Assessment of weighted Carbon Intensity (CI) for California Air Resources Board (CARB) - certified U.S. corn ethanol producers

Report for

U.S. GRAINS COUNCIL

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Confidential

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List of abbreviations

AEZ-EF	Agro-Ecological Zone Emission Factor
AF	Allocation Factor
ANL	Argonne National Laboratory
CARB	California Air Resources Board
CO_2	Carbon Dioxide
CI	Carbon Intensity
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CEF	CORSIA Eligible Fuel
DGS	Distillers Grains with Solubles
DDGS	Dried Distillers Grains with Solubles
EC	European Commission
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
FF	Feedstock Factor
gCO_2eq/MJ	Grams of Carbon Dioxide Equivalent per Megajoule
GREET	Greenhouse Gases, Regulated Emissions, and Energy use in Technologies
GTAP	Global Trade Analysis Project
GHG	Greenhouse Gases
iLUC	Indirect Land Use Change
ILUC	Induced Land Use Change
IPCC	Intergovernmental Panel on Climate Change

ICAO	International Civil Aviation Organization
IIASA	International Institute for Applied Systems Analysis
ISCC	International Sustainability and Carbon Certification
kg	Kilogram
LCA	Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
CH_4	Methane
MDGS	Modified Distillers Grains with Solubles
N_2O	Nitrous Oxide
RED	Renewable Energy Directive
RFA	Renewable Fuels Association
SAF	Sustainable Aviation Fuel
US	United States
USD	United States dollar
WDGS	Wet Distillers Grains with Solubles

1 Introduction

The global corn market plays a vital role in agriculture as a key commodity for food, feed, and industrial applications. The predicted size of the global market for corn in 2023 was USD 297.27 billion, with an anticipated compound annual growth rate of 3.6% between 2024 and 2030. Corn plays a significant role in the global agricultural industry, serving a multitude of purposes, including food, animal feed, and industrial applications such as ethanol production. It is a versatile commodity and a crucial component of many diets worldwide. A predominant portion of global corn production is utilized for human consumption in various forms, including food, sweeteners, and cooking oil. Additionally, a considerable amount of corn is employed as animal feed, providing essential nourishment for livestock such as chickens, cattle, and swine. (GVR Market Research 2024)

Into the future, the market is anticipated to increase due to the broad demand for corn’s across several end-user sectors, including food processing, feed production, ethanol generation, medicines, and cosmetics. The diverse and increasing demand highlights corns crucial place in the world's industrial and agricultural industries. (GVR Market Research 2024)

In the United States of America (US), the potential to produce corn ethanol for use as a fuel for transportation is increasing at a rapid rate. The main factors driving this expansion are rising petrol costs, government regulations and incentives, the necessity for cleaner fuels, and the objective of enhanced energy independence. The viability of the corn ethanol market depends on the profitability of suppliers and producers. This profitability, in turn, is contingent upon several factors, including demand, government incentives, feedstock availability and pricing, processing plant capacity, and improvements in farming and ethanol processing technology. (Kibira and Shao 2011)

Despite the favorable factors, the US has maintained steady ethanol consumption for nearly a decade. The Environmental Protection Agency's (EPA) discretionary waivers and restrictions on combining ethanol with petrol have been identified as two of the key factors that have contributed to the slow rise in this trend. These limitations have precluded a notable increase in the demand for ethanol derived from corn starch. Moreover, the lack of progress for cellulosic ethanol has been caused by technological, financial, and regulatory barriers. While low-carbon fuel regulations in western states such as California may result in additional revenue, there is a possibility that these rules, which frequently favor electric vehicles and other biofuels that compete with corn-based ethanol, may not provide corn-based ethanol with long-term development potential. (Andrew Swanson 2024)

In this context, the aviation sector presents an untapped market with a need for alternative sources of fuel that do not rely on fossil fuels. In response to mounting pressure from stakeholders, investors, and regulators to reduce greenhouse gas emissions, airlines are increasingly seeking low-emission alternative liquid fuels in place of petroleum jet fuel. Such alternative fuels are derived from plant biomass, vegetable oils, sugars, and alcohols, including ethanol, and are designated as Sustainable Aviation Fuel (SAF). (Andrew Swanson 2024)

SAF are renewable or waste-derived aviation fuels that meet the sustainability criteria set by the International Civil Aviation Organization (ICAO). These criteria include reducing Greenhouse Gas (GHG) emissions, limiting biomass sourced from land with high carbon stock, and ensuring soil, air, and water quality. Technical analyses indicate that SAF has significant potential to reduce CO_2 and conventional air pollutant emissions from international aviation and ICAO proposes different possibilities for accounting those benefits. GHG emissions under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) can be calculated using two methods: the methodology described in the ICAO document "CORSIA Methodology for Calculating Actual Life Cycle Emissions Values" or an alternative approach using default values available in the ICAO document "Default Life Cycle Emissions Values for CORSIA Eligible Fuels”. In both methods, the calculated GHG values must be compared with a fossil fuel comparator, to demonstrate the GHG emissions benefit of using SAF in an aircraft.

According to the latter mentioned ICAO document, SAF derived from corn-starch ethanol has higher emissions than the fossil fuel reference value. The default values indicate that SAF from corn ethanol has a total emission value of 90.8 gCO_2eq/MJ (ICAO 2024a) whereas the fossil fuel comparator - which requires at least a 10% savings - is 89 gCO_2eq/MJ (ICAO 2024b). Therefore, SAF *derived* from ethanol cannot meet the emission reduction requirements of the CORSIA scheme if the default values are used. Such limitation underscores the potential challenges of positioning corn ethanol as a viable feedstock for SAF under current regulatory standards. It shall be noticed that this value was first published in 2019 and has not yet been re-calculated by ICAO.

Against this background, this study has a main objective of evaluating and calculating a weighted average Carbon Intensity (CI) score for US corn ethanol producers who hold California Air Resources Board (CARB) LCFS certification. This assessment is relevant as the ICAO CORSIA currently utilizes, as previously highlighted, a default CI index of approximately 90.8 gCO_2eq/MJ for US produced corn ethanol. Given the increasing focus on sustainability issues in the agricultural industry and technological developments in SAF's production area, this value could potentially be lower than the original one published in 2019. A CARB-recognized CI score representative of the whole of the US corn ethanol market will:

- Inform policy decisions and industry practices related to SAF.
- Be shared with international ethanol importers, policymakers, and SAF producers.
- Facilitate informed decision-making on feedstocks and technologies for future SAF production.

2 Literature review

2.1 CARB – Low Carbon Fuel Standard:

In 2009, the CARB approved the Low Carbon Fuel Standard (LCFS) to reduce the CI of transportation fuels by at least 10% by 2020, using 2010 as a baseline. Amendments in 2011 aimed to clarify and streamline the regulation. In 2015, the LCFS was re-adopted to address procedural issues, with implementation beginning in 2016. Further amendments in 2018 strengthened the CI benchmarks through 2030, aligning with California's greenhouse gas (GHG) target. (CARB 2009)

The LCFS is a critical pillar designed to reduce GHG emissions in California. However, its benefits extend beyond GHG reduction. The LCFS diversifies California's fuel pool reduces petroleum dependency, and achieves significant air quality improvements. By targeting the transportation sector, which is responsible for about 50% of the state's GHG emissions (including emissions from refining and crude production), 80% of ozone-forming gas emissions, and over 95% of diesel particulate matter, the LCFS addresses one of the largest sources of pollution.

Furthermore, the LCFS sets annual CI standards, or benchmarks, that decrease over time, for gasoline, diesel, and their alternatives. The CI is measured in Grams of Carbon Dioxide Equivalent per Megajoule of energy provided by the fuel (gCO_2eq/MJ), encompassing GHG emissions from the entire lifecycle of the fuel. Under the current LCFS regulation, the standard of a 20% CI decline by 2030 will apply to all subsequent years, ensuring continued progress in reducing CI and supporting California’s long-term environmental objectives. This ongoing reduction in CI is vital for the state's strategy to combat climate change and promote cleaner, more sustainable transportation fuels.

LCFS employs the Global Trade Analysis Project (GTAP) model to calculate the Indirect Land Use Change (iLUC) values under LCFS, which was incorporated into the original LCFS adoption. In 2011, the board instructed the LCFS staff to collaborate with stakeholders to update the iLUC values for various biofuels. As part of the 2015 LCFS re-adoption, the staff worked with stakeholders to update the GTAP model and developed the Agro-Ecological Zone Emission Factor (AEZ-EF) model to supplement GTAP's estimates of greenhouse gas emissions resulting from different types of land conversions.

In order to calculate emissions according to the LCFS requirements, fuel producers shall apply the Greenhouse Gases, Regulated Emissions, and Energy use in Technologies (GREET) model, which was developed by the Argonne National Laboratory (ANL), a US funded research and development center. Currently, the ANL is chiefly financed by the United States Department of Energy (DOE). A specific model focused on the California requirements arising from the LCFS was developed by the ANL.

2.2 ICAO - Carbon Offsetting and Reduction Scheme for International Aviation

Established in 2016, CORSIA has the ambitious target of achieving carbon-neutral growth starting from 2020 and supporting the aviation sector to move towards its goal of achieving net-zero emissions by 2050. SAF is prominently included under CORSIA, as airlines can reduce their offsetting obligations under CORSIA by using SAF that is CORSIA eligible, the so-called CORSIA eligible fuel (CEF). To be CORSIA eligible, a SAF must comply with a strict set of sustainability criteria developed by ICAO and certified accordingly by an ICAO-recognized certification scheme.

As previously mentioned, CORSIA requires that SAF must achieve a GHG emissions saving of at least 10% compared to the baseline life cycle emissions of aviation fuels to be eligible under the scheme. In this comparison, the reference value for conventional fossil jet fuel is set at 89 gCO_2eq/MJ, as defined directly by the regulation. To determine whether SAF meets the 10% life cycle emissions saving required under CORSIA, ICAO has put in place a comprehensive GHG methodology following a life cycle approach.

Under CORSIA, the GHG emission intensity of a fuel is termed as the total LS_f. These are the result of the sum of the core LCA value and the induced land use change (ILUC) value, as shown in Equation 1. The core LCA emission information for a given CEF can be provided through default values or actual values, which are further defined in this chapter.

$$LS_f = \text{CORE LCA Value} + \text{ILUC Value}$$

Equation 1 Equation to calculate total life cycle emissions of SAF under ICAO CORSIA methodology

A list of default LCA emission values for CEF is published in the ICAO Document "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels" (ICAO 2022). Per each fuel feedstock and fuel conversion process, a core LCA value is provided. Additionally, depending on the region, an ILUC value is reported. It should be noted that in some cases, the ILUC value can be applicable on a global level as well. CEF producers can use the reported default value only if all the necessary parameters match the scenario of the CEF producer. In addition, the ILUC value is mandatorily always a default value – fuel producers are not allowed to calculate an actual value for this formula element.

Actual values can be calculated for the core LCA part of the equation, if a producer wishes to demonstrate a lower core LCA value compared to the default core LCA value or if a CEF producer has defined a new pathway that does not have default LCA value. In fact, it is important to note that feedstocks are only eligible for certification under CORSIA if both a default core LCA value and a default ILUC value have been calculated by ICAO.

The system boundary of the core LCA value calculation shall include the full supply chain of CEF production and use, including all associated emissions from the following life cycle stages:

1. Production at source (e.g., feedstock cultivation);
2. Conditioning at source (e.g., feedstock harvesting, collection, and recovery);
3. Feedstock processing and extraction;
4. Feedstock transportation to processing and fuel production facilities;
5. Feedstock-to-fuel conversion processes;
6. Fuel transportation and distribution to the blend point; and
7. Fuel combustion in an aircraft engine.

In case the feedstock is classified as a waste, residue or by-product, life cycle step 1, production at source, is set to incur zero GHG emissions. For life cycle steps 1-6 (i.e., for calculating the core LCA value), emissions from non-biogenic CO_2, as well as carbon dioxide equivalents of CH_4 and N_2O must be included, based on 100-year global warming potential. Global warming potential values for CH_4 and N_2O can be obtained from the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC-AR5). For life cycle step 7 (fuel combustion in an aircraft engine), only emissions from non-biogenic CO_2 need to be accounted for.

If a CEF production process yields multiple outputs, emissions must be allocated between products and co-products. The emissions burdens shall be distributed with an energy allocation, where emissions are distributed between products and co-products in proportion to their energy contribution to the total CEF process energy content. It is important to note that no emissions can be allocated to wastes, residues, or by-products (ICAO 2024b).

Airplane operators may decide to take advantage of the benefits of utilizing land use change-risk mitigation approaches, (e.g., land management practices) to avoid ILUC emissions. In this case, an ILUC value of zero will be used in place of the default ILUC value to calculate total LSf. According to ICAO CORSIA methodology, the low land use change risk feedstock include: (a) feedstocks that do not result in expansion of global agricultural land use for their production, (b) waste, residues, and by-products, and (c) feedstocks that have yields per surface unit significantly higher than terrestrial crops (approximately one order of magnitude higher). For induced land use change to occur, the feedstock must be grown on an existing agricultural area. It could be the same crop which is now used as a bioenergy feedstock instead of food, feed, or material uses. This reduces the supply of those feedstocks in the food, feed, and material biomass markets. In practice, diverting vegetable oils such as corn oil from food use to biodiesel production, will lower the supply of vegetable oils globally.

The ICAO has commissioned the institutions that developed GTAP-BIO and GLOBIOM – Purdue University and International Institute for Applied Systems Analysis (IIASA) respectively – to compute ILUC values for the different SAF feedstocks for several world regions and crops.

The model results for the different ILUC values are derived by simulating the impact of supplying additional feedstocks for SAF production. The overall reactions of all economic sectors in the case of GTAP-BIO and all agricultural sectors in the case of GLOBIOM are then used to compute the changes in GHG emissions through net land use change. This includes the expansion of farmland for growing SAF feedstocks, as well as the expansion of land for non-energy biomass. The two models achieve similar, yet in some cases quite diverse results that can be attributed to the different modelling methodologies.

In order to prove compliance with the CORSIA requirements set by ICAO, a certification must take place according to a recognized certification scheme by ICAO. One of the certification schemes recognized by ICAO is the International Sustainability and Carbon Certification (ISCC), the leading certification system contributing to climate and environmental protection, decarbonization, and traceability along supply chains. ISCC has a long working history supporting sustainable agriculture that increases biodiversity and promotes the transition to a circular economy. ISCC certification covers agricultural and forestry biomass, biogenic wastes and residues, recycled carbon-based materials, and non-biological renewable materials. As of now, ISCC has issued more than 40,000 certificates in over 100 countries, works with 50 certification bodies, and has close to 7,000 system users. Currently, there are about 57 ISCC certificate holders in Colombia for different raw materials.

In 2020, ISCC developed the ISCC CORSIA certification system. In November of 2020, the International Civil Aviation Organization (ICAO) officially recognized ISCC CORSIA under its global CORSIA scheme. Since then, economic operators can show compliance with CORSIA's requirements for CORSIA-eligible fuels by becoming certified under the ISCC CORSIA scheme. So far, more than 30 operators along SAF value chains have become certified, among which some have calculated their individual life cycle emissions following ISCC CORSIA's in-depth GHG methodology for SAF.

Apart from ISCC CORSIA, ISCC also operates two other certification schemes. ISCC EU is recognized by the European Commission (EC) to demonstrate compliance with the European Union Renewable Energy Directive (EU RED) II focusing on the transport sector. ISCC PLUS is a voluntary certification scheme for non-regulated markets covering food, feed, plastics, and chemicals on a global scale, as well as biofuels for non-European markets. These two additional certification systems strengthen ISCC experience in the biofuels area.

2.3 Allocation methods

The allocation of greenhouse gas emissions in Life Cycle Assessment (LCA) is a critical factor in determining the environmental performance of products, especially in systems where co-products are generated alongside the main product (De Jong et al. 2017). Different methods of allocating emissions to co-products are possible, as follows:

1. **Energy Allocation:** Emissions are distributed based on the energy content of the main product and co-products.
2. **Mass Allocation:** Emissions are allocated according to the mass of the main product and co-products.
3. **Economic Value Allocation:** Emissions are divided based on the economic value of the main product and co-products.
4. **Displacement Method (System Expansion):** Emission credits are assigned to co-products based on the amount of the co-product produced and the GHG emission intensity of the equivalent displaced product (e.g., a fossil fuel counterpart).

For this study, the differences about allocation by energy and displacement method are particularly relevant. The main aspects are highlighted in the following.

2.3.1 Energy Allocation

In the energy allocation method, GHG emissions are allocated to products and co-products in proportion to their energy content. This method ensures that emissions are consistently related to the energy value, yielding strictly positive emission intensities. This type of energy allocation is widely used in the GHG calculation of biofuels, such as those in the ICAO CORSIA GHG calculation and the EU RED II (2018/2001) GHG methodology. An example can be found the ISCC system document, which is a recognized voluntary scheme under both ICAO CORSIA and EU RED II. The ISCC system document 205 v4.1 defines that *"Allocation is done based on the allocation factor (AF), which reflects the relation of the total energy content of the final biofuel main product to the total energy content of all products. The energy content is calculated from the lower heating value and the yield of the respective product." (ISCC 2024)*

The AF can be calculated as defined in Equation 2. The advantage of applying an energy allocation is its simplicity, as only the fuel production along with its co-products are evaluated.

$$AF_{product} = \frac{Energy\ content_{product}[MJ]}{Total\ energy\ content\ \left(energy\ content_{product}[MJ] + energy\ content_{co-product}[MJ]\right)}$$

Equation 2 Equation to calculate allocation factor under ICAO CORSIA methodology

2.3.2 Displacement method

The displacement method, or system expansion, awards an emission credit to co-products based on the yield and GHG emission intensity of the displaced product. This approach can lead to negative emission intensities if the credits for co-products exceed the total system emissions. This method acknowledges the environmental benefit of displacing higher-emission products and can provide a more holistic view of the GHG impacts. Displacement allocation in the context of corn ethanol production involves understanding how using co-products, such as Distillers Grains with Solubles (DGS), can offset or "displace" the need for other resources or processes - particularly in terms of GHG emissions. Displacement allocation specifically investigates how the use of DGS as animal feed can replace other traditional feeds, like corn or soybean meal, and how this replacement affects overall emissions. Hence, displacement allocation provides a path to account for the environmental benefits of using co-products like DGS instead of traditional feeds. By doing so, it ensures a more accurate assessment of the carbon footprint of corn ethanol production, promoting a holistic view of its sustainability, while also better guiding policy and economic decisions. The use of displacement also has downsides. For example, if the non-fuel product (like soy meal in soybean biodiesel production) is a large part of the total output, the emissions allocated to the fuel (biodiesel) can appear much lower than they should be. This happens because the total emissions are spread over a smaller basis (the fuel product), which makes the fuel seem more environmentally friendly than it really is (Wang, Huo, and Arora 2011). This type of allocation is predominantly used in the US-GREET and CA-GREET models. For example, the corn ethanol CI available in the LCFS database follows this type of allocation.

A key element of this method is the displacement ratio. In the context of corn oil mill, the co-products are ethanol and DGS. The DGS displacement ratio refers to how much traditional animal feed (like corn or soybean meal) can be replaced by DGS in livestock diets. In other words, it is a measure of the effectiveness of DGS as a substitute for other feeds. For example, we can define a fictitious corn ethanol plant that produces 1 ton of DGS. If this produced DGS can replace 0.8 tons of traditional feed that a farmer would otherwise use, the displacement ratio is then 0.8. This means the farmer can use DGS instead of buying 0.8 tons of other feed, thereby saving costs and utilizing the co-product efficiently.

2.4 Weighted average

As defined in the introduction, the corn CI proposed by this study will be calculated utilizing a weighted average. The weighted average involves multiplying each data point in a set by a value which is determined by some characteristic of whatever contributed to the data point (Wilcox 2012). Unlike the arithmetic average, which treats all values equally, the weighted average assigns different weights to different values based on their significance or frequency. The weighted mean is found from the following equation:

$$Weighted\ Average = \frac{\sum_{i=1}^{n}(wi * x_i)}{\sum_{i=1}^{n} w_i}$$

Equation 3 Equation for finding weighted average (Wilcox 2012)

Where,

w_i is the weighting given to the i^{th} data point

x_i is the value of the i^{th} data point

n is the number of data points in the set.

The weighted average method is widely used in various applications in inventory management, finance, education, and statistics. Such a method provides a more accurate representation of datasets where not all values contribute equally, making it a crucial tool for analysis and decision-making in various disciplines.

3 Data Collection

To conduct the study, a comprehensive research strategy was employed to gather data on several pivotal aspects of the corn ethanol industry in the US. This entailed the compilation of data pertaining to the CI of corn ethanol, in addition to the production capacity of several CARB-certified ethanol plants. Further research was conducted to ascertain the differences in allocation methods employed by the various plants, as these can have a significant impact on the calculated CI values. The conversion process of ethanol to SAF was also subjected to a comprehensive review. This consisted of an analysis on the required inputs and outputs for the production pathway, thereby ensuring a comprehensive understanding of the technological and environmental aspects involved in the production of SAF from corn ethanol. In this chapter, all aspects related to the data collection and sources will be described. Specifically, the two major points of data collection are outlined:

1. Data Collection of CARB Certified CI and Production Capacity of CARB Certified Plants
    - **CI Data**: Gathering CI values from CARB-certified plants, including reviewing plant-specific reports and emissions data for accurate assessments.
    - **Production Capacity**: Documenting the production capacities of these plants to understand their output scale and implications for the market and CI calculations.
2. Data Collection on Corn Ethanol to SAF Fuel Production Pathway
    - **Conversion Process**: Reviewing the technical details of the ethanol-to-SAF conversion pathway, including the necessary inputs (e.g., energy, catalysts) and outputs (e.g., SAF, by-products).

3.1 Data Collection of CARB Certified CI and Production Capacity of CARB Certified Plants

The CARB-certified CI values are derived from the LCFS database. This comprehensive database provides detailed lists of certified fuel pathways under the presented LCFS, including hydrogen, biodiesel, Bio-LNG, ethanol, and alternative jet fuel, among others. The objective is to compile a comprehensive data set on the production of ethanol from corn using the dry milling process. The LCFS database, in short, is a spreadsheet that contains a list of certified pathways by feedstock, fuel, classification, and facility name. These include:

- Lookup Table, Tier 1, and Tier 2 fuel pathways using the CA-GREET3.0 model.
- Applications certified using the older generation CA-GREET2.0 model.
- Pathways certified under initial validation and subsequent annual verification.

This study was conducted based on the most recent version of the LCFS database, released on June 24th, 2024. The data range employed encompasses the period from 2016 to the initial six months of 2024. A total of 440 data points were collected, with focus on feedstocks identified as corn and corn (009), and eight distinct pathways leading to the production of ethanol as a final product were identified.

The most common pathways over the years entail the production of corn ethanol with the co-products of Dried Distillers Grains with Solubles (DDGS), Wet Distillers Grains with Solubles (WDGS), and combinations of these co-products. Pathways with Modified Distillers Grains with Solubles (MDGS), combinations of MDGS and DDGS, combinations of DDGS, WDGS, and MDGS, mixed distillers grains with solubles, or pathways with no co-products comprise the less common pathways. (LCFS 2024)

Table 1 provides a comprehensive overview of the data points available from 2016 to the first half of 2024. A fluctuation in the number of available data points over the specified period can be observed, as there is a range between 8 to 137 certified pathways per year and 6 to 62 certified plants per year. Such inconsistency may be attributed to the fact that some plants did not handle sustainable materials or were not certified in some years, for reasons which are not specified. This approach accounts for variability and ensures a more accurate and representative CI assessment.

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024
Actual number of Plants	37	6	8	63	29	18	11	62	14
Number of pathways	63	8	9	137	56	39	19	110	18
Total name plate capacity (in million gallons)	3685	717	700	5335	3372	2006	1087	4084	1360

Table 1 Summary of available CARB certified ethanol data points from 2016 to 2024 (LCFS 2024)

Subsequently, the production capacities of the identified CARB-certified ethanol plants were determined using the Renewable Fuels Association (RFA) database. Any gaps in the RFA database were filled using information from the U.S. Energy Information Administration (EIA) and the U.S. Grains Council. This comprehensive approach ensured that the data gathered was as accurate and complete as possible for the analysis.

The dataset from Table 1 was subjected to further analysis to remove any instances of duplicate entries, whereby the same plant was mentioned on two separate occasions within the same year but with different CI values. Instead, a conservative approach was adopted using the highest certified CI for the plant and eliminating other repetitions. To gain further insight on the final market of the identified plants, the CARB-certified plants were cross-verified with the ISCC certificate database. The objective was to identify any plants exporting ethanol outside the US. Over the nine-year period studied in this report, a maximum of ten ethanol plants were certified by ISCC. Of the aforementioned plants in Table 1, only one was certified under ISCC in the years 2023 and 2024.

Two approaches were considered to determine the contribution, or weight, of each data point. The first approach was to use the export volumes of each plant, which meant identifying the volume of corn ethanol exports from the US. The data collected from readily available sources was considered insufficient to calculate the weighted average CI of ethanol based on export volumes. The precise volumes of ethanol exported by these plants over time could not be determined, as such data is often proprietary and not readily available. Furthermore, a considerable number of plants have undergone substantial alterations in their managerial structure over time, which has introduced additional complexities in the acquisition of data.

The following approach focused on the calculation of the CI of corn ethanol based on the total production capacity of CARB-certified ethanol plants. This approach ensures a more reliable and consistent assessment of CI values, utilizing the available production capacity data to derive meaningful insights. For that, data related to production capacities of the CARB-certified ethanol plants was determined with information available on the RFA and EIA databases (Renewable Fuels Association 2024; EIA 2023). Table 2 provides a comprehensive overview of the number of certified corn ethanol plants per year and the pathways through which they operate.

Year	DDGS	WDGS	MDGS	DDGS & WDGS	MDGS & DDGS	All three	Mixed DGS	Only Ethanol
2016	7	8	4	5	5	-	1	15
2017	1	1	1	missing	3	-	-	1
2018	1	2	-	3	-	1	-	1
2019	17	28	2	23	9	3	-	-
2020	11	9	8	3	5	1	-	-
2021	11	7	1	6	2	-	-	-
2022	9	3	4	1	2	-	-	-

2023	32	33	12	14	3	2	-	-
2024	3	5	3	2	5	-	-	-

Table 2 Number of CARB certified ethanol pathways per year

Table 2 shows that the two pathways with data sets available along all the study years are those for the production of ethanol with the co-products DDGS and WDGS.

3.2 Data Collection on Corn Ethanol to SAF Fuel Production Pathway

So far, the research has concentrated on the gathering of CI values related to corn ethanol and has the potential to be incorporated for SAF production. It is, however, important to note that SAF is the final product that can be certified under the provisions of ICAO CORSIA. In order to estimate the potential final CI of SAF produced from corn ethanol, a variety of literature sources were consulted, thereby enabling the accurate forecasting of these values. Three primary models were employed in this analysis: the ICAO GREET 2019 model, the CA GREET 3.0, model and the 40B Modified model. By applying these models, a more accurate estimation of the final CI for SAF was derived, ensuring that the results align with the latest standards and methodologies. Table 3, Table 4, and Table 5 display the collected data from the aforementioned GREET models, including the conversion factors from corn ethanol to SAF and the consumption quantities of various process inputs used for the conversion of corn ethanol to SAF. (Argonne National Laboratory 2019; CARB 2019; U.S. Department of Energy 2024)

Inputs / Outputs	**Quantities**	**Units**
Corn ethanol	1.78	MJ ethanol/MJ Jet fuel
Hydrogen	0.07	MJ hydrogen /MJ Jet fuel
Natural gas	0.52	MJ natural gas/MJ Jet fuel
Electricity	0.04	MJ electricity /MJ Jet fuel
Jet Fuel (SAF)	1	MJ Jet fuel
Renewable Diesel	0.25	MJ renewable diesel /MJ Jet fuel
Naphtha	0.36	MJ Naphtha /MJ Jet fuel
Heavy oil	0.08	MJ heavy oil /MJ Jet fuel

Table 3 Lifecycle inventory for corn grain ethanol ATJ pathway under ICAO GREET 2019 model

Inputs / Outputs	**Quantities**	**Units**
Corn ethanol	1.49	MJ ethanol/MJ Jet fuel
Hydrogen	0.081	MJ hydrogen /MJ Jet fuel
Natural gas	0	MJ natural gas/MJ Jet fuel
Electricity	0.03	MJ electricity /MJ Jet fuel
Jet Fuel (SAF)	1	MJ Jet fuel
Renewable Diesel	0.115	MJ renewable diesel /MJ Jet fuel
Gasoline fuel	0.212	MJ gasoline fuel /MJ Jet fuel

Table 4 Lifecycle inventory for corn grain ethanol ATJ pathway under CA GREET 3.0 model

Inputs / Outputs	**Quantities**	**Units**
Corn ethanol	1.06	MJ ethanol/MJ Jet fuel
Hydrogen	0.04	MJ hydrogen /MJ Jet fuel
Natural gas	0.11	MJ natural gas/MJ Jet fuel
Electricity	0.05	MJ electricity /MJ Jet fuel
Jet Fuel (SAF)	1	MJ Jet fuel
Renewable Diesel	0.05	MJ renewable diesel /MJ Jet fuel

Table 5 Lifecycle inventory for corn grain ethanol ATJ pathway under 40B Modified model

In order to obtain a more representative total emissions profile for SAF derived from corn ethanol according to the CORSIA framework, a number of additional factors were identified as data sources. In particular, the ILUC value for corn in the US, which is 25.1 gCO_2eq/MJ of jet fuel (ICAO 2024a), was incorporated in accordance with the specifications outlined in Equation 1. Furthermore, to account for the downstream transport of the produced jet fuel, an emission factor of 0.4 gCO_2eq/MJ jet fuel (ICAO 2022) was considered for the overall emissions calculation. These adjustments ensure a comprehensive assessment of the total emissions associated with the SAF production pathway.

4 Application of method and results

In this chapter, the methodologies and results employed to modify the CARB-certified ethanol CI into CI SAF in alignment with the CORSIA methodologies are outlined. Moreover, the findings obtained through the aforementioned methodology are presented. Using the research and data collected in chapters 3.1 and 3.2, a step-by-step methodology was employed as seen in the following steps, and described in detail throughout the chapter.

1. Removal of the iLUC value from the data collected on CARB-certified ethanol plants

2. Conversion of the displacement allocation to energy collection

3. Conversion of values for ethanol to SAF production pathway

4.1 Conversion of CARB-certified ethanol CI values

As a first step, it is important to note that the certified corn ethanol CI values included in the LCFS database incorporate a default iLUC value for California, which is 19.8 gCO_2eq/MJ (CARB 2018). To obtain an accurate representation of the emissions associated with the conversion of corn to ethanol, the iLUC value is excluded. By using the total number of certified ethanol plants and the total available capacity of these plants, the weighted average of the certified CIs is calculated based on these tables and Equation 1. A summary of the findings can be found in Table 6, which presents the CI values with the LCFS iLUC value excluded.

As previously stated in the data collection chapter, the accessibility of precise data regarding plant capacities and export volumes remained uncertain. The decision to remove the study on export volumes was predicated on the absence of transparent data, given that such information is often confidential and highly business-related. This raises a valid concern about the suitability of the weighted average approach for assessing plant capacities, particularly considering the split between DDGS and WDGS capacities in each plant, which is also attributable to similar confidentiality issues.

To assess the applicability of the weighted average approach, a comparative analysis was conducted between the years 2019 and 2023, as these years exhibited the most comprehensive data across various pathways. The analysis, presented in Table 7, demonstrates minimal variance between the weighted average and other potential approaches. Furthermore, it is essential to acknowledge that the CI values, expressed in grams of carbon dioxide equivalent per megajoule of fuel, remain unaffected by fluctuations in production volumes over a given period. Consequently, the weighted average method can still provide a valid representation of CI trends, even in the absence of precise knowledge of production splits between DDGS and WDGS pathways.

	DDGS	WDGS	MDGS	DDGS &WDGS	MDGS &DDGS	All three	Mixed DGS	Only Ethanol
2016	56.81	45.69	54.66	57.06	57.81	-	58.18	54.66
2017	61.05	52.52	49.09	missing	54.76	-	-	49.67
2018	54.23	50.16	-	31.51	-	62.06	-	59.99
2019	53.01	45.8	47.65	52.16	49.61	52.01	-	-
2020	52.01	45.66	47.65	50.51	51.85	41.75	-	-
2021	52.87	45.19	48.97	45.19	45.89	-	-	-
2022	53.01	42.33	49.87	52.36	50.83	-	-	-
2023	53.98	45.72	48.83	52.01	51.24	46.59	-	-
2024	53.38	45.25	50.98	51.27	50.4	-	-	-

Table 6 Weighted average of CI corn ethanol CARB certified plants– gCO_2eq/MJ (following displacement allocation method)

Year	Method	**DDGS**	**WDGS**	**MDGS**	**DDGS & WDGS**	**MDGS & DDGS**	**DDGS & WDGS & MDGS**
2019	Arithmetic	53.51	45.74	47.68	49.74	49.1	49.28
	Weighted	53.01	45.8	47.21	52.16	49.61	52.01
2023	Arithmetic	53.92	45.99	48.54	48.09	50.78	47.48
	Weighted	53.98	45.72	48.83	52.01	51.24	46.59

Table 7 Comparison between arithmetic and weighted average for 2019 and 2023 per pathway

As mentioned in Chapter 3.1, the focus of this study will be the DDGS pathway, the WDGS pathway, and the mixed pathway. This approach ensures a more streamlined analysis by concentrating on the most representative and data-rich pathways, thereby improving the accuracy and reliability of the results. Therefore, the values from Table 6 have been further simplified by focusing on the three main pathways for which data is consistently available. Table 8 and Figure 1 provide a summary of the weighted average for these pathways.

Year	DDGS pathway	WDGS pathway	Mixed pathway
2016	56.81	45.69	56.57
2017	61.05	52.52	53.67
2018	54.23	50.19	31.51
2019	53.01	45.8	50.97
2020	52.01	45.66	49.48
2021	52.87	45.19	50.34
2022	53.01	42.33	50.34
2023	53.98	45.72	50.30
2024	53.38	45.25	50.72

Table 8 Weighted Average of certified CI of ethanol plants by studied pathways – gCO_2eq/MJ (following displacement allocation method)

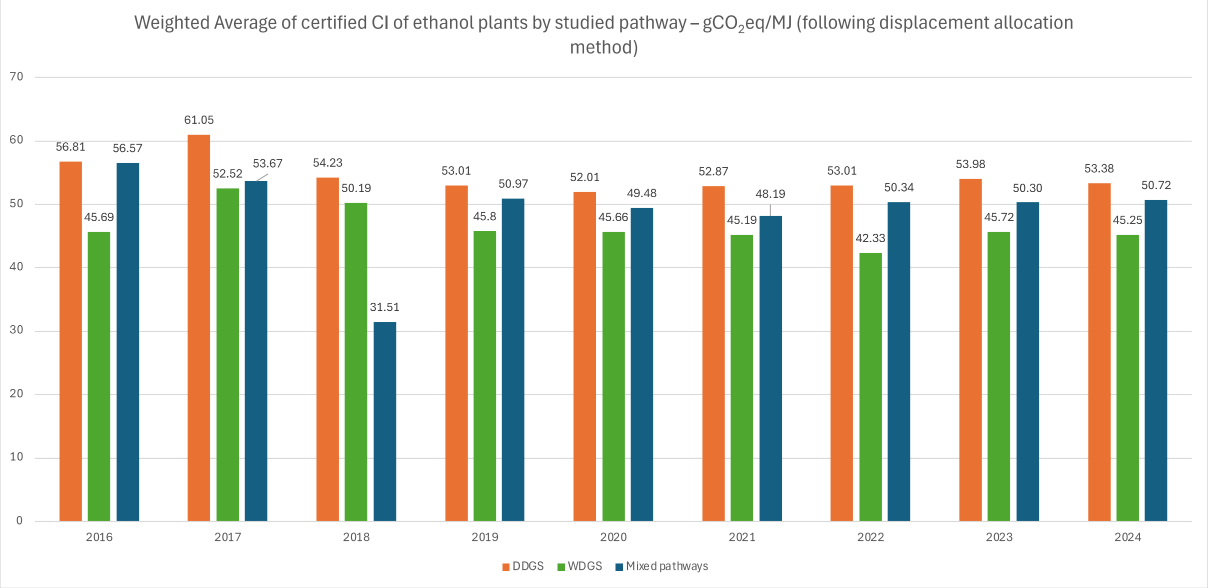


Figure 1 Weighted Average of certified CI of ethanol plants by studied pathway – gCO2eq/MJ (following displacement allocation method)

Considering the quality and availability of data for the DDGS and WDGS pathways, a standard deviation by sample was calculated.

As previously mentioned, the LCFS database presents certified CI values using CA GREET 3.0 and CA GREET 2.0, as the current method and the CA GREET 2.0 for older generations. Both calculators employ the allocation type of displacement method. This type of allocation is not allowed under the ICAO CORSIA methodology, which allows only energy allocation. Hence it becomes imperative to change the displacement allocation to energy allocation for the certified ethanol plants.

To convert these values in Table 8 from the displacement allocation to energy allocation, the following formula (Wang, Huo, and Arora 2011) is used:

$$GHG_{total} = (GHG_{\ ethanol} * \ Output_{\ ethanol}) + \left(GHG_{convproduct} * R * \ Output_{DGS}\right)$$

Equation 4 Equation to calculate the total emissions of processing at the ethanol plant

Where,

GHG_{total}	Total emissions of the ethanol plant gCO_2eq/year
$GHG_{ethanol}$	CI of the produced ethanol in gCO_2eq/MJ
$Output_{ethanol}$	Output energy of ethanol in MJ
$GHG_{convproduct}$	CI of the conventional product that the DGS displaces in gCO_2eq/kg
R	Displacement ratio
$Output_{DGS}$	Output of DGS in kg/Metric ton of corn

Here, the displacement ratio refers to how much traditional animal feed (like corn or soybean meal) can be replaced by DGS in livestock diets. In other words, its a measure of the effectiveness of DGS as a substitute for other feeds. If a corn ethanol plant produces 1 ton of DGS and this DGS can replace 0.8 tons of traditional feed that a farmer would otherwise use, the displacement ratio is 0.8. The displacement ration used in this calculation is 0.781 (Argonne National Laboratory 2019; CARB 2019), i.e., here the DGS can replace 0.781 tons of traditional feed. The $GHG_{ethanol}$ values are utilized from Table 8. The $GHG_{convproduct}$ is calculated from the DGS displacement credit of 12.31 gCO2e/MJ ethanol (CARB 2018).

Upon analyzing the CA GREET 3.0 model, an additional pathway was identified for dry mill ethanol production, specifically dry mill plants with corn oil extraction, and the dry mill plants without corn oil extraction. These pathways have been incorporated into the study to evaluate their impact on the CI of ethanol across the various ethanol production pathways. By including these additional pathways, the study aims to provide a more comprehensive understanding of how different production methods influence CI, thereby offering a more detailed view of the environmental impact of ethanol production across different technological configurations. The output quantities of are used from the CA GREET 3.0, the Table 9 shows the input volumes, were considered for this study.

	DDGS as co-product		WDGS as co-product		Units
	Dry Milling Plant w/o Corn Oil extraction	Dry Milling Plant w Corn Oil extraction	Dry Milling Plant w/o Corn Oil extraction	Dry Milling Plant w Corn Oil extraction	
Corn	1.00	1.00	1.00	1.00	bushel
	0.02	0.02	0.02	0.02	Metric tons/ one bushel of corn
	1.00	1.00	1.00	1.00	Metric tons of corn
Ethanol	2.86	2.76	2.86	2.76	gal/bushel of corn
	0.01	0.01	0.01	0.01	Metric tons of ethanol /bushel of corn
	0.40	0.38	0.40	0.38	Metric tons of ethanol /Metric tons of corn
DGS	4.21	5.52	4.21	5.26	lb/gal ethanol
	0.01	0.005	0.01	0.01	Metric tons of DGS/bushel of corn
	0.25	0.23	0.33	0.46	Metric tons of DGS/ Metric tons of corn

Table 9 Lifecycle inventory for corn grain ethanol following different pathways under CA GREET 3.0 model

By inputting the values from Table 8 and Table 9 into Equation 4 we can calculate the total emissions of the ethanol produced per year. Following this, the annual values are then allocated to the produced ethanol based on the allocation factor (AF) which is based in energy terms. The allocation factor is found using the described formulas below. Furthermore, the calculated allocation factor, has no units as AF is a ratio, based on the production pathway shown in Table 10.

$$AF_{ethanol} = \frac{Energy\ content_{ethanol}[MJ]}{Total\ energy\ content\ (energy\ content_{ethanol}[MJ] + energy\ content_{DGS}[MJ])}$$

Equation 5 Equation for allocation factor of ethanol under ICAO CORSIA methodology

$$AF_{DGS} = \frac{Energy\ content_{DGS}[MJ]}{Total\ energy\ content\ (energy\ content_{ethanol}[MJ] + energy\ content_{DGS}[MJ])}$$

Equation 6 Equation for allocation factor of DGS under ICAO CORSIA methodology

	DDGS as co-product		WDGS as co-product	
	Dry Milling Plant w/o Corn Oil extraction	Dry Milling Plant w Corn Oil extraction	Dry Milling Plant w/o Corn Oil extraction	Dry Milling Plant w Corn Oil extraction
Ethanol	0.68	0.69	0.61	0.52
DGS	0.32	0.31	0.39	0.48

Table 10 Calculated allocation factor for co-products of ethanol plants under different production pathways

With the allocation factor determined, it was possible to calculate the corn ethanol CI based on energetic allocation. The results are summarized in Table 11 and visualized in Figure 2. From these results, it can be inferred that by using the energy allocation method, the emissions are reduced by a range of 23% to 34%, depending on the chosen production pathway. These values are comparable with the results of the 2011 study, which indicated that a 19% reduction in emissions to ethanol was achieved when the energy allocation was preferred over the displacement method. (Wang, Huo, and Arora 2011)

Year	DDGS		WDGS		Mixed - without DDGS & WDGS
	Dry Milling Plant w/o Corn Oil extraction	Dry Milling Plant w Corn Oil extraction	Dry Milling Plant w/o Corn Oil extraction	Dry Milling Plant w Corn Oil extraction	Dry Milling Plant
2016	42.54	43.14	32.99	30.01	33.84
2017	45.40	46.07	37.18	33.59	32.45
2018	40.79	41.37	35.75	32.37	21.8
2019	39.97	40.52	33.05	30.07	31.15
2020	39.29	39.83	32.97	30.00	30.44
2021	39.87	40.43	32.68	29.75	29.81
2022	39.97	40.52	30.92	28.25	30.85
2023	40.62	41.19	33.00	30.03	30.83
2024	40.22	40.78	32.72	29.78	31.04

Table 11 Weighted Average of certified CI of ethanol plants by pathway - gCO$_2$eq/MJ (following energy allocation)

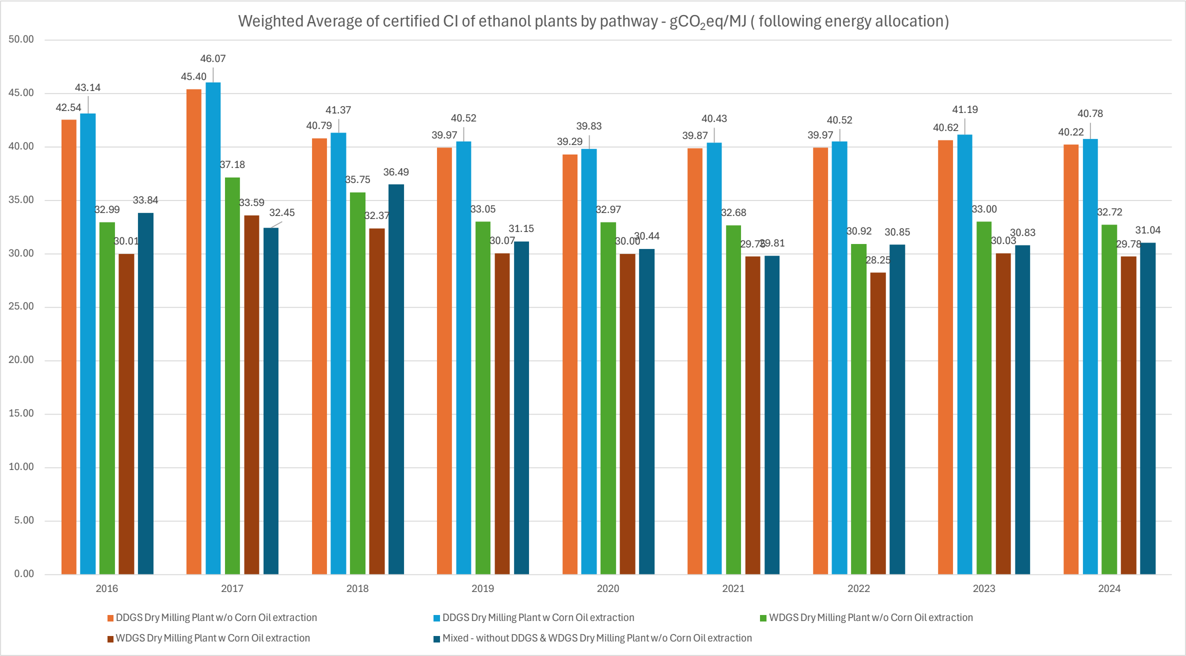


Figure 2 Weighted Average of certified CI of ethanol plants by pathway - gCO2eq/MJ (following energy allocation)

4.2 Calculating the CI of SAF from ethanol fuel pathway

In the final stage of the calculation process, the emissions linked to the conversion of corn ethanol to SAF are recalculated in accordance with the ICAO CORSIA methodology. In order to achieve this, the life cycle inventory data presented in Table 3, Table 4, and Table 5 are utilized. Furthermore, to obtain a more accurate and representative total emissions profile for SAF derived from corn ethanol, the ILUC value and a conservative estimate for downstream transport and distribution emissions are incorporated. Finally, the incoming emissions of ethanol, in gCO_2eq/MJ ethanol, were converted into emissions relating to the final products, i.e., in gCO_2eq/MJ SAF using feedstock factor Equation 7 (ISCC 2024). Subsequently, the total emissions, comprising both the incoming emissions from ethanol and the emissions associated with the conversion of ethanol to SAF, were allocated to SAF using an allocation factor Equation 8 (ISCC 2024).

$$FF_{SAF} = \frac{Energy\ content_{ethanol}[MJ]}{Energy\ content_{SAF}\ [MJ]}$$

Equation 7 Equation for feedstock factor of SAF under ICAO CORSIA methodology

$$AF_{SAF} = \frac{Energy\ content_{SAF}[MJ]}{Total\ energy\ content\ \left(energy\ content_{SAF}[MJ] + energy\ content_{DGco-products}[MJ]\right)}$$

Equation 8 Equation for allocation factor of SAF under ICAO CORSIA methodology

After determining the total emissions of the SAF using the above-described methodology, the GHG emissions savings associated with SAF from ethanol were calculated. For such, the below formula was applied:

$$Savings = \left\{1 - \frac{LS_f}{LC}\right\}$$

Equation 9 Equation to calculate the GHG reductions savings under ICAO methodology

Where,

LS_f – Life cycle emissions value of the CORSIA eligible fuel

LC – Baseline life cycle emissions, fixed value, 89 gCO_2eq/MJ for jet fuels

A comprehensive breakdown of the key factors influencing the overall CI of SAF derived from corn ethanol is presented in Table 12, Table 13, and Table 14. The following parameters are covered in the aforementioned tables:

- Emissions from processing ethanol to SAF
- Incoming ethanol emissions
- Default ILUC value for corn ethanol
- Downstream transport emissions

Finally, using Equation 9, the overall savings of the SAF, that can be potentially produced from corn ethanol, are calculated by comparing the total emissions of the SAF to a fossil jet fuel comparator. According to the ICAO CORSIA methodology, for SAF to be classified as a CEF, it must achieve at least a 10% reduction in emissions compared to fossil jet fuel (ICAO 2024b). The tables display color-coding to explicitly demonstrate whether the produced jet fuel is classified as a CEF in accordance with the CORISA standard. In particular, green highlights are utilized to indicate instances where the produced jet fuel fulfills the mandatory GHG savings criteria and can be considered a CEF. In contrary, red highlights signify scenarios where the produced jet fuel does not meet the required GHG savings criteria, rendering it ineligible to be classified as a CEF.

Year	Parameters	Carbon Intensity of SAF (gCO2eq/MJ) DDGS					
		Dry Milling Plant w/o Corn Oil extraction			Dry Milling Plant w Corn Oil extraction		
		ICAO GREET 2019	CA GREET 3.0	40B SAF-GREET 2024	ICAO GREET 2019	CA GREET 3.0	40B SAF-GREET 2024
2016	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	44,80	47,69	42,97	45,44	48,37	43,59
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	99,47	81,37	85,55	100,11	82,06	86,17
	Savings	-11,64%	8,67%	3,98%	-12,36%	7,91%	3,29%
2017	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	47,82	50,90	45,87	48,52	51,64	46,54
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	102,49	84,59	88,45	103,19	85,33	89,12
	Savings	-15,03%	5,07%	0,73%	-15,82%	4,23%	-0,03%
2018	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	42,97	45,73	41,21	43,57	46,37	41,79
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	97,64	79,42	83,79	98,24	80,06	84,37
	Savings	-9,58%	10,86%	5,96%	-10,26%	10,14%	5,31%
2019	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	42,10	44,81	40,38	42,68	45,43	40,94
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	96,77	78,50	82,96	97,35	79,11	83,52
	Savings	-8,61%	11,90%	6,89%	-9,26%	11,21%	6,26%
2020	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	41,39	44,05	39,70	41,96	44,66	40,24
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	96,06	77,74	82,28	96,63	78,35	82,83
	Savings	-7,81%	12,75%	7,66%	-8,45%	12,07%	7,04%
2021	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	42,00	44,70	40,28	42,58	45,32	40,84
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	96,67	78,39	82,87	97,25	79,01	83,42
	Savings	-8,49%	12,02%	7,00%	-9,15%	11,32%	6,37%
2022	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	42,10	44,81	40,38	42,68	45,43	40,94
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	96,77	78,50	82,96	97,35	79,12	83,52
	Savings	-8,61%	11,90%	6,89%	-9,26%	11,20%	6,26%
2023	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	42,79	45,54	41,04	43,39	46,18	41,61
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	97,46	79,23	83,62	98,06	79,87	84,20
	Savings	-9,38%	11,08%	6,15%	-10,05%	10,36%	5,50%
2024	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	42,36	45,09	40,63	42,95	45,72	41,20
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	97,03	78,78	83,21	97,62	79,40	83,78
	Savings	-8,90%	11,59%	6,61%	-9,56%	10,88%	5,97%

Table 12 Calculated CI of SAF (gCO2eq/MJ) under the DDGS pathway

As evidenced by the analysis of Table 12, the performance of SAF in terms of emissions savings is dependent on the literature data utilized. When applying the processing data sourced from the ICAO GREET 2019 model and 40B Modified, the SAF is unable to attain the requisite minimum savings of 10% in comparison to fossil jet fuel. The principal factor responsible for this discrepancy is the incorporation of 0.52 MJ of natural gas per MJ of jet fuel and 0.04 MJ of natural gas per MJ of jet fuel respectively into the model's calculations, which increases the overall CI of the SAF.

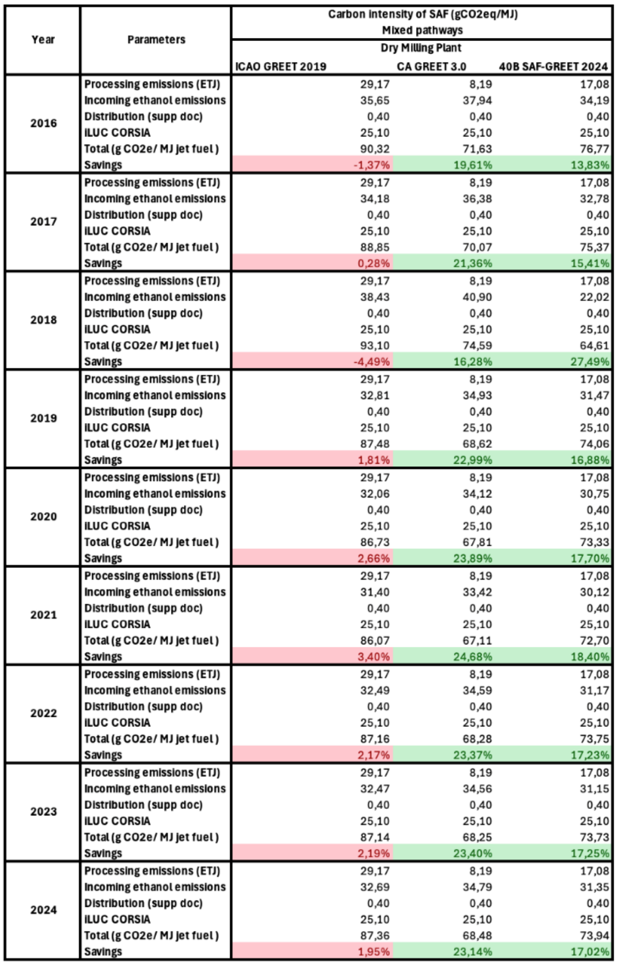
In contrast, the SAF produced under the DDGS pathway in the CA GREET 3.0 model meets the requisite savings threshold. The primary distinction between the two models lies in the accounting for natural gas consumption. The CA GREET 3.0 model does not incorporate any natural gas usage, resulting in a lower CI and consequently higher emissions savings.

The 40B Modified model indicates that the SAF has the potential to reach the requisite emissions savings in most years, starting from 2019. The discrepancy in performance between 2016 to 2018 can be attributed to the utilization of older CI values, which were calculated using the older CA GREET 2.0 model. It is notable that from 2019 to 2023, the SAF falls just below the threshold lowest amount of savings at 6.15%. This shortfall could potentially be addressed by implementing more efficient production pathways, such as integrating green hydrogen or renewable electricity into the SAF production process.

Year	Parameters	Carbon intensity of SAF (gCO2eq/MJ) WDGS					
		Dry Milling Plant w/o Corn Oil extraction			Dry Milling Plant w Corn Oil extraction		
		ICAO GREET 2019	CA GREET 3.0	40B SAF-GREET 2024	ICAO GREET 2019	CA GREET 3.0	40B SAF-GREET 2024
2016	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	34,74	36,98	33,32	31,61	33,65	30,32
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	89,41	70,67	75,91	86,28	67,34	72,90
	Savings	-0,35%	20,69%	14,81%	3,16%	24,43%	18,18%
2017	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	39,16	41,68	37,56	35,38	37,65	33,93
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	93,83	75,37	80,14	90,05	71,34	76,51
	Savings	-5,31%	15,41%	10,05%	-1,06%	19,93%	14,12%
2018	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	37,65	40,07	36,11	34,09	36,29	32,70
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	92,32	73,76	78,70	88,76	69,98	75,28
	Savings	-3,62%	17,21%	11,68%	0,38%	21,46%	15,51%
2019	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	34,81	37,05	33,39	31,67	33,71	30,38
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	89,48	70,74	75,97	86,34	67,40	72,96
	Savings	-0,43%	20,61%	14,73%	3,10%	24,36%	18,11%
2020	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	34,72	36,96	33,31	31,60	33,63	30,31
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	89,39	70,65	75,89	86,27	67,32	72,89
	Savings	-0,33%	20,71%	14,83%	3,18%	24,45%	18,20%
2021	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	34,42	36,63	33,01	31,34	33,35	30,06
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	89,09	70,32	75,60	86,01	67,04	72,64
	Savings	0,01%	21,07%	15,16%	3,47%	24,76%	18,47%
2022	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	32,57	34,67	31,24	29,76	31,68	28,54
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	87,24	68,36	73,82	84,43	65,36	71,13
	Savings	2,09%	23,28%	17,15%	5,24%	26,64%	20,17%
2023	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	34,76	37,00	33,34	31,63	33,66	30,34
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	89,43	70,69	75,93	86,30	67,35	72,92
	Savings	-0,37%	20,66%	14,79%	3,14%	24,41%	18,16%
2024	Processing emissions (ETJ)	29,17	8,19	17,08	29,17	8,19	17,08
	Incoming ethanol emissions	34,46	36,68	33,05	31,37	33,39	30,09
	Distribution (supp doc)	0,40	0,40	0,40	0,40	0,40	0,40
	iLUC CORSIA	25,10	25,10	25,10	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	89,13	70,37	75,63	86,04	67,08	72,67
	Savings	-0,03%	21,03%	15,11%	3,43%	24,72%	18,44%

Table 13 Calculated CI of SAF (gCO2eq/MJ) under the WDGS pathway

The results of the analysis presented in Table 13 and Table 14 indicate that the SAF generated using the ICAO GREET 2019 model for the WDGS and mixed pathways does not achieve the required 10% GHG savings in any of the studied years or production pathways. However, when the same pathways are analyzed using the CA GREET 3.0 and 40B Modified models, the SAF comfortably exceeds the required GHG savings, with reductions of at least 15%. In the case of the WDGS pathway, the SAF achieves the requisite savings due to the avoidance of the additional energy needed to dry the DGS at the ethanol plants during the production process. This results in a reduction in energy consumption and carbon emissions, enabling the SAF to meet the requisite savings under the other prevailing models. Similarly, under the mixed pathway, the SAF achieves a range of 10.5% to 24.68% reduction in GHG emissions when analyzed using the CA GREET 3.0 and 40B Modified models.



Year	Parameters	Carbon intensity of SAF (gCO2eq/MJ) Mixed pathways		
		Dry Milling Plant		
		ICAO GREET 2019	CA GREET 3.0	40B SAF-GREET 2024
2016	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	35,65	37,94	34,19
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	90,32	71,63	76,77
	Savings	-1,37%	19,61%	13,83%
2017	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	34,18	36,38	32,78
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	88,85	70,07	75,37
	Savings	0,28%	21,36%	15,41%
2018	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	38,43	40,90	22,02
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	93,10	74,59	64,61
	Savings	-4,49%	16,28%	27,49%
2019	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	32,81	34,93	31,47
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	87,48	68,62	74,06
	Savings	1,81%	22,99%	16,88%
2020	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	32,06	34,12	30,75
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	86,73	67,81	73,33
	Savings	2,66%	23,89%	17,70%
2021	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	31,40	33,42	30,12
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	86,07	67,11	72,70
	Savings	3,40%	24,68%	18,40%
2022	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	32,49	34,59	31,17
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	87,16	68,28	73,75
	Savings	2,17%	23,37%	17,23%
2023	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	32,47	34,56	31,15
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	87,14	68,25	73,73
	Savings	2,19%	23,40%	17,25%
2024	Processing emissions (ETJ)	29,17	8,19	17,08
	Incoming ethanol emissions	32,69	34,79	31,35
	Distribution (supp doc)	0,40	0,40	0,40
	ILUC CORSIA	25,10	25,10	25,10
	Total (g CO2e/ MJ jet fuel)	87,36	68,48	73,94
	Savings	1,95%	23,14%	17,02%

Table 14 Calculated CI of SAF (gCO2eq/MJ) under the Mixed pathway

Lastly, the processing emissions associated with the conversion of ethanol to SAF, as calculated using the 40B Modified model, fall within the range of emissions estimated by the other two models. In particular, the emissions are 29.17 gCO_2eq/MJ SAF, 8.19 gCO_2eq/MJ SAF, and 17.08 gCO_2eq/MJ SAF for ICAO GREET 2019, CA GREET 3.0, and 40B Modified respectively. The mid-range value of the 40B Modified model offers a balanced perspective, incorporating both conservative and optimistic estimates of processing emissions.

5 Discussion (or) sensitivity analysis

As observed in Chapter 3, the data points for CARB-certified ethanol plants exhibited inconsistency over the studied years. Nevertheless, the WDGS and DDGS pathways were identified as the two pathways with the most comprehensive and reliable data, as evidenced in Table 2 and Table 6. Following the findings of chapter 4.2, the detailed study of the CI of SAF from US corn ethanol is available in Appendix B. However, the year 2023 exhibited the most extensive data available from the LCFS database, with 137 certified plants. Considering the abundance of recent data and the absence of missing CI values or plant production data for these pathways, a more extensive evaluation was conducted, focusing specifically on the data from 2023.

To achieve the minimum savings of 10% in comparison to the fossil jet fuel comparator under the CORSIA methodology, it is necessary for the SAF to have a CI of no more than 80.1gCO_2eq/MJ SAF. This threshold is indicated by the red dotted line in Figure 3 and Figure 4. A comparative analysis of the DDGS and WDGS pathways reveals that the SAF is unable to achieve the requisite savings when utilizing the data from the ICAO GREET 2019 model. As illustrated in Figure 4, the SAF generated through the WDGS pathway demonstrably fulfils the requisite savings. However, Figure 3 illustrates that the SAF derived from the DDGS pathway only fulfills the requisite savings under the CA GREET 3.0 model. The contribution of the incoming ethanol emissions in all the models given below range between 41.04 gCO_2eq/MJ and 46.18 gCO_2eq/MJ in the DDGS case and 33.34 gCO_2eq/MJ and 37 gCO_2eqMJ in the WDGS case.

In the figure below 40B Modified model has not achieved the savings by 3.51 gCO2eq/MJ and 3.11 gCO2eq/MJ, respectively in both dry milling plant with and without corn oil extraction.

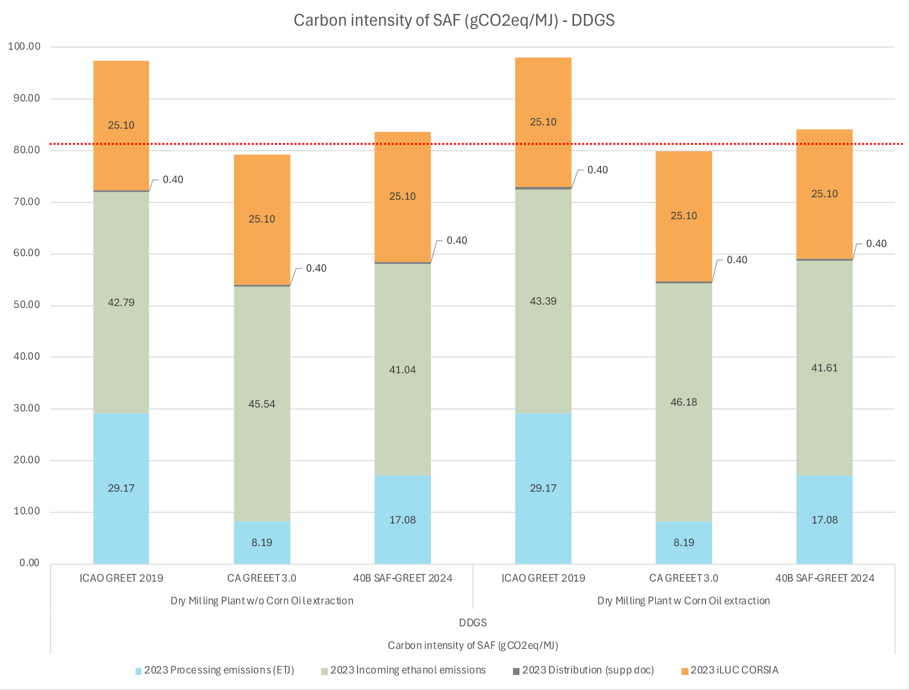


Figure 3 CI of SAF from corn ethanol following DDGS pathway in year 2023

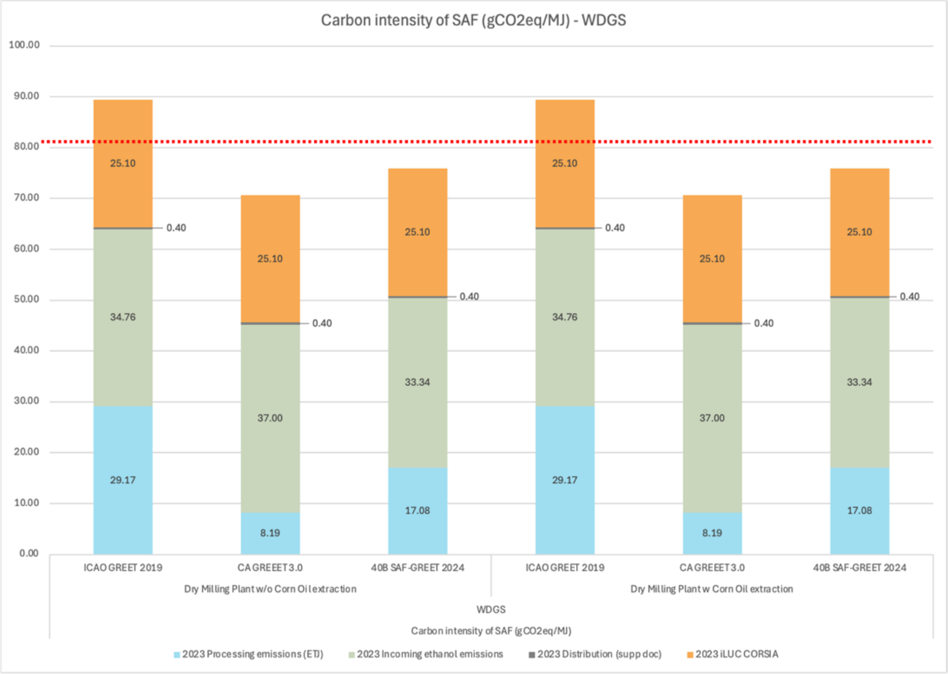


Figure 4 CI of SAF from corn ethanol following WDGS pathway in year 2023

A detailed examination of 33 and 34 data points for DDGS and WDGS pathways respectively is illustrated in Figure 5. From Figure 5, it can be noticed that the WDGS pathway easily reaches the required savings while the DDGS savings reaches the required savings in only one of the 34 data points of the DDGS pathway. In total, 67 certified pathways are displayed in Figure 5, collected across 44 different plants, with some plants certified for multiple pathways. According to the data collected regarding the production capacity of each plant, Figure 5 represents a total potential capacity of 6,218 million gallons of corn ethanol in the year 2023. As previously discussed in Chapter 4, incorporating green hydrogen or green electricity into the supply chain has the potential to meet the required savings, which could significantly reduce the CI of the SAF and help achieve the 10% savings threshold.

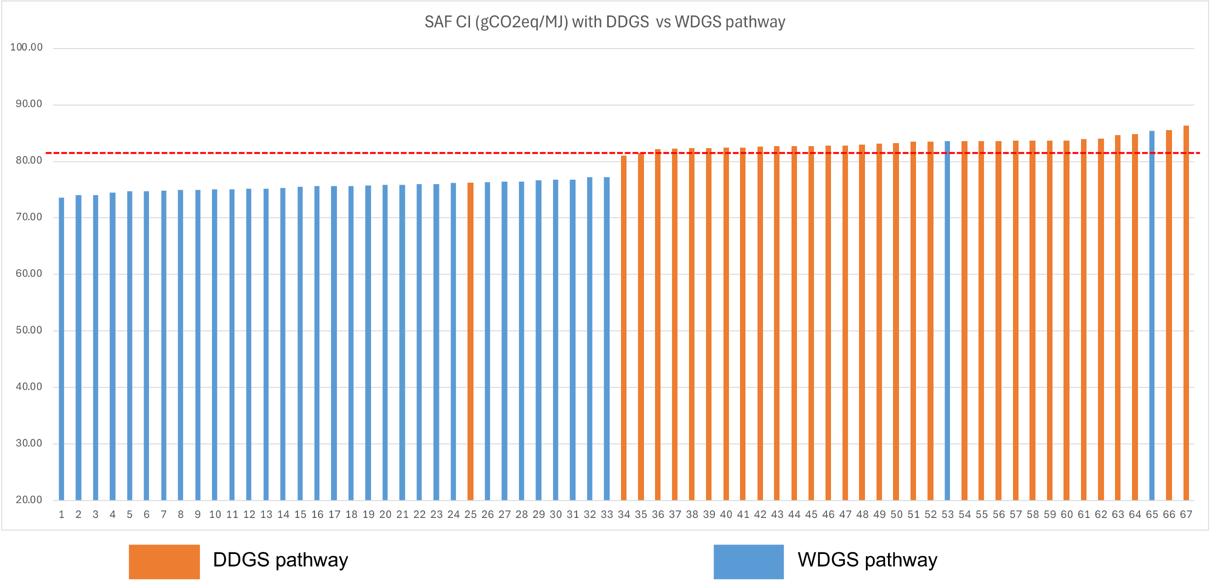


Figure 5 Total CI of SAF from ethanol following DDGS and WDGS pathway under 40B Modified model

The default values utilized in the 40B Modified model have been characterized as conservative by renowned researchers and experts in the US. To pursue this further, a concise sensitivity analysis was conducted, applying a 5% and 10% reduction in the total emissions of SAF CI, calculated using the 40B Modified model. The results of this analysis are presented in Figure 6 and Figure 7. From these figures, it is evident that when more optimistic values are assumed, the SAF from US corn ethanol successfully meets the required savings under the CORSIA methodology.

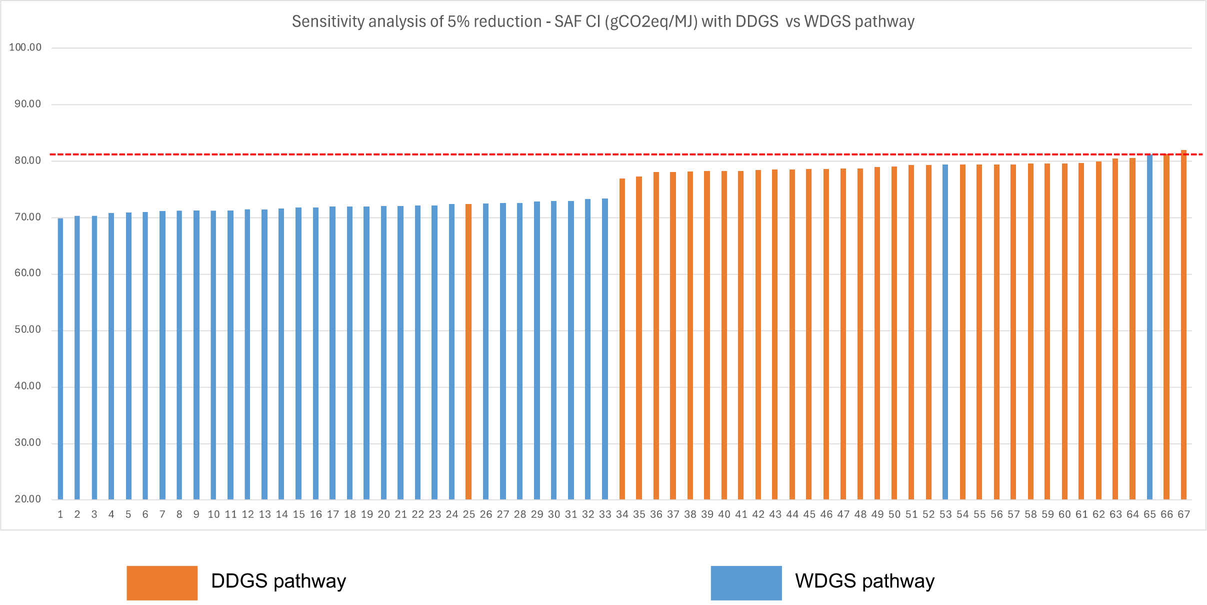


Figure 6 Sensitivity Analysis of 5% reduction in total CI of SAF from ethanol following DDGS and WDGS pathways under 40B Modified model

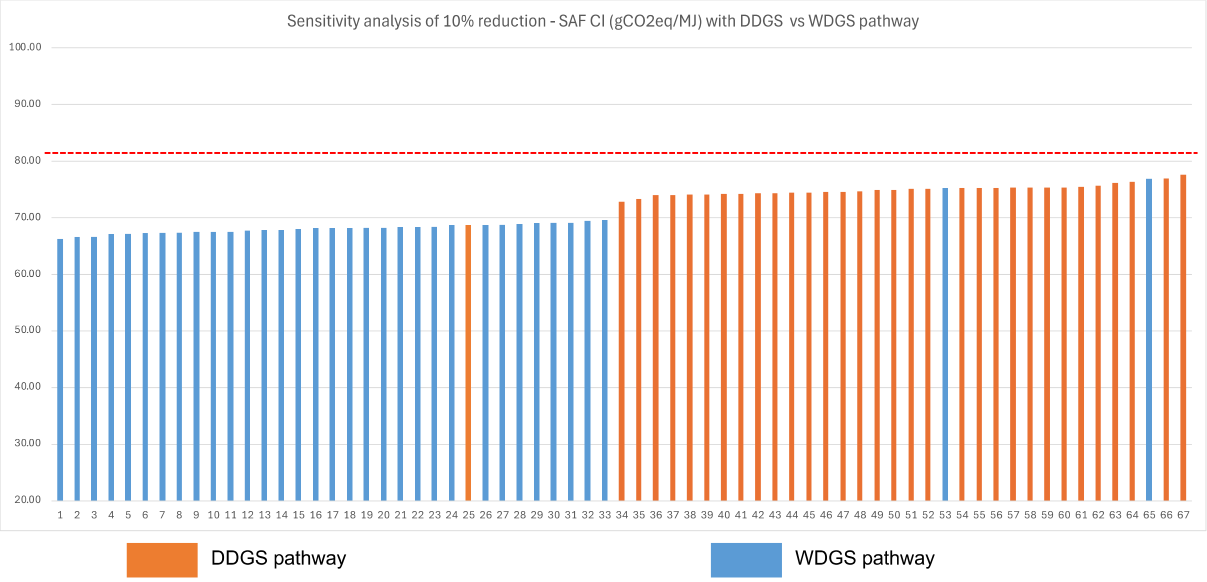


Figure 7 Sensitivity Analysis of 10% reduction in total CI of SAF from ethanol following DDGS and WDGS pathways under 40B Modified model

This analysis underscores the critical role of literature values in evaluating the environmental performance of SAF. It suggests that small adjustments in production processes could enable SAF to meet the required emissions savings under various regulatory frameworks. As a part of the study the CI values of each plant are then combined in a weighted average to further calculate the savings from the CI. Given that all literature data used in this analysis are conservative estimates and taken from databases publicly available, employing actual data from modern, plant-specific operations could further reduce the CI of SAF. This would improve the emissions savings, potentially allowing the resulting jet fuel to be classified as a CEF compliant under relevant regulations.

6 Conclusion

The principal objective of this report is to evaluate and calculate a weighted average CI score for U.S. corn ethanol producers who hold CARB LCFS certification. This assessment is of particular importance, as the ICAO CORSIA currently employs a default CI index of approximately 90.8 gCO_2eq/MJ for U.S.-produced corn ethanol. However, to meet the minimum savings requirement of 10% in comparison to the fossil jet fuel comparator under the CORSIA methodology, the SAF must have a CI of no more than 80.1 gCO_2eq/MJ SAF. Accordingly, this report is of considerable importance to ethanol producers in the United States, as it directly affects their capacity to contribute to the expanding SAF market.

One of the study's key achievements was the successful conversion of the displacement method of allocation, which is predominant in the US GREET model for the ethanol supply chain, to energy allocation, utilized in the CORSIA methodology. The results of this conversion were found to be positive and in alignment with existing studies, including those conducted in 2011. Moreover, existing models and literature were consulted to ascertain the consumption and conversion rates for ethanol to SAF production, with three primary models employed: the ICAO GREET 2019, the CA GREET 3.0, and the 40B Modified.

Nevertheless, the study was constrained by three limitations. First, there was an inconsistency in the availability of CI data for ethanol producers from 2016 to 2024. The data exhibited considerable variability over the study period, with no instance of consistent data availability for any single ethanol plant from 2016 to 2024. This resulted in a degree of variation in the CI of ethanol. Secondly, the study was constrained by the unavailability of plant-specific consumption and conversion rates for ethanol to SAF, as this process is not often applied at a commercial scale. The consumption and conversion rates utilized were derived from existing models; however, these models are based on conservative estimates. Lastly, it should be noted that the ICAO CORSIA framework permits the utilization of actual value calculations in instances where default values are unavailable or exceed actual values of existing pathway. Nevertheless, it is important to note that the ICAO default values are from 2019, and when compared to the default values from the other two databases studied in this report, they appear to be on the extremely conservative end of the spectrum. These values may also be outdated, given the technological advancements in the sector. For instance, the 40B Modified model still employs conservative estimates for processing inputs required to produce SAF from corn grain ethanol. Despite these conservative assumptions, the model demonstrates significantly better emissions savings when compared to the fossil fuel comparator used in the ICAO CORSIA methodology. This suggests that the potential of the SAF from corn ethanol to meet the CI requirements under CORSIA is possible, particularly when considering modern technology; more recent data and assumptions would likely show even higher carbon savings.

The decarbonization of the ethanol supply chain and the use of modern SAF production facilities make the classification of ethanol-derived SAF as a CEF increasingly feasible. This not only substantiates the viability of SAF for ethanol producers, but also presents them with a substantial opportunity to contribute to the SAF demand of airlines, thereby reinforcing the role of ethanol in the future of sustainable aviation.

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