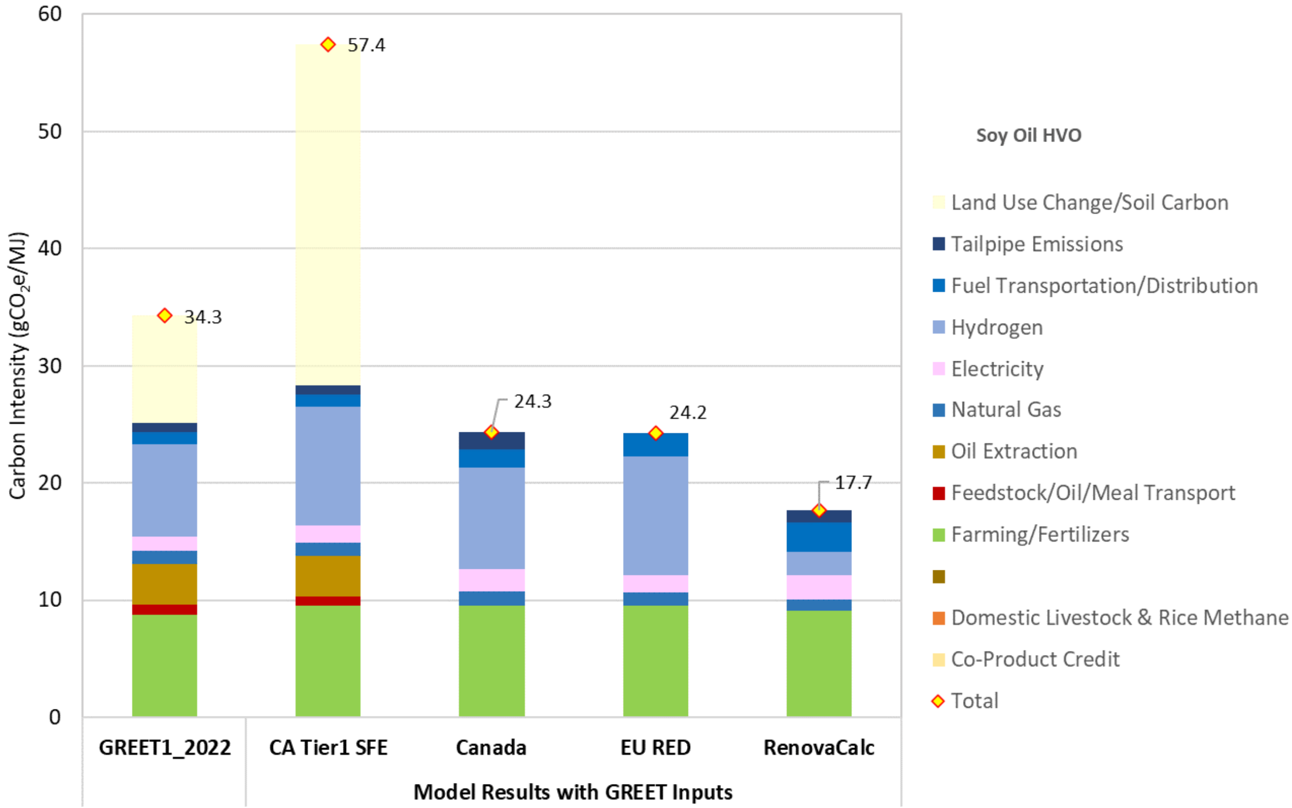
Table 4-11 and Figure 4-12 present the GHG analysis for GREET1_2022, Tier 1 Calculator, Canada CFR, EU RED, and RenovaCalc for the same set of GREET1_2022 based inputs summarized in Appendix A. The key differences between the GREET1_2022 results and the Tier 1 Calculator are ILUC and a smaller difference in the contribution of hydrogen. The difference in hydrogen impact is due to the allocation method and a slightly lower GHG footprint for SMR hydrogen in GREET1_2022 versus the Tier 1 Calculator. The farming emissions for Canada, EU RED, and RenovaCalc appear comparable to GREET, but they include oil extraction emissions. RenovaCalc also appears to have a lower emission factor for hydrogen than typical values for natural gas steam reformer-based hydrogen.

The results differ fairly dramatically between GREET1_2022 and the Canada CFR model. The largest difference between the models is the exclusion of ILUC within the Canada CFR model, accounting for about 85% of the overall CI delta. The Canada CFR model also assumes lower farming emissions than GREET1_2022 and greater hydrogen and electricity emission factors. Similar to the GHGenius model discussed above, the Canada CFR model also includes CO2 from lube oil within the tailpipe emissions.

Table 4-11. GHG Emissions for Soy Oil Renewable Diesel – GREET Inputs

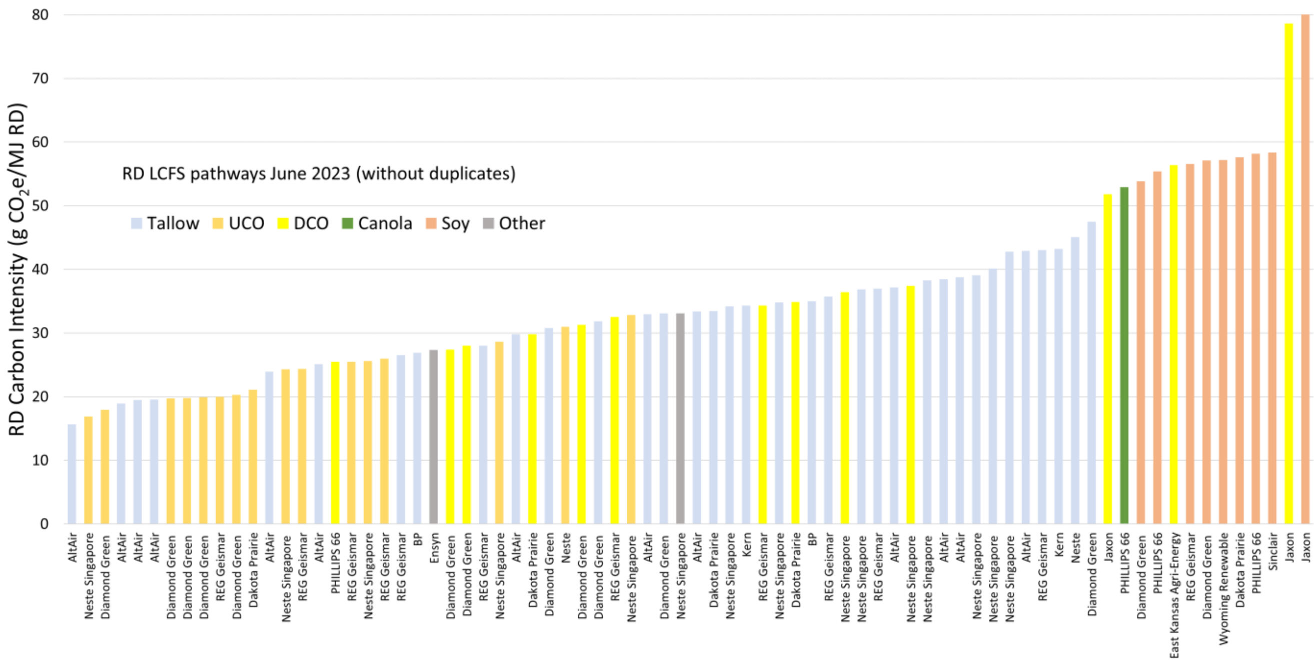
	Renewable Diesel Carbon Intensity (gCO_2e/MJ), GREET Inputs				
Lifecycle Component	**GREET1_2022**	**CA Tier1 BDRD**	**Canada**	**EU RED**	**RenovaCalc**
Fuel	**Diesel**	**Diesel**	**Diesel**	**Diesel**	**Diesel**
SBO Production					
Farming/Field Emissions	1.52	9.54			
Fertilizers/Herbicides/Pesticides	7.21				
Soybean Transportation	0.42	0.35			
Extraction/Processing	3.45	3.39			
Soy Oil Transport	0.47	0.47			
Domestic Livestock/Rice Methane	--				
International Livestock/Rice Methane	--				
Feedstock & Co-Product Transport	--				
Total Feedstock Production/Transport	**13.07**	**13.75**	**9.56**	**9.50**	**9.10**
Land Use Change/ Soil Carbon	**9.20**	**29.1**	**0.0**	**0.0**	**0.0**
Soybean Oil Hydrotreating					
Hydrogen	7.91	10.06	8.72	10.06	10.06
Electricity	1.16	1.50	1.88	1.50	2.0
Natural Gas/Fuel Gas	1.18	1.17	1.19	1.17	1.0
Other Processing Inputs	--		--	0.00	0
Total SBO Refining to RD	**10.24**	**12.73**	**11.79**	**12.73**	**13.06**
Co-Product Credits					
Renewable Propane/LPG	Process Level Allocation	Energy Allocation	Energy Allocation	Energy Allocation	Energy Allocation
Renewable Naphtha					
Total Co-Product Credits					
RD Transportation/Distribution	**1.00**	**1.09**	**1.50**	**2**	**2.5**
Tailpipe Emissions	**0.78**	**0.76**	**1.46**	**0**	**1.10**
Total Carbon Intensity	**34.3**	**57.4**	**24.3**	**24.2**	**25.8**

Figure 4-12. GHG Emissions for Soy Oil Renewable Diesel – GREET Inputs



As shown in Figure 2-1, soy renewable diesel pathways rank highest among the CI of fuels in the LCFS due to the higher iLUC emissions compared to other feedstocks. Most RD producers have registered pathways for a variety of feedstocks. All of the processing emissions are roughly the same for each producer, regardless of feedstock. Differences in CI among SBO pathways correspond to feedstock-to-fuel yield, processing energy, and transport logistics for feedstocks. Soy farming and crushing are the same per pound of oil. The tallow pathways are much more variable due to a wider range in transport logistics, as well as source-specified pathways that include actual rendering data.

Figure 4-13. Certified LCFS Renewable Diesel Pathways



4.4 CORSIA GHG Analysis for SBO Renewable Aviation Fuels

This section of the report presents additional details on the CORSIA-based analysis of SBO-based sustainable aviation fuel (SAF).

Background – The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is a program established by the United Nations International Civil Aviation Organization (ICAO) to reduce GHG emissions from the aviation sector. The goal of this program is to achieve carbon-neutral growth from 2020 via the use of offset credits. CORSIA eligible fuels (CEFs) can help aircraft operators reduce their offsetting obligation. A CEF must meet certain sustainability requirements, which includes a CO_2e reduction of at least 10% relative to the petroleum jet fuel baseline, which has been set at 89 gCO_2e/MJ on a "well-to-wake" basis. Within the CEF category is sustainable aviation fuel (SAF), which is a drop-in fuel made from biomass or waste resources.

For this analysis, we have presented CORSIA LCA results for soybean oil-based jet fuel and compared those to the soybean oil-based diesel results from GREET1_2022. This is an appropriate comparison, as the inputs to the LCA modeling for soybean cultivation, soybean oil extraction, and fuel production are very similar when hydrotreating soybean oil to produce jet fuel and diesel fuel.

Lifecycle Analysis – ICAO has published several documents on lifecycle analysis for jet fuels under the CORSIA framework. A methodology document is available that steps through the process of calculating WTW emissions for a specific fuel pathway.[60] In addition, default carbon intensity values have been

[60] International Civil Aviation Organization (ICAO). (2022, June). CORSIA methodology for calculating actual life cycle emissions values. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2007%20-%20Methodology%20for%20Actual%20Life%20Cycle%20Emissions%20-%20June%202022.pdf

established for a number of different feedstocks and production pathways,[61] with the details of those calculations provided in a separate report.[62]

Hydrotreating soybean oil to produce jet fuel, which falls within the hydro processed esters and fatty acids (HEFA) class of fuels within the CORSIA framework, qualifies as SAF as it has a default WTW carbon intensity of 64.9 gCO_2e/MJ for U.S.-sourced soybeans and 67.4 gCO_2e/MJ for Brazil-sourced soybeans. This includes a "core" LCA value of 40.4 gCO_2e/MJ and ILUC values of 24.5 gCO_2e/MJ for the U.S. case and 27.0 gCO2e/MJ for the Brazil case. The default core LCA values for SBO-based jet fuel, reported by LCA component and region, are summarized in Table 4-12. Several items are worth noting with respect to these results:

- The core LCA value of 40.4 gCO_2e/MJ is the midpoint of four different modeling results based on energy allocation. They use a variety of inputs and models (a low of 37.7 gCO_2e/MJ and a high of 43 gCO_2e/MJ). These GREET core LCA is lower since more farming emissions are allocated to soybean meal mass.
- Fuel pathways are modeled for the U.S., the E.U., and Latin America.
- Two LCA modeling platforms are used: GREET and the JRC E3 database (E3db).
- Based on ICAO's documentation, there are differences in transportation assumptions between GREET and E3db, and E3db assumes the use of the NEXBTL HEFA conversion technology, while GREET assumes the use of Honeywell's UOP technology. These differences are reflected in the LCA results reported in Table 4-12.

Table 4-12. Default Core LCA Results for Soybean HEFA (gCO_2e/MJ) *

Data Source	Model	Cultivation	Feedstock Transport	Oil Extraction	Oil Transport	Fuel Production	Fuel Transport	Total*
US	GREET	8.6	1.1	7.3	0.7	14.0	0.5	32.2
EU BioGrace	GREET	17.9	1.1	3.7	0.7	13.8	0.5	37.7
Latin America	GREET	19.5	1	7.7	0.7	13.5	0.5	43.0
EU (JRC)	GREET	19.1	1.1	4.1	0.7	14.1	0.5	39.7
EU (JRC)	E3db	20.6	2.3	3.3	3.3	11.5	0.3	41.4

* Sum of components may not equal total because of rounding.

[61] International Civil Aviation Organization (ICAO). (2022, June). CORSIA default life cycle emissions values for CORSIA eligible fuels. International Civil Aviation Organization. Available at: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf

[62] International Civil Aviation Organization (ICAO). (2022, June). CORSIA eligible fuels – Life cycle assessment methodology (Version 5). Available at: https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA%20Eligible%20Fuels_LCA_Methodology_V5.pdf

The CORSIA methodology includes an ILUC value added to the core value of 40.4 gCO2e/MJ. Two ILUC models were used for the analysis: GTAP-BIO and GLOBIOM. Results were presented for soybeans grown in the U.S. and in Brazil as summarized in Table 4-13 below. The differences between GTAP-BIO and GLOBIOM are quite large. For fuel pathways where the GTAP-BIO and GLOBIOM results were within 8.9 gCO2e/MJ, a simple average of results was used as the default value. For cases where the GTAP-BIO and GLOBIOM results differed by more than 8.9 gCO2e/MJ, the "reconciled" (i.e., default) value is based on the lower value plus 4.45 gCO2e/MJ.

Table 4-13. Default Regional and Global ILUC Values (gCO_2e/MJ)

Soybean Region	ILUC Results		
	GTAP-BIO	GLOBIOM	Reconciled
U.S.	20.0	50.4	24.5
Brazil	22.5	119.9	27.0
Global	21.3	88.1	25.8

Table 4-14 compares the overall LCA results for the CORSIA (U.S. GREET analysis) SAF to the GREET1_2022 and GREET 40B model results for SBO-based diesel. Of note in Table 4-14 is the following:

- Cultivation, feedstock transport, and oil extraction are roughly double for CORSIA versus GREET1_2022 and 40B. That is a result of different methods of allocating emissions between soybean oil (SBO) and soybean meal (SBM). Under the CORSIA guidelines, co-products are treated with an energy allocation approach, whereas the default GREET1_2022 model uses mass to allocate emissions between SBO and SBM.
- Fuel production emissions are slightly higher for the CORSIA analysis versus GREET1_2022. That is a result of much higher natural gas consumption under the CORSIA analysis that more than offsets the lower hydrogen usage under the CORSIA analysis.
- The GREET1_2022 analysis includes combustion CH_4 and N_2O in the total, whereas the CORSIA analysis does not.
- The 40B calculator includes other ILUC categories based on an analysis of the RFS rice, livestock, and other ILUC factors.
- GHG emissions from ILUC are over 2.5 times higher in the CORSIA analysis versus the GREET1_2022 results for SBO-based diesel. The differences are due to the version of GTAP, the yield from SBO to fuel, the emission factors used to convert GTAP results to emissions, and the amount of biofuel shock assumed in the analysis.
- Overall, the CORSIA SBO HEFA lifecycle GHG results are nearly double those of SBO-based diesel from GREET1_2022 – 66.0 gCO_2e/MJ versus 33.7 gCO_2e/MJ.

Regarding the allocation method for cultivation, feedstock transport, and oil extraction, CORSIA implements an energy allocation approach. As a result, it exhibits approximately twice the level of emissions compared to GREET1_2022, which employs mass allocation between SBO and soybean meal (SBM). In terms of fuel production emissions, CORSIA demonstrates slightly higher figures due to its substantial consumption of natural gas, while exhibiting marginally lower hydrogen usage when contrasted with GREET1_2022.

Table 4-14. Comparison of CORSIA (US – GREET) SBO HEFA Results

LCA Component	SBO HEFA GHG Emissions (gCO_2e/MJ)		
	CORSIA Jet (US– GREET)	Diesel Default GREET1_2022	40B GREET Default GREET1_2023
Cultivation	17.9	8.7	9.2
Feedstock Transport	1.1	0.4	0.4**
Oil Extraction	7.3	3.4	3.4**
Oil Transport	0.7	0.5	0.5**
Fuel Production	14	10.2	10.5
Fuel Transport	0.5	0.4*	0.4**
"Core" LCA Value	41.5	24.5	23.9
ILUC	24.5	9.2	16.3
Total LCA Result	66.0	33.7	40.2

*Note that GREET1_2022 fuel transport emissions here are slightly lower than in Table 4-11 because of differing assumptions related to transport distance and mode.

** GREET value shown here to determine cultivation and fuel production by difference

4.5 Summary of Model Comparison

The results presented above demonstrate the sources of variability in GHG emissions among fuel pathways. The drivers for these differences result in significantly different GHG results depending upon the analysis methods of the modeling as well as specific inputs. The analysis presented above shows that:

- Impacts of land use change differ significantly between models, driving much of the difference in total GHG emissions associated with a fuel pathway.
- Allocation of emissions between primary product and co-products can also have a significant impact on the GHG results. In particular, the difference in accounting between mass-based allocation, energy-based allocation, and displacement can result in significantly different GHG results for the same fuel pathway.
- GHG emissions from the fuel processing step are similar across models for a given fuel pathway. This is not unexpected, as chemistry and thermodynamics drive those estimates, and they are not reliant on complicated agro-economic and land cover models as used in the land use change modeling.
- GHG emissions associated with finished fuel transportation/distribution result in significant variability when the analysis rules apply default values for transport or introduce an empty backhaul. These emissions can range from 1 to 4 g CO_2e/MJ, depending on the transport distance.
- Fuel combustion makes up a small portion of the overall net GHG emissions associated with biofuel pathways. While this category has a large variability among modeling systems, the overall effect is less than 1% of a fuel's CI.
- Other factors contribute to differences in GHG emissions, but their effect on the outcome is relatively small.

The comparisons presented in this section illustrate the differences in the calculation of GHG emissions for feedstock, fuel production, and fuel combustion components of the lifecycle of fuels. Since the results are compared on a well-to-tank basis, no effect of fuel efficiency is examined here. The primary differences correspond to:

- Land Use Emissions
- Agricultural Inputs
- Transport Logistics
- Fossil Fuel Upstream Lifecycle
- Allocation Method
- Global Warming Potential

The following sections summarize the key differences in LCA models and the assumptions in GHG analysis frameworks.

4.5.1 Standard Values

Several key parameters are predetermined within the GHG frameworks and are generally unique to a particular GHG framework. These include indirect land use change, standard values for transport ranging from distance to grain elevator to international marine transport. The following parameters are fixed components of LCA models that generally differ among the frameworks examined here.

- Indirect Land Use Change is a fixed value for every feedstock/fuel combination or zero. This value does not depend on user model input even though feedstock to fuel and co-product yields may vary by 1% to 5%.
- All values in GREET1_2022 are potential user inputs. However, many transport components have been set as standard values in the Tier 1 Calculator and RenovaCalc. These include feedstock to grain elevators and fuel transport and distribution.
- The Tier 1 Calculator applies a 1% moisture to corn oil co-products to reduce the effect on the credit and avoid data requirements for verification.
- All farming emissions are standard values in the Tier 1 Calculator, whereas these are required user inputs for EU RED and RenovaCalc. Other GHG policy frameworks allow the use of the default values in the models for GHG certification.
- Tailpipe emissions corresponding to CH_4 and N_2O are uniquely different in all the modeling systems.

4.5.2 Land Use Emissions

Land use emissions span the range from zero to over 30 g CO2e/MJ based on the modeling framework.

- Indirect Land Use Change model input
  - EPA RFS, GREET, and California Tier 1 Calculator have external ILUC calculations. These emissions are independent of the model users' feedstock to fuel yield.
- ILUC proportional to processing yield
  - LCFS uses constant ILUC factor for each feedstock regardless of feedstock to fuel yield
  - 40B calculator
- Soil carbon release calculation
  - GHGenius includes internal soil carbon release calculation that is on the order of magnitude of land use conversion emissions in the models that have an ILUC component.
- Soil carbon storage credit

- GREET and the EU RED provide an opportunity for the calculation of GHG savings associated with climate smart agriculture. The model inputs are implemented in the GREET FD-CIC calculator. The BioGrace model, which was used for RED-I, also provides a template for soil carbon accumulation credit calculations.

► No indirect land use emissions
  - GHGenius (built into displacement effect), Canada CFR, EU RED, and RenovaCalc include zero iLUC emissions. The programs exclude high iLUC risk feedstocks which are defined in each program.

4.5.3 Agriculture Inputs

► Upstream LCI for fertilizer
  - The sources of upstream lifecycle data differ among the modeling systems partially due to differences in the GHG intensity of natural gas. GHG emissions associated with Mono-Ammonium Phosphate (MAP) and Di-Ammonium Phosphate (DAP) fertilizers that provide both nitrogen and phosphate result in the largest differences among fertilizer types. However, the net effect on total agriculture emissions is small.

► N_2O conversion rate from applied nitrogen
  - Nitrogen conversion from chemical fertilizer ranges within 20% of the IPCC factor used in GREET.

► Conversion of carbon in limestone and urea to CO_2 in the field
  - The conversion of carbon in limestone and urea after field application ranges from 50% to 100% among modeling systems.

► Farming Energy
  - Data inputs for farming energy in GREET and GHGenius vary over time, presumably due to improved farming efficiency. The primary data are not as well documented as fertilizer application rates. For RED and RenovaCalc, farming inputs are required data.

► Fertilizer Application Rate
  - Fertilizer application rate data and yields are available from USDA, and these provide the basis for GREET and GHGenius inputs.
  - Fertilizer application data are required inputs for RED and RenovaCalc.

4.5.4 Fossil Fuel and Electricity Upstream Lifecycle

Sources of upstream lifecycle data vary considerably among modeling systems. The key sources include internal calculations in GREET and GHGenius, EcoInvent data for RenovaCalc, similar database values for Canada CFR, and ISCC 205 emission factors for EU RED. Factors affecting the variability in emissions include:

► Natural gas upstream emissions including methane leakage rates
► Upstream LCI for crude oil extraction
► Upstream LCI for crude oil refining to multiple products
► Hydrogen carbon intensity, which is highly dependent on natural gas carbon intensity for SMR-based hydrogen production
► Carbon factor for fuel combustion based on fuel composition and density
► Allocation of emissions in oil refineries between diesel, gasoline, and other products

4.5.5 Database Models versus System Models

Database models obtain upstream data through a collaboration of prior studies and research from the database developers. The documentation is generally only available when the models are licensed, and the level of detail of documentation varies among the products.

In the case of GREET and GHGenius, the upstream LCI data for all fertilizers are calculated internally within the model. The primary starting points are energy inputs per pound or ton of fertilizer. The documentation for these inputs is available over the evolution of updates and research papers from ANL.

4.5.6 Transport Parameters

Transportation parameters determined by the modeling frameworks can have a significant effect on total GHG emissions for some transport modes. The key inputs are:

- Empty back-haul
- Standard value assumptions for feedstock transport
- Standard value for fuel delivery
- Election of model assumptions in standard values

Both the California Tier 1 Calculator and RenovaCalc assume empty backhauls for all transport modes, while the EU RED allows the use of actual fuel transport data for marine vessels. All of the modeling systems have somewhat consistent assumptions on transport emissions though marine vessel capacity has a significant effect on the emissions for overseas fuel delivery.

4.5.7 Allocation Method

Allocation methods vary among the frameworks analyzed here. The RFS applies the more complex consequential analysis to assess the use of feedstock and impact of co-products. GREET and GHGenius apply a co-product allocation method and the energy content of co-products reduces the emissions of farming and fuel production for RED and RenovaCalc. The key inputs include:

Corn Ethanol Allocation Methods
- Distillers' grains: Substitution or energy allocation
- Animal feed: Credit for DGS feeding
- Corn oil: Substitution or energy allocation

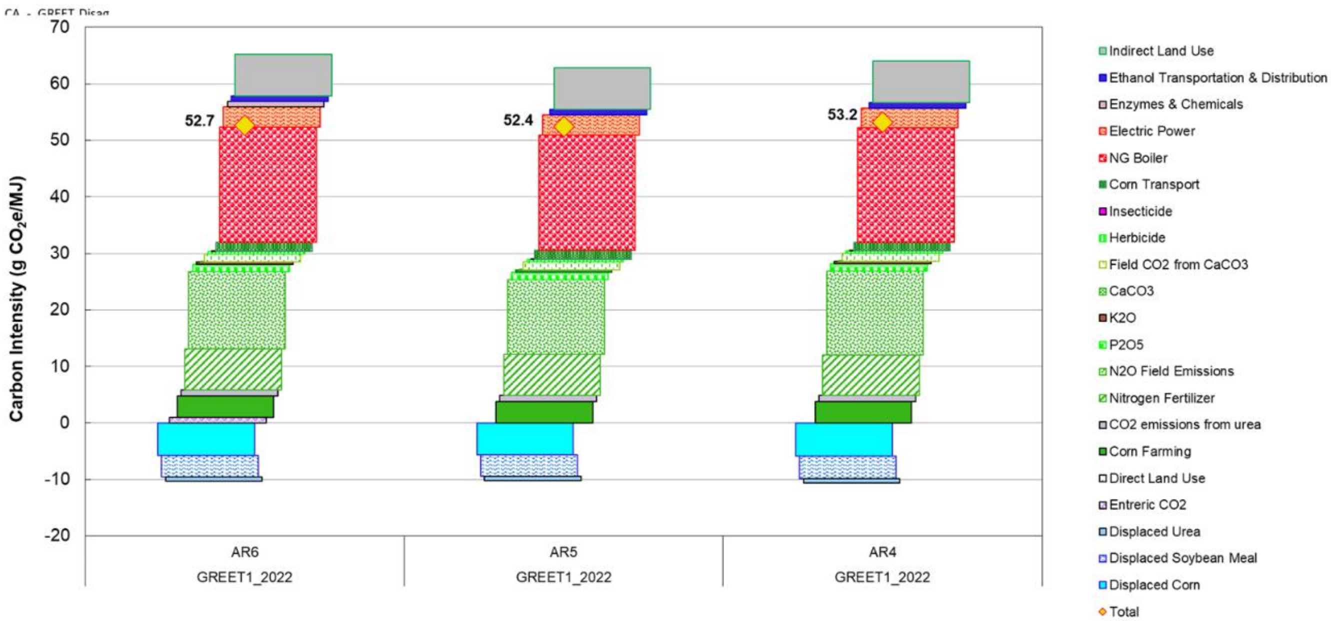
Soy Renewable Diesel Allocation Methods
- Soybean meal: Substitution, mass, or energy allocation
- Soy oil extraction: Mass or energy allocation
- Renewable diesel: Energy allocation to diesel, jet, and naphtha

4.5.8 Global Warming Potential

The GWP of GHG species includes the warming effect of CH_4 and N_2O, as well as VOC and CO emissions. The GHG frameworks have identified GWP factors that were generally adopted at the time rulemakings for low carbon fuel programs. The GWP for CH_4 has increased over recent assessments while AR4 has the highest GWP for N_2O. The net effect on fuel pathways depends on the relative contribution of natural gas as a process fuel and nitrogen application and related N_2O emissions. While these values have varied +/- 10 to 20%, the net effect on the corn ethanol pathway shown in Figure 4-14 is less than 1% of the overall CI.

Other variations in GWP are less well known. For example, an interpretation of the IPCC guidelines implemented in the RED indicates that CO_2 is the only carbon emission counted as a greenhouse gas which differs from the approach of assuming that fully oxidized VOC and CO are also counted as GHG emissions. This choice provides an odd incentive of incomplete combustion; however, the value of fuel and concern over criteria pollutants do not drive operations to achieve more CO and less CO_2. The GREET GWP approach has been incorporated into the EF3.1 impact assessment methodology that is used for environmental product footprint assessments in Europe[63].

Figure 4-14. Effect of GWP on GREET Corn Ethanol



4.5.9 Sensitivity Analysis

Variability to key inputs to the GHG calculations affect the CI of different fuel pathways. The effect depends on the feedstock type, as well as the process configuration. For example, fuel pathways that use natural gas as a process fuel or feedstock for hydrogen are affected by the CI of natural gas fuel, which depends on leak rate assumptions. Similarly, pathways with long transport distances are affected by the inclusion of an empty backhaul.

4.5.9.1 Corn Ethanol Variability

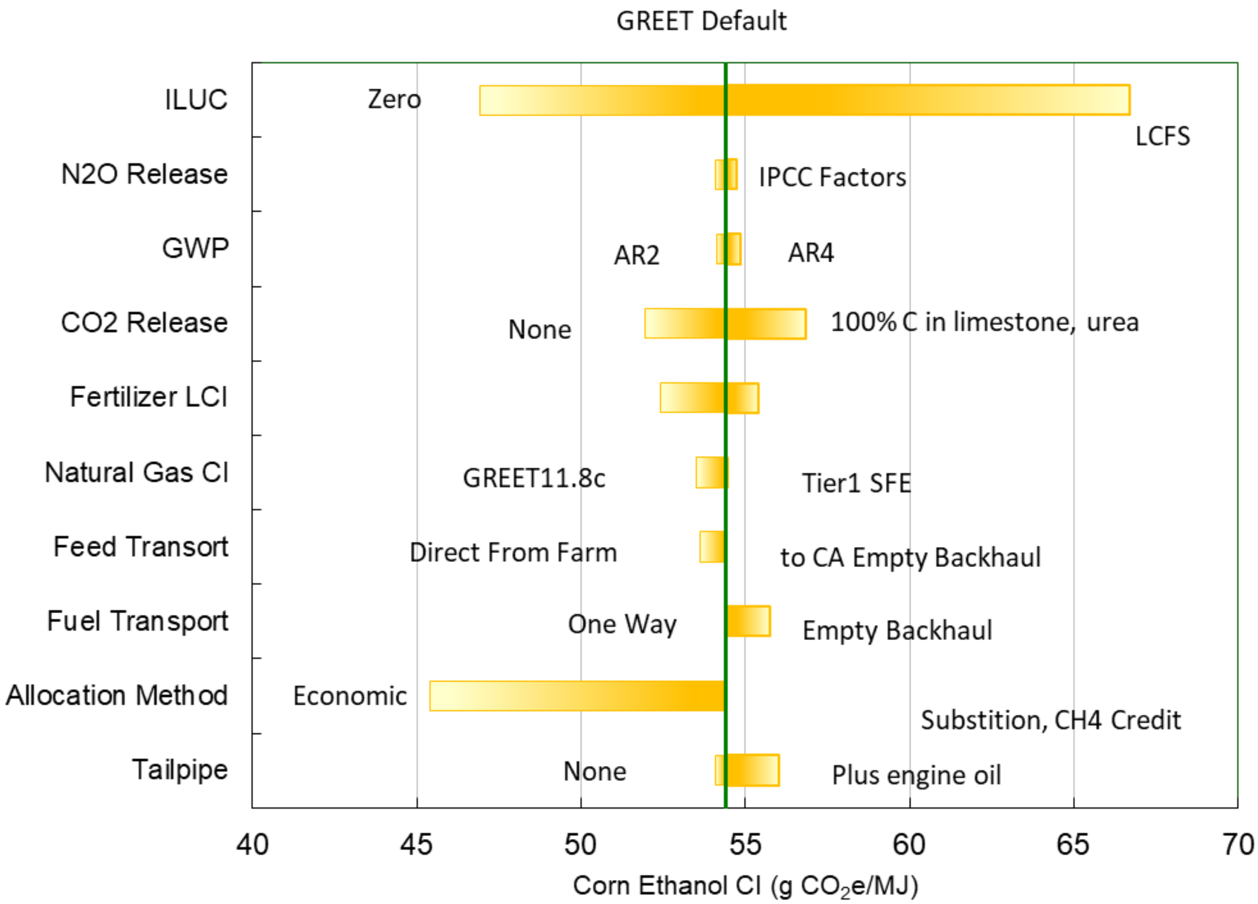
The effect of key inputs and GHG emissions for the corn ethanol pathway are shown in Figure 4-15, relative to the GREET1_2022 results with a consistent set of data inputs. The variability shown here is due only to the model differences. The central line represents the GREET1_2022 result from Table 4-6 with the effect of key assumptions identified. The largest differences are due to decisions embedded in the policy framework. iLUC is the most prominent factor. However, this component also has many subcomponents.

The treatment of carbon in fertilizer components has a significant variability, as the accounting for these emissions may be zero, depending on the GHG guidance or the entire release rate as calculated under RenovaCalc. Other variables are clearly the result of calculation rules. They include counting backhauls as part of fuel transport, as well as lubricating oil emissions in the total lifecycle. The choice of energy

[63] https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html

allocation assigns more emissions from corn farming, natural gas, and electric power to DGS than does a displacement credit.

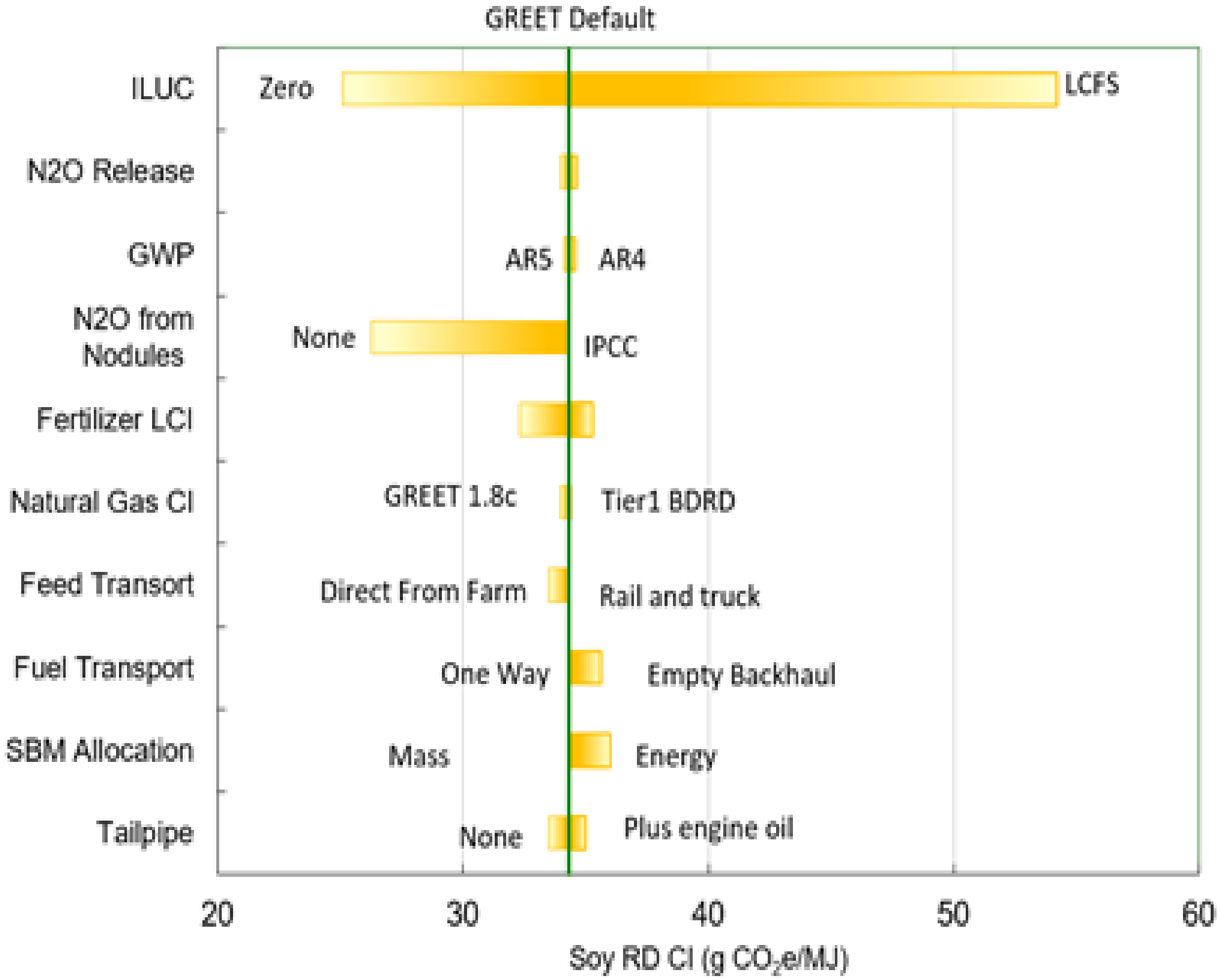
Figure 4-15. Sensitivity Analysis of Key Factors Affecting Corn Ethanol



4.5.9.2 SBO Renewable Diesel Variability

The effect of key inputs and GHG emissions for the SBO renewable diesel pathway are shown in Figure 4-16, relative to the GREET1_2022 results with a consistent set of data inputs. The variability shown here is due only to the model differences. The central line represents the GREET1_2022 result from Table 4-11 with the effect of key assumptions identified. The largest differences are due to decisions embedded in the policy framework. iLUC is the most prominent factor. However, this component also has many subcomponents. Fossil fuels reflect a smaller contribution to the fuel pathway than corn ethanol. The largest variability is associated with the treatment of N_2O emissions and ILUC. Differences in mass and energy allocation are distinguishing factors affecting GREET and CORSIA results as more emissions are allocated to soybean meal mass than energy.

Figure 4-16. Sensitivity Analysis of Key Factors Affecting Soy Renewable Diesel



5. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

Given the widespread interest in the assessment and reduction of the GHG emissions/CI of transportation fuels, a number of regulatory programs and LCA methodologies have been developed. While the basic approaches used in LCA of GHG emissions from transportations fuels are generally similar, the LCA methodologies that are incorporated into these regulatory programs can yield substantially different results for a given biofuel produced using a specific pathway.

This study involved a detailed analysis of the LCA methodologies used in the most significant regulatory programs targeting GHG reductions from transportation fuels focused on identifying the sources of differences in CI results. These differences arise from the use of different and distinct approaches and assumptions in the various LCA methodologies, including differences in system boundaries, allocation methods, temporal and geographical considerations, assessments of fuel production processes, and data sources. These factors create significant differences in the estimated CI values for specific biofuels and production pathways across the different LCA methodologies.

The choice of system boundaries in terms of the consideration of LUC plays an essential role as it determines whether all stages or only specific phases of a biofuel's lifecycle GHG emissions are considered. Likewise, employing different allocation methods, such as economic, energy, or mass-based approaches, can lead to varied GHG emissions estimates for co-products, which impact resulting biofuel CI values. Temporal factors, such as location-specific emission factors and technology lifespans, introduce additional variability. Additional differences result from varying approaches to quantifying GHG emissions with fuel production pathways and reliance on diverse databases for input data, some of which are proprietary.

Overall, it was found that even when estimating emissions from the same biofuel production pathway, there are substantial variations in LCA results observed from the different LCA methodologies examined in this study. To put the magnitude of these variations into perspective, CI values for dry mill corn ethanol derived using default LCA inputs for those methodologies where they are available ranged from about 53 to 75 gCO_2e/MJ. Using GREET1_2022 inputs for dry mill corn ethanol, the CI values obtained from the different LCA methodologies ranged from about 38 to 69 gCO_2e/MJ when iLUC is taken into account. The range narrows to 33 to 49 gCO_2e/MJ when iLUC is excluded. Similar results were observed for the soybean oil-based renewable diesel pathway, where the range of CI values observed using default values was about 22 to 66 gCO_2e/MJ. Using GREET1_2022 inputs, CI values ranged from about 18 to 57 gCO_2e/MJ when iLUC is taken into account. This range narrows to about 18 to 28 gCO_2e/MJ when iLUC is excluded.

Although assessment of the implications of these types of variations in CI values for the same fuels across the various regulatory programs and associated LCA methodologies considered was outside the scope of this study, the observed level of variability clearly highlights the need for more consistent, more transparent, and more thoroughly documented LCA methodologies. Based on this, it is recommended that future studies in this area focus on attempting to achieve consensus on how LCA methodologies are structured, as well as on the assumptions and input data, so that they can be embraced by all of the regulatory bodies seeking to reduce the GHG emissions associated with transportation fuels.

Appendix Table A-1. Corn Farming Inputs on Monthly and Application Rate Basis

	GREET Units			RenovaCalc Units	
Fuel Inputs (Corn Basis)	Btu/bu	Tractor	Stationary Engine	L/tonne Corn	
Total Energy	8,833				
Diesel	5,200	80.0%	20.0%	6.05	
Gasoline	802	100.0%	0.0%	1.03	
Natural gas	479	0.0%	100.0%	0.54	Nm^3/tonne
Renewable Natural gas	0	0.0%	0.0%	0.00	Nm^3/tonne
LPG	1,026	0.0%	100.0%	1.84	
Yield (bu/acre), 15.5% Moisture	178.4				

Electricity Input	kWh/bu	Btu/bu	kWh/tonne Corn
Electricity	0.389	1,325.9	15.3
Corn grinding	At EtOH Plant		

	Fertilizer Inputs	Input Basis	g/bu	kg/ha	kg/tonne corn
	Total N	N	401.5	390.2	15.8
31.0%	Ammonia (NH_3)	N	124.5	121.0	4.9
23.0%	Urea (NH_2CONH_2)	N	92.3	89.7	3.6
2.0%	Ammonium Nitrate (NH_4NO_3)	N	8.0	7.8	0.3
2.0%	Ammonium Sulfate (NH_4SO_4)	N	8.0	7.8	0.3
32.0%	Urea-Ammonium Nitrate Solution	N	128.5	124.9	5.1
4.0%	Monoammonium Phosphate	N	16.1	15.6	0.6
6.0%	Diammonium Phosphate	N	24.1	23.4	0.9
	Phosphate (PO_4)	P_2O_5	151	146.4	5.9
50.0%	Monoammonium Phosphate	P_2O_5	75	73.2	3.0
50.0%	Diammonium Phosphate	P_2O_5	75	73.2	3.0
	Potash	K_2O	152	148.1	6.0
	Limestone	$CaCO_3$	1,457	1,416.0	57.4

	Pesticide Inputs	g/bu	kg/tonne corn	kg/ha
	Herbicide	5.853		
31.2%	Atrazine	1.826	0.07	0.81
28.1%	Metolachlor	1.645	0.06	0.73
23.6%	Acetochlor	1.381	0.05	0.61
17.1%	Cyanazine	1.001	0.04	0.44
	Insecticide	0.012	0.00	0.01

Soil Emissions (g/bu corn)		N_2O	g CO_2
N in N_2O as % of N in N fertilizer	1.374%	8.67	641.1
N in N_2O as % of N in biomass	1.264%	2.81	
N content of ag system	141.6		
Urea in UAN (ton/ton)	1.09		
Ratio of Nutrient to Product for Fertilizer (Ure	46.70%		
		g N_2O/bu	g CO_2/bu
Urea		11.48	
Urea			247.88
Limestone	49.2%		315.40

Appendix Table A-2. Ethanol Plant Inputs on Monthly and Use Rate Basis

Fuel, Electricity Region	U.S. Average	GREET Units	T1 SFE Units	RED	RenovaCalc Units

Yields	Parameter	Units	Monthly Throughput		
					8,870
Ethanol yield	2.86	gal/bu	1,000,000	gal	349,200
DDGS yield	-4.61	dry lb/gal	2,305	ton 0% moisture	
Front End Corn Oil Extraction	0.00	dry lb/bu			
Back End Corn Oil Extraction	-0.27	dry lb/bu	273,400	lb, 0% moisture	

Thermal Energy Inputs	Parameter	Units			
Natural gas	22,480.24	Btu/gal, LHV	24,895	MMBtu, HHV	647,993
Coal	0.00	Btu/gal			

Electricity Input	Parameter	Units		
Baseline fuel plant	0.61	kWh/gal	614,872	kWh
CCS Power	150.00	kWh/tonne CO2		
CCS Efficiency	97.5%			

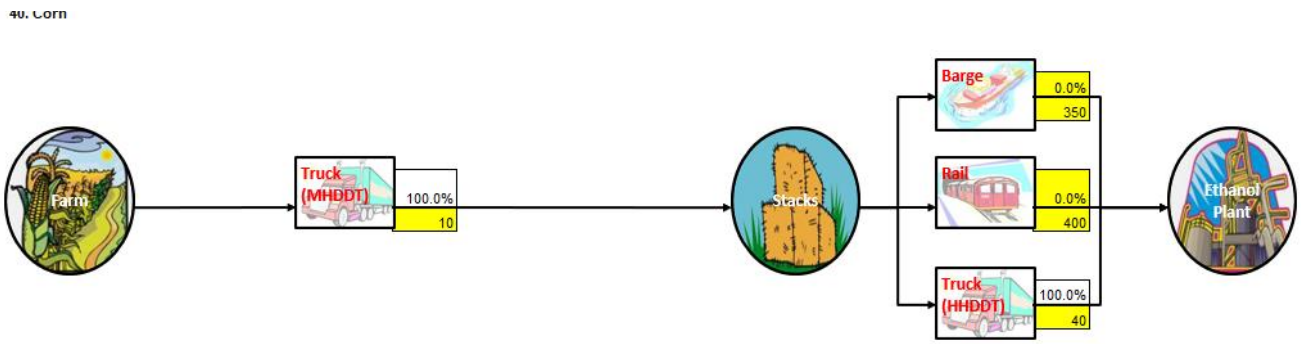
Enzymes and yeast	g/gal	ton	
Alpha Amylase	2.51	5,531	Standard Values in Tier1 SFE
Gluco Amylase	5.40	11,901	
Cellulase	0.00	0	
Yeast	2.74	6,034	
Sulfuric acid (H_2SO_4)	4.64	10,237	
Ammonia (NH_3)	17.79	39,222	
NaOH	22.31	49,196	
CaO	10.64	23,466	
Urea	0.00	0	

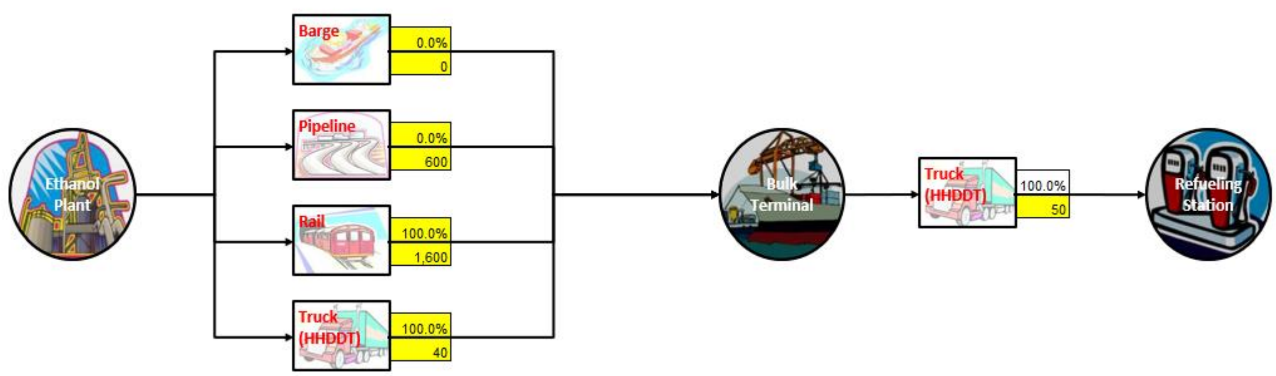
Products Displaced by DDGS	Displacement Ratio, lb/lb DGS
Feed corn	0.781
Soybean meal	0.307
N-urea	0.023

GREET1_2022 Results for Corn Ethanol

	Dry Milling Corn Ethanol w/ Corn Oil Extraction			
	Corn	**Ethanol**		
Loss factor		1.001		
Total energy	-304,250	1,244,044		
Fossil fuels	119,990	425,253		
Coal	2,979	24,856		
Natural gas	70,667	373,822		
Petroleum	46,343	26,575		
Water consumption	370.544	44		
VOC	4.799	55.679		
CO	20.415	22.879		
NOx	55.930	36.753		
PM10	3.164	13.123		
PM2.5	2.572	3.540		
SOx	14.935	6.804		
BC	0.468	0.231		
OC	0.374	0.697		
CH4	39.251	84.051		
N2O	38.987	0.787		
CO2	15,434	26,877		
CO2 (w/ C in VOC & CO)	15,481.3908	27,086		
GHGs	27,294.449	29,806.055		
	Feed x LF	**Fuel**	**Tailpipe**	**Total**
GHG (g/MJ)	25.88	28.25	0.33	**54.47**

Appendix Table A-3.





sdfdsfsfsd
Corn

Appendix Table A-4. Summary of Common Model Inputs for Corn Ethanol

Assumptions	
1. Ethanol produced via dry mill process with corn oil extraction.	
2. Natural gas used as process fuel.	
3. Inputs based largely on GREET1_2022.	
4. Ethanol plant assumed to be located in Midwest.	
5. Finished fuel transportation assumes Midwest to California via rail (1600 miles).	
6. Tailpipe CH4 and N2O emissions for GREET are below - use model-specific data if they exist.	
7. Emission factors built into the various models to be used for calculating carbon intensity.	
8. Not all of these inputs are applicable to all models.	
Proposed Model Inputs	**Input Value**
Domestic Corn Farming Agricultural Inputs	
Corn Yield (bu/acre)	178.4
Corn Farming Fuel Consumption (Btu/bu)	
Diesel	5,200
Gasoline	802
Natural Gas	479
LPG	1,026
Electricity	1,326
Fertilizer Inputs (g/bu)	
Nitrogen	401
P2O5	151
K2O	152
Limestone (CaCO3)	1,457
Herbicide & Pesticide Inputs (g/bu)	
Herbicides	5.9
Pesticides	0.7
Corn Transport to EtOH Plant (mi)	
Medium-Duty Diesel Truck	10
Heavy-Duty Diesel Truck	40
Corn Ethanol Production	
Product & Co-Product Yields	
Ethanol, Dry Mill (gal/bu)	2.86
Dry DGS (lb/bu)	13.2
Corn Oil (lb/bu)	0.27
DDGS Displacement (lb/lb DDGS)	
Feed corn	0.781
Soybean meal	0.307
N-urea	0.023
Natural Gas Consumption (BTU/gal EtOH)	
Dry DGS	22,480
Electricity Consumption (BTU/gal EtOH)	
Dry DGS	2,098
Other Processing Inputs & Chemical Use (g/gal)	
Enzymes and Yeast	10.6
Sulfuric acid (H2SO4)	4.6
Ammonia (NH3)	17.8
NaOH	22.3
CaO	10.6
Ethanol Transport & Distribution (miles)	
Rail to Storage in CA	1,600
Heavy-Duty Diesel Truck to Product Terminal	40
Heavy-Duty Diesel Truck - Fuel Distribution	50
Tailpipe CH4 and N2O Emissions - GREET Values Below	
Emissions (g/MJ)	
CH4	0.0032
N2O	0.0009

Appendix Table A-5. Soybean Farming Inputs on Monthly and Application Rate Basis

	GREET	ISCC	RenovaCalc
Energy Inputs	Btu/bu		L/tonne Soybean
Total Energy	13,723.7		
Diesel	9,352.5		10.16
Gasoline	2,064.7		2.48
Natural gas	176.4		0.19
Coal	0.0		0.00
Liquefied petroleum gas	662.0		1.11
Electricity	1,468.0		16.94
Yield per acre	50.60	bu/acre	60

	GREET	ISCC	RenovaCalc
Fertilizer	g/bu	kg/ha/y	kg/tonne soybean
Nitrogen Total	43.7	12.1	1.6
Ammonia (NH3)	13.6	3.7	0.5
Urea (NH2CONH2)	10.1	2.8	0.4
Ammonium Nitrate (NH4NO3)	0.9	0.2	0.0
Ammonia Sulfate ($(NH_4)2SO4$)	0.9	0.2	0.0
Urea-Ammonium Nitrate Solution	14.0	3.9	0.5
Monoammonium Phosphate	1.7	0.5	0.1
Diammonium Phosphate	2.6	0.7	0.1
P2O5 Total	207.8	57.3	7.6
Monoammonium Phosphate	103.9	28.6	3.8
Diammonium Phosphate	103.9	28.6	3.8
K2O Total	329.6	90.8	12.1
CaCO3	0.0	0.0	0.0
Herbicide	19.4	5.4	0.7
Atrazine	7.0	1.9	0.3
Metolachlor	12.4	3.4	0.5
Acetochlor	0.0	0.0	0.0
Cyanazine	0.0	0.0	0.0
Insecticide	0.281	0.078	0.010

Field Emissions	g/bu	kg/ha	kg/tonne soybean
CO_2 from urea use	27.0	7.442	0.992
N_2O from N-fertilizer	19.3	5.322	0.709
N content of above and below ground biomass: grams			557.000
N_2O emissions from N fixation: grams N_2O			7.300
N_2O emissions: N in N_2O as % of N in N fertilizer			1.37%
N_2O emissions: N in N_2O as % of N in Biomass			1.26%

GREET1_2022 Results for SBO Renewable Diesel

	Soy Oil-based Renewable Diesel II			
	Feedstock	**Fuel**		
Loss factor		1.000		
Unit	per mmBtu	per mmBtu		
Total energy	40,771	477,918		
Fossi lfuels	39,265	222,900		
Coal	5,449	30,165		
Natural gas	13,754	181,052		
Petroleum	20,062	11,683		
Water consumption	625.892	7.919		
VOC	1.562	18.918		
CO	8.080	8.435		
NOx	9.259	14.397		
PM10	0.936	0.922		
PM2.5	0.777	0.640		
SOx	5.147	7.003		
BC	0.277	0.062		
OC	0.146	0.178		
CH4	6.828	41.816		
N2O	22.808	0.331		
CO2	2,960	24,309		
CO2 (w/ C in VOC & CO)	2,978	24,381		
GHGs	9,227	25,723		
	Feed * LF	**Fuel**	**TTW**	**Total**
GHGs (g CO2e/MJ)	8.75	24.38	0.78	33.91

Appendix Table A-6. HVO Facility Inputs on Monthly and Use Rate Basis

Soy Farming

	GREET		RenovaCalc	
Energy Inputs	Btu/bu		L/tonne Soybean	
Diesel	9353		10.16	
Gasoline	2065		2.48	
Natural gas	176		0.19	Nm^3/tonne
Coal	0		0.00	Nm^3/tonne
Liquefied petroleum gas	662		1.11	
Electricity	1468			
Yield per acre	50.60	bu/acre	60 lb/soy bushel	
Fertilizer	g/bu	kg/ha	kg/tonne soybean	
Nitrogen	43.73	0.0	1.6	
P2O5	207.8	0.0	7.6	
K2O	329.6	0.0	12.1	
CaCO3	0.0	0.0	0.0	
		0.0	0.0	
		0.0	0.0	

	Fertilizer Inputs	Input Basis	g/bu	kg/ha	kg/tonne corn
	Total N	N	43.7	12.1	1.61
31.0%	Ammonia (NH_3)	N	13.6	3.7	0.50
23.0%	Urea (NH_2CONH_2)	N	10.1	2.8	0.37
2.0%	Ammonium Nitrate (NH_4NO	N	0.9	0.2	0.03
2.0%	Ammonium Sulfate (NH_4SC	N	0.9	0.2	0.03
32.0%	Urea-Ammonium Nitrate Sc	N	14.0	3.9	0.51
4.0%	Monoammonium Phosphate	N	1.7	0.5	0.06
6.0%	Diammonium Phosphate	N	2.6	0.7	0.10
	Phosphate (PO_4)	P_2O_5	207.8	57.3	7.6
50.0%	Monoammonium Phosphate	P_2O_5	104	28.6	3.8
50.0%	Diammonium Phosphate	P_2O_5	104	28.6	3.8
	Potash	K_2O	329.6	90.8	12.1
	Limestone	$CaCO_3$	0	0.0	0.0

Herbicide	19.4	5.36		0.714
Pesticide	0.3	0.08		0.010

Appendix Table A-7. Summary of Common Model Inputs for Soy Renewable Diesel

Assumptions	
1. Renewable diesel produced via hydrotreating soybean oil.	
2. Natural gas used for hydrogen production and as process fuel.	
3. Inputs based largely on GREET1_2022.	
4. Renewable diesel plant assumed to be located in Gulf Coast.	
5. Soybean oil transported by rail from Midwest to Gulf Coast (1000) miles.	
6. Finished fuel transportation assumes Gulf Coast to California via rail (1600 miles).	
7. Tailpipe CH4 and N2O emissions for GREET are below - use model-specific data if they exist.	
8. Emission factors built into the various models to be used for calculating carbon intensity.	
9. Not all of these inputs are applicable to all models.	
Proposed Model Inputs	**Input Value**
Domestic Soybean Farming Agricultural Inputs	
Soybean Yield (bu/acre)	50.6
Soybean Oil Yield (lb SBO/dry bu)	11.2
Soybean Farming Fuel Consumption (Btu/bu)	
Diesel	9,353
Gasoline	2,065
Natural Gas	176
LPG	662
Electricity	1,468
Fertilizer Inputs (g/bu)	
Nitrogen	44
P2O5	208
K2O	330
Herbicide & Pesticide Inputs (g/bu)	
Herbicides	19.4
Pesticides	0.3
Soybean Transport to Crushing Plant (mi)	
Medium-Duty Diesel Truck	10
Heavy-Duty Diesel Truck	40
Crushing Plant Fuel Consumption, Unallocated (Btu/lb SBO)	
Natural gas*	2,652
Electricity	372
n-Hexane (Petroleum-Based Solvent)	49
SBO to RD Plant Transport Distance by Mode	
Rail (miles)	1,000
Soybean Oil Hydrotreating	
Product Yields (lb/lb SBO or kg/kg SBO)	
Renewable Diesel	0.791
Jet Fuel	--
Naphtha	--
Propane/LPG	Captured in Fuel Gas
Hydrogen Consumption	
Native Units	BTU/lb RD
Model Value	2,071
Value in Common Units (SCF H2/BBL SBO)	**1,918**
Electricity Consumption	
Native Units	Btu/lb RD
Model Value	185.2
Value in Common Units (kWh/BBL SBO)	**14.2**
Natural Gas/Fuel Gas Consumption	
Native Units	Btu/lb RD
Model Value	352
Value in Common Units (Btu NG/BBL SBO)	**101,977**
Other Processing Inputs & Chemical Use	
Misc. Chemicals	--
Renewable Diesel Transport & Distribution	
Transport Distance (mi)	
Rail from Gulf Coast to CA	1,600
Heavy-Duty Diesel Truck - Fuel Distribution	50
Tailpipe CH4 and N2O Emissions	
Emissions (g/MJ)	
CH4	0.024
N2O	0.00018

Appendix Table A-8. Soy Oil HEFA Results from GREET Aviation Module

GREET Aviation Module

Input Parameters

Process Input Parameters

Farming (per bu soybean)	Type	User Defined	Default	Unit	Technology	Deactivate
Diesel		1870.5	1870.5	btu	Stationary Reciprocating Engine	
Diesel		7482.0	7482.0	btu	Off-road equipment	
Gasoline		2064.7	2064.7	btu	Off-road equipment	
Natural gas		176.4	176.4	btu	Stationary Reciprocating Engine	
LPG		662.0	662.0	btu	Commercial Boiler	
Electricity		1468.0	1468.0	btu		
Nitrogen fertilizer		43.7	43.7	g		
P2O5		207.8	207.8	g		
K2O		329.6	329.6	g		
Herbicides (Soybeans)		19.4	19.4	g		
Insecticide		0.3	0.3	g		
[Insert New Items]						
Extraction (per lb Soyoil)						
Soybean	Sourcing	0.1	0.1	bu soybean		
Residual oil		26.7	26.7	btu	Commercial Boiler	
Diesel		4.4	4.4	btu	Commercial Boiler	
Diesel		4.4	4.4	btu	Stationary Reciprocating Engine	
Diesel		4.5	4.5	btu	Large Gas Turbine	
Natural gas		861.7	861.7	btu	Large Industrial Boiler	
Natural gas		861.7	861.7	btu	Small Industrial Boiler	
Coal		848.4	848.4	btu	Commercial Boiler	
Electricity		371.8	371.8	btu		
N-hexane		49.2	49.2	btu		
Forest Residue		26.7	26.7	btu	Small Industrial Boiler	
Landfill Gas		6.6	6.6	btu	Large Industrial Boiler	
Landfill Gas		6.6	6.6	btu	Small Industrial Boiler	
VOC	Emission	1.2	1.2	g		
[Insert New Items]						
Production (per lb Renewable Jet fuel)						
Soyoil	Sourcing	1.4	1.4	lb		
Natural gas		1692.2	1692.2	btu	Large Industrial Boiler	
Natural gas		1692.2	1692.2	btu	Small Industrial Boiler	
Electricity		94.4	94.4	btu		
H2		2812.0	2812.0	btu	Process Use	

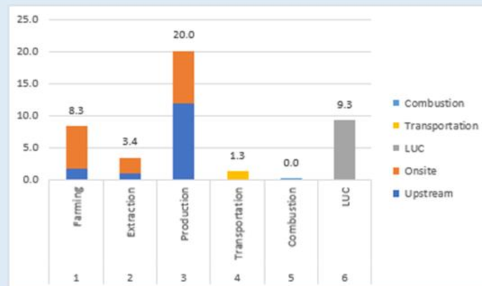
Results: Soybean HEFA (GREET)

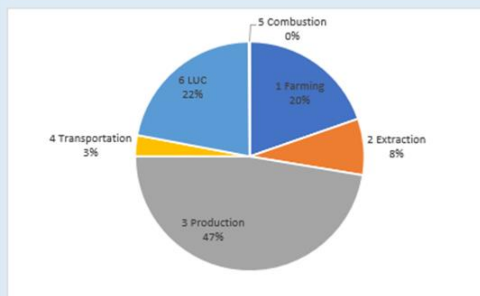
Metrics

Total Energy
Fossil Fuels
Coal
Natural Gas
Petroleum
Water Consumpti...
VOC
CO
NOx
PM10
PM2.5
SOx
BC
OC
CH4
N2O
CO2
CO2 (w/ C in VOC...
GHGs
VOC: Urban
CO: Urban
NOx: Urban
PM10: Urban
PM2.5: Urban
SOx: Urban
BC: Urban
OC: Urban

	Energy	Water	Emissions
Unit	MJ	gal	g
Functional unit	MJ	Jet	
LUC	Include when available		

Life-cycle GHGs = 42.29 g/MJ LUC (USA) included





Appendix Table A-9. Soybean Oil HEFA Results from GREET 40B calculator

40BSAF-GREET 2024

Select a 40B Pathway:

Soybean HEFA

Generate LCA Results

SAF Production (per period of operation)

Parameter	Sample Input	User Input	Unit
SAF production	30.0	30.0	million gallons
Renewable diesel production	30.0	30.0	million gallons
Renewable gasoline production	0.0	0.0	million gallons
Renewable naphtha production	0.0	0.0	million gallons
Feedstock: Soybean Oil consumption	443.8	443.8	million lbs
Grid electricity (selected eGRID region)	19.0	19.0	million kWh
Renewable Electricity Credit (REC)	0.0	0.0	million kWh
Onsite behind-the-meter electricity	0.0	0.0	million kWh
Total fossil NG consumption	123.6	123.6	thousand mmBtu
Total LFG-derived RNG consumption	0.0	0.0	thousand mmBtu
Offsite, Fossil NG-derived H2 consumption	6,392	6,392	metric tons
Offsite, 45V Modeled H2 consumption	0.0	0.0	metric tons
Offsite, 45V Modeled H2 CI	3.0	3.0	kg CO2e/kg H2

Selections (per period of operation)

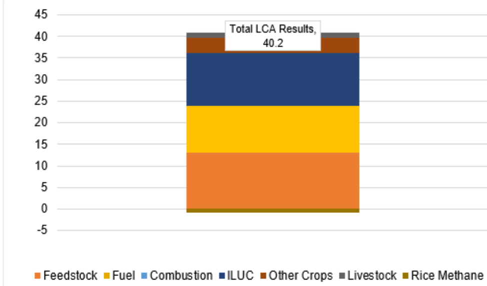
Parameter	User Selection	Input Type
SAF Production, Grid Electricity Source (eGRID by default)	1	Selection

Transportation Data (per period of operation)

Transportation Type	Share (%)	Distance (mi)	Share (%)	Distance (mi)
SAF - From SAF facility to Terminal: Barge	8%	520.0	8%	520.0
SAF - From SAF facility to Terminal: Pipeline	0%	0.0	0%	0.0
SAF - From SAF facility to Terminal: Rail	29%	800.0	29%	800.0
SAF - From SAF facility to Terminal: Heavy-Duty Truck (Tanker)	63%	50.0	63%	50.0
Fossil NG SMR H2 - From H2 facility to SAF facility: Pipeline	100%	150.0	100%	150.0
Fossil NG SMR H2 - From H2 facility to SAF facility: Tube Traile	0%	0.0	0%	0.0
Fossil NG SMR H2 - From H2 facility to SAF facility: Liquid Trucl	0%	0.0	0%	0.0
45V Modeled H2 - From H2 facility to SAF facility: Pipeline	100%	150.0	100%	150.0
45V Modeled H2 - From H2 facility to SAF facility: Tube Trailer	0%	0.0	0%	0.0
45V Modeled H2 - From H2 facility to SAF facility: Liquid Truck	0%	0.0	0%	0.0

Results: Soybean HEFA

Total LCA Results (g CO_2e/MJ)



Life Cycle Stage	Value (g CO_2e/MJ)
D-LCA	23.9
Feedstock	13.0
Fuel	10.9
Combustion	0.0
I-Effects	16.2
ILUC	12.2
Other Crops	3.5
Livestock	1.4
Rice Methane	-0.8
Total LCA Results	40.2
% Reduction From Baseline	54.9%

Reset Parameters