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Ethanol's Petroleum Footprint

An Analysis of the Petroleum Energy Balance for Ethanol

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Executive Summary

Much analysis has focused on the energy used to generate a gallon of corn ethanol. To present that information from a different perspective, this research estimates the petroleum (in equivalent gallons of crude oil) and the natural gas (in cubic feet) that are used in the production of one gallon of corn-based ethanol. Figure 1 illustrates these findings.

Figure 1: Petroleum Use in Production of Ethanol from Corn

As highlighted in Table 1, petroleum use in ethanol production is minimal, with less than 0.04 gallons of crude oil being used to produce each gallon of fuel ethanol from corn. While petroleum is used in corn farming, and also in the transportation of corn and ethanol, these processes use relatively little energy from petroleum per gallon of ethanol.

Compared to petroleum, natural gas is a more used energy input to produce fuel ethanol from corn, with around 31 cubic feet of natural gas being used to produce one gallon of fuel ethanol from corn. Natural gas use is primarily from the production of nitrogen fertilizer used in corn farming and as a fuel input in ethanol fuel production. Petroleum and natural gas combined account for 95 percent of the total energy used for

fuel ethanol production from corn. Most of the energy used is for ethanol fuel production as compared to corn farming, corn transport, and ethanol transport.

Table 1: Petroleum Use and Natural Gas Use to Produce Fuel Ethanol from Corn

Stages of Energy Use	**Ethanol's Share of Total Petroleum Use,** in equivalent gallons crude oil/ gallon ethanol	**Ethanol's Share of Total Natural Gas Use,** in equivalent cubic feet natural gas/ gallon ethanol
Corn Farming	0.018	5.90
Corn Transport	0.007	0.10
Ethanol Fuel Production Energy Use	0.00	25.18
Ethanol Transport	0.007	0.00
Total Energy Used	**0.032**	**31.18**

Note: Ethanol Fuel Production Energy Use includes energy use for the co-production of Distiller's Grains and Solubles (DGS).
Sources: DOE Argonne Labs GREET1 2022 Model; RFA "Corn Ethanol's Energy Balance Continues to Improve", April 2022; authors' calculations.

The Department of Energy's Argonne National Laboratory developed a now widely-used model, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, that is used for Life-Cycle Analysis of transportation fuels. The 2022 version was used as a primary data source of these estimates, supplemented with data from the Energy Information Administration, the United States Department of Agriculture, and various other sources.

Additional background on corn ethanol production, as well as further discussion on the factors that can affect the estimated energy use in ethanol production from corn is also included in the report.

Introduction and Background on Corn Ethanol and Energy Use

The U.S. corn ethanol industry requires several inputs, including corn grain and energy from a variety of energy sources to convert corn grain into ethanol for fuel use. Much research has been conducted on the energy balance of corn ethanol, most often as a measure of energy per gallon of ethanol produced, or as a ratio of energy in versus energy out, or the "energy balance" of ethanol. These metrics are often given as the net energy in Btu per gallon of ethanol.

As defined by the U.S. Energy Information Agency (EIA), British thermal unit (Btu) is a measure of the heat content of fuels or energy sources. One Btu is the quantity of heat required to raise the temperature of one pound of liquid water by 1° Fahrenheit (F) at the temperature that water has its greatest density (approximately 39° F).[1]

This report focuses on the types of energy used to produce corn ethanol. It builds on existing research to estimate the petroleum used to produce a gallon of ethanol from corn grain. As a point of comparison, the natural gas used to produce a gallon of ethanol from corn is also included.

The analysis includes energy used for manufacturing of farm machinery, energy used by that machinery for farming, energy used indirectly in farming to produce fertilizers and pesticides, energy used for transportation of corn to ethanol plants, energy used for the ethanol production process, and energy used for the transport of ethanol.

Ethanol is a fuel alcohol produced through a fermentation process that is highly concentrated to remove water and blended with compounds to make the fuel undrinkable. Corn is one of many feedstocks that can be used to produce ethanol. Through this fermentation process, yeast convert sugars to ethanol and carbon dioxide. Corn is a valued feedstock for ethanol because of the high concentration of starches in corn grain, which can readily be converted to the simple sugars that fuel the ethanol production process. Beyond capturing the ethanol and potentially the carbon dioxide produced through this process, commercial ethanol production typically captures other byproducts as well. For example, carbon dioxide that is captured can be compressed and used for carbonation of soft drinks or for production of dry ice.

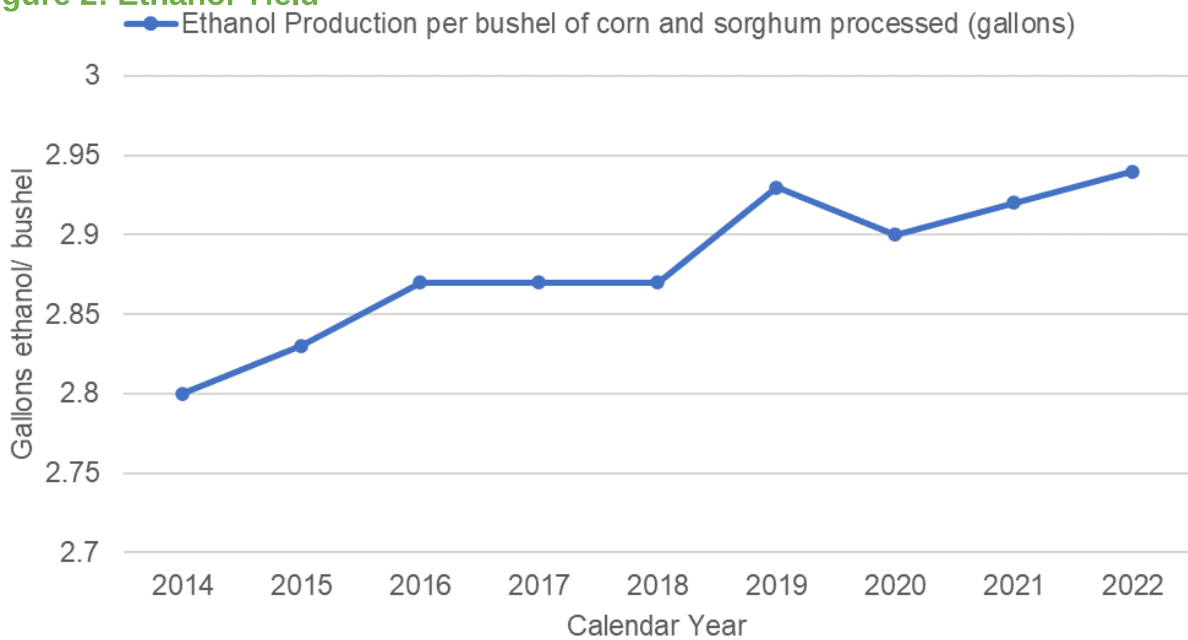
Ethanol dry mills are the most common type in the United States. In these mills, residual components of ethanol production are gathered in later stages of ethanol production and are known as co-products. An animal feed called Distiller's Dried Grains with Solubles (DDGS) is commonly produced, or this co-product can be sold without drying to nearby markets as wet distiller's grains. Dry mill ethanol plants also extract corn distiller's oil (CDO), which can be used as an animal feed or as an input into biodiesel or renewable diesel production. Corn gluten meal and corn gluten feed are co-products of the ethanol wet milling process. The relationship of some of these co-products, in particular distiller's grains with solubles and CDO, with the ethanol energy estimate is discussed in more detail later in the report.

Another factor in the efficiency of ethanol production and its energy use is the yield of ethanol per bushel of corn. This metric of the efficiency of ethanol production has continued to improve, based on USDA observed yields in gallons of ethanol per bushel of corn of 2.5 in 1980, 2.666 in 1998, and 2.68 in 2002.[2] In data estimates for 2022, these yields have improved to 2.94 gallons of ethanol per bushel of corn and

[1] U.S. Energy Information Agency. Units and Calculators Explained.
[2] U.S. Energy Information Agency. "Monthly Energy Review." December 2023.

sorghum processed.[3] Trends in the ethanol yield per bushel of corn and sorghum processed for 2014 through 2022 are shown in the following figure. These trends are relevant because the assumption on the amount of corn used for the ethanol production process implies various amounts of energy inputs that were used to produce that corn, as well as the amount of energy that is captured in the ethanol production process.

Figure 2: Ethanol Yield



Note: Ethanol volume produced includes denaturant.
Source: farmdoc daily, University of Illinois at Urbana-Champaign. March 1, 2023.

Research by the Renewable Fuels Association[4] has reviewed the energy efficiency of ethanol plants and has also found improvements in ethanol plant efficiency over time. Regardless of whether considering a co-product credit to account for energy of co-products or not, and whether considering the average for the industry or the top quartile of ethanol mills, there was observed improvement in the energy balance ratio of ethanol from corn from 2016 to 2021. (The energy balance ratio is a measure of how much energy a fuel source provides compared to the energy needed to produce and distribute the fuel). RFA's research found that following multi-year improvements, corn ethanol's energy balance ratio is 2.8 to 3.0 on average, and the top 25 percent of facilities have a ratio of 3.7 to 4.0. Improvements in the energy inputs relative to outputs at ethanol facilities can reflect improvements in the quantity of other energy used in ethanol production.

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[3] Irwin, S. "Trends in the Operational Efficiency of the U.S. Ethanol Industry: 2022 Update." farmdoc daily (13):37, Department of Agricultural and Consumer Economics, University of Illinois at Urbana-Champaign, March 1, 2023.

[4] Renewable Fuels Association. "Corn Ethanol's Energy Balance Continues to Improve", April 2022. https://d35t1syewk4d42.cloudfront.net/file/2216

Analysis

As mentioned previously, much analysis has focused on the energy used to generate a gallon of corn ethanol. To consider that subject from a different perspective, this analysis, summarized in the table below, provides the volume of petroleum (equivalent gallons of crude oil) and natural gas (cubic feet) needed to produce a gallon of corn-based ethanol.

Table 2: Petroleum Use and Natural Gas Use to Produce Fuel Ethanol from Corn

Stages of Energy Use	**Ethanol's Share of Total Petroleum Use,** in equivalent gallons crude oil/ gallon ethanol	**Ethanol's Share of Total Natural Gas Use,** in equivalent cubic feet natural gas/ gallon ethanol
Corn Farming	0.018	5.90
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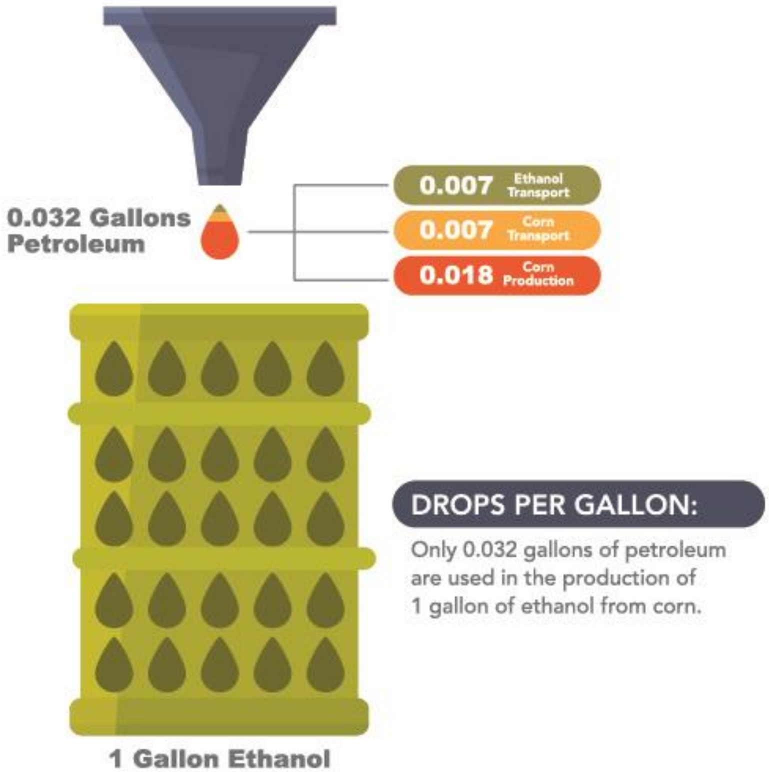
Note: Ethanol Fuel Production Energy Use includes energy use for the co-production of Distiller's Grains and Solubles (DGS).
Sources: DOE Argonne Labs GREET1 2022 Model; RFA "Corn Ethanol's Energy Balance Continues to Improve", April 2022; authors' calculations.

As highlighted in the table above, petroleum use in ethanol production is minimal, with less than 0.04 gallons of crude oil being used to produce each gallon of fuel ethanol from corn. While petroleum is used in corn farming, and transportation of corn and ethanol, these processes use relatively little energy from petroleum per gallon of ethanol, as illustrated in the following figure.

Figure 3: Petroleum Use in Production of Ethanol from Corn



Natural gas is a more important energy input to produce fuel ethanol from corn, with around 31 cubic feet of natural gas being used to produce one gallon of fuel ethanol from corn, not considering the allocation of a portion of the energy usage to co-product output. Natural gas use is primarily from the production of nitrogen fertilizer used in corn farming and as a fuel input in ethanol fuel production. Petroleum and natural gas combined account for 95 percent of the total energy use for fuel ethanol production from corn.

Examining this energy use in more detail, the table below provides additional detail of the calculations of petroleum use and natural gas use to produce fuel ethanol from corn. Most of the energy used is for ethanol fuel production as compared to corn farming, corn transport, and ethanol transport.

To assist in understanding the following detailed table, a description of each row and the columns are provided here:

- Columns for stages of fuel ethanol from corn

- ‘Corn Farming’ includes the energy used directly in farming corn for ethanol, as well as the energy used indirectly for production of fertilizer, crop protection products, and machinery used.
    - ‘Corn Transport’ includes energy used for transportation of corn from the field to the ethanol production facility.
    - ‘Ethanol Fuel Production Energy Use’ includes energy used by the ethanol plant for production of ethanol fuel.
    - ‘Ethanol Transport’ includes energy use for transportation of ethanol fuel to the fuel pump. These calculations conservatively assume 100% of the fuel used for transport of ethanol, which is primarily by rail, truck, or barge, is from petroleum.
    - ‘Total Energy Used’ is the sum of the prior 4 columns.
- ‘Ethanol’s Share of Total Energy Use’ provides the quantity of energy used for each phase of fuel ethanol production from corn, in Btu per gallon of ethanol produced.
- ‘Of Total Energy Use, Share as Petroleum’ gives the percentage from petroleum of the total energy used for the respective stage of the process.
- ‘Of Total Energy Use, Share as Natural Gas’ gives the percentage from natural gas of the total energy used for the respective stage of the process.
- ‘Of Total Energy Use, Share from Other Sources’ gives the percentage from energy sources other than petroleum and natural gas of the total energy used for the respective stage of the process. For corn ethanol, these other energetic inputs are coal and electricity. The shares from petroleum, natural gas, and other sources sum to 100% for each stage (column) of the process.
- ‘Petroleum Energy Use’ gives the amount of energy derived from petroleum, measured in Btu per gallon of ethanol produced, for the respective stage of the process.
- ‘Natural Gas Energy Use’ gives the amount of energy derived from natural gas, measured in Btu per gallon of ethanol produced, for the respective stage of the process.
- ‘Ethanol's Share of Total Petroleum Use’ converts the petroleum energy use to equivalent gallons crude oil per gallon ethanol.
- ‘Ethanol's Share of Total Natural Gas Use’ converts the natural gas energy use to equivalent cubic square feet of natural gas per gallon ethanol.

Table 3: Detailed Petroleum Use and Natural Gas Use to Produce Fuel Ethanol from Corn

Stages of Energy Use	Corn Farming	Corn Transport	Ethanol Fuel Production Energy Use	Ethanol Transport	Total Energy Used
Ethanol's Share of Total Energy Use, Btu/gallon ethanol	9,453	1,028	26,925	993	**38,399**
Of Total Energy Use, Share as Petroleum	26%	88%	0%	100%	**11%**
Of Total Energy Use, Share as Natural Gas	65%	10%	97%	0%	**84%**
Of Total Energy Use, Share from Other Sources	9%	1%	3%	0%	**4%**
Petroleum Energy Use, Btu/ gallon ethanol	2,494	907	0	993	**4,394**
Natural Gas Energy Use, Btu/ gallon ethanol	6,108	108	26,083	0	**32,298**
Ethanol's Share of Total Petroleum Use, in equivalent gallons crude oil/ gallon ethanol	0.018	0.007	0.00	0.007	**0.032**
Ethanol's Share of Total Natural Gas Use, in equivalent cubic feet natural gas/ gallon ethanol	5.90	0.10	25.18	0.00	**31.18**

Note: "Other Sources" of energy use includes coal and electricity. Ethanol Fuel Production Energy Use includes energy use for the co-production of Distiller's Grains and Solubles (DGS).
Source: DOE Argonne Labs GREET1 2022 Model; RFA "Corn Ethanol's Energy Balance Continues to Improve", April 2022; authors' calculations.

The Department of Energy's Argonne National Laboratory developed a now widely-used model, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model, that is used for Life-Cycle Analysis of transportation fuels. The 2022 version was used as a primary data source of these estimates. In general, default assumptions of that model with regards to corn ethanol production were maintained.

When calculating energy use and source, proportionate composite value ethanol yield per bushel and energy used per gallon is used for Dry Milling without Corn Oil, Dry Milling with Corn Oil, and Wet Milling. Most of the ethanol production in the United States with Dry Milling with Corn Oil production, at 85.5 percent share of plants producing ethanol from corn as the value in the GREET model.

The value of energy used for ethanol transport draws from RFA's 2022 analysis of ethanol's energy balance, which in turns reflects the value used by USDA in its 2016 analysis of ethanol's energy balance.

The conversion factors presented in the table below were also utilized in the calculations.

Table 4: Conversion Factors Used

Description	Value	Notes/ Source
Energy content of 1 cubic foot of natural gas (Btu/cubic foot)	1,036	EIA, 2022 preliminary estimate
Gallons per barrel	42	EIA
Energy content of 1 barrel of crude oil produced in the U.S. (Btu/barrel)	5,684,000	EIA, 2022 preliminary estimate
Energy content of ethanol (Btu/gallon)	76,300	RFA 2022 Corn Ethanol's Energy Balance Continues to Improve
Starch fraction	0.66	USDA OCE OEPP 2016, "2015 Energy Balance for the Corn Ethanol Industry"

Sources: EIA, RFA, USDA (respectively, as indicated in table).

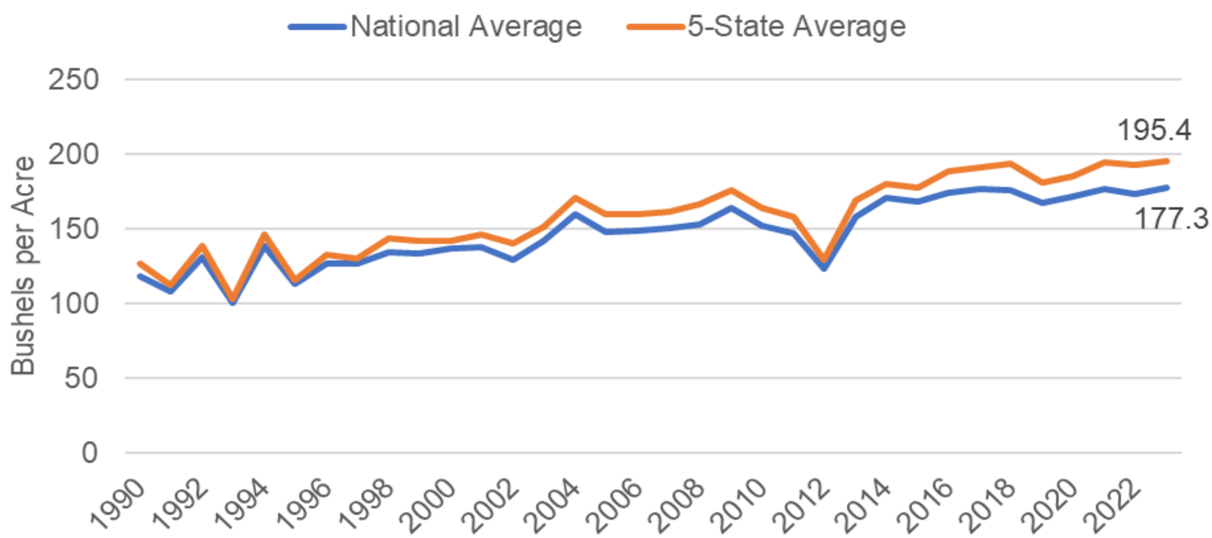
Further Discussion

This further discussion section provides additional context on factors such as corn yields, corn inputs, and ethanol production that can affect estimates of the energy use of production of fuel ethanol from corn.

Corn Yields

Corn yields in the U.S. have continued to improve over time. This analysis assumes corn yields of 178.4 bushels per acre. This value is very similar to the 2023 USDA corn grain national average yield of 177.3 bushels per acre. However, corn is grown in many states in the U.S., some with higher average yields and some with lower yields, and some with larger volumes of production and some with lower volumes of production. Ethanol production is most concentrated in the key corn producing regions of the U.S., where both corn production and yields are higher. The 5-state average for the 5 highest corn grain production states (2023 values for Iowa, Illinois, Nebraska, Minnesota, and Indiana) is 195.4 bushels per acre, about 10% higher than the national average corn yield. These yields and trends over time are compared in the figure that follows.

Figure 4: National and 5-State Average U.S. Corn Yields



Note: 5-states are Illinois, Iowa, Indiana, Minnesota, Nebraska.
Source: USDA NASS, authors' calculations.

The implication of the higher corn yields in the major corn and ethanol producing region of the U.S. is that the estimated energy use for corn farming per bushel of corn production may be an overestimate, and that the yield assumption used by the GREET1 model likely indicates higher energy use from petroleum and natural gas than would be found with a higher yield assumption, all else being equal. However, the degree of this difference is complex to estimate because of the relationship between input use and yields. Sometimes, higher input use is needed, particularly higher nitrogen fertilizer use, to achieve higher yields. However, we expect this would affect the estimated natural gas use more than petroleum use.

Corn Inputs

Beyond the improvements over time in corn yields in the U.S., farmers are also producing that yield more efficiently. Corn farming in the U.S. typically requires large nitrogen fertilizer inputs, as well as a number of passes across the fields for any tillage practices, planting, application of fertilizer and crop protection products, harvest, and crop residue management. USDA ERS[5] found that improvements in corn production efficiency have also come from improved genetics and seeding technology. USDA ERS also reports that in 2016, nitrogen was applied to 96 percent of U.S. corn acres, and that in 2016 there were an average of 3.6 herbicide treatments per acre, along with an average of 0.13 insecticide treatments per acre and 0.13 fungicide treatments per acre.

Adjustments in the use of corn inputs over time has the potential to affect the use of petroleum and natural gas per acre, with increased fertilizer use or increased crop protection product use causing a corresponding increase in the energy used per gallon of ethanol produced, all else being equal. In an on-farm situation, there will be impacts in both direction as the use of these inputs likely also is protective of or improves yields.

Ethanol Production Assumptions

Like the improving efficiencies in the production of corn, ethanol production processes have also continued to improve over time.

The analysis assumes the following ethanol yields for each type of ethanol plant, and the following ratios of types of plants. These assumptions provide a weighted average ethanol yield of 2.85 gallons of ethanol per bushel of corn for the analysis.

Table 5: Ethanol Yield Assumptions

	Dry Milling Plant without Corn Oil Extraction	Dry Milling Plant with Corn Oil Extraction	Wet Milling Plant
Ethanol yield: gallons per bushel of corn	2.84	2.86	2.74
Share of Corn Ethanol Plant Types	4.5%	85.5%	10.0%

Note: Ethanol yield does not include denaturant.
Source: DOE Argonne Labs GREET1 2022 Model.

As existing ethanol plants continue to improve their efficiencies, as new ethanol milling technologies develop, and as new facilities are built using the latest technologies, ethanol yields are likely to continue the trend of improvement over time.

The GREET1 2022 model does include a reflection of some of this improved technology. Values are given for use of "1.5 gen ethanol dry milling with corn oil extraction" (newer technology where the outer layer of

[5] Monica Saavoss, Tom Capehart, William McBride, and Anne Effland. ERR-294, July 2021. Trends in Production Practices and Costs of the U.S. Corn Sector, U.S. Department of Agriculture, Economic Research Service.

the corn kernel is removed to be converted to ethanol). This technology is assumed to have an ethanol yield of 3.13 gallons per bushel of corn for the facilities using this newer technology.

Distiller's Grains and Solubles (DGS) and Net Energy Usage Associated with Ethanol Production

These total energy calculations include the energy used in ethanol production for the co-production of Distiller's Grains and Solubles (DGS). These coproducts can either be marketed dried or wet, which impacts the amount of energy used to dry the DGS. Energy used for drying distiller's grains is typically from natural gas. Prior research from RFA[6] provides a co-product credit of 14,717 to 16,591 Btu per gallon of ethanol produced, equivalent to a reduction in energy use of 29.3% to 41.3% (depending on the original data used) when adjusting from gross energy use to net energy use. Because this energy use is at the ethanol production stage, and the energy use at the ethanol production stage is 97% natural gas[7], it can be assumed that applying a co-product credit to the total energy use would reduce the calculated energy use of natural gas by 13.76 to 15.51 cubic feet of natural gas per gallon of ethanol when net of coproduct production.

Corn Distiller's Oil

These calculations do not fully capture the processing of Corn Distiller's Oil (CDO), which is its own energetic pathway. Removal of CDO, as reflected in prior RFA analysis[8], has an impact on ethanol's energy efficiency. CDO can be used as a feedstock for biodiesel or renewable diesel production. As reflected above, the vast majority of ethanol plants extract CDO from distiller's grains. Although the energy use (primarily electricity) is modest, CDO is an energy output generated in addition to the energetic value of each gallon of ethanol. The GREET1 2022 model estimates 0.78 pounds of corn oil are extracted per bushel of corn, with an energy use of 183 Btu per pound of corn oil, or 143 Btu per bushel of corn; 100% of that energy use is from electricity. While we have matched the GREET1 2022 model assumptions and used the most conservative assumption of not including the CDO pathway as further improving the energy efficiency of ethanol production, were the CDO energy pathway fully included, the overall energy efficiency of ethanol production would be improved but the explicit use of petroleum and natural gas to generate a gallon of ethanol would be minimally impacted.

[6] RFA 2022, "Corn Ethanol's Energy Balance Continues to Improve".
[7] DOE Argonne Labs GREET1 2022 Model
[8] RFA 2022, "Corn Ethanol's Energy Balance Continues to Improve".

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