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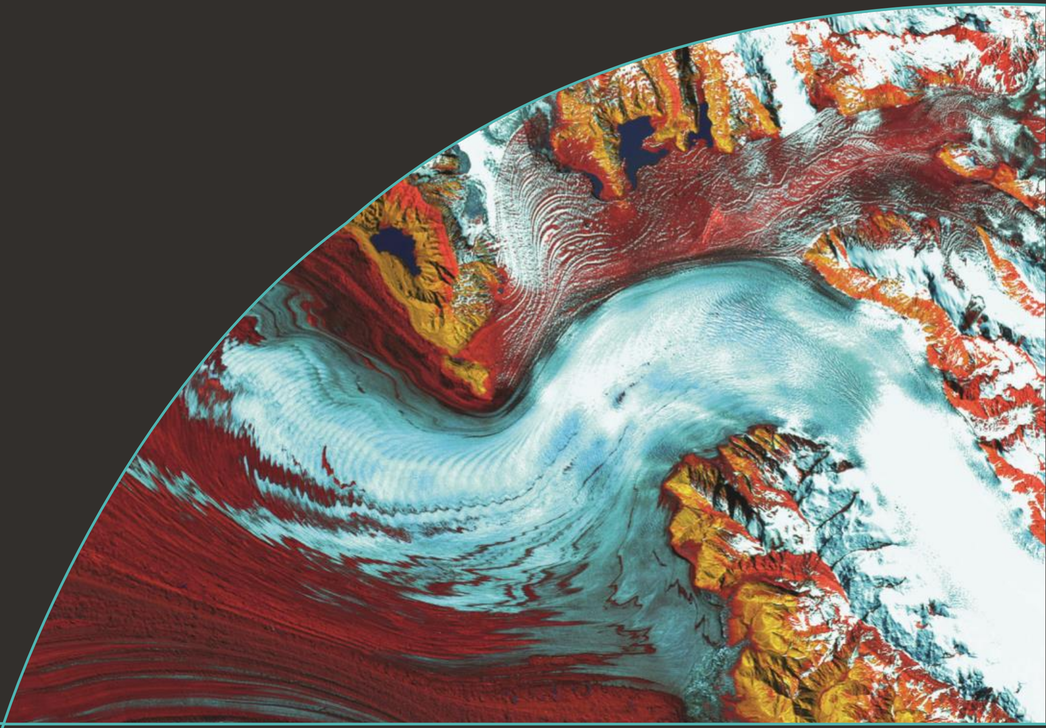
Merging Strategy, Technology, and Tax Incentives in Ethanol Production

Prepared for:
Renewable Fuels Association (RFA)
Topic 2 Report



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	List of Acronyms Used
AD	Anaerobic Digestion
ATJ	Alcohol-to-Jet
ANL GREET	Argonne National Laboratory Greenhouse gases, Regulated Emissions, and Energy use in Technologies model
CARB	California Air Resource Board
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture, Utilization, and Sequestration
CFPC	Clean Fuels Production Credit
CHP	Combined Heat and Power
CI	Carbon Intensity
CKF	Corn Kernel Fiber
DDGS	Dried Distiller's Grains with Solubles
DOE	Department of Energy
EOR	Enhanced Oil Recovery
EVs	Electric Vehicles
ILUC	Indirect Land-Use Change
IRA	Inflation Reduction Act
LCFS	Low Carbon Fuel Standard
RFA	Renewable Fuels Association
RFS	Renewable Fuel Standard
RNG	Renewable Natural Gas
TS	Thin Stillage
USEPA	U.S. Environmental Protection Agency
VFD	Variable Frequency Drive
WDG	Wet Distillers' Grains

Section 1: Executive Summary

The opportunity and need for ethanol producers to merge strategy, technology, and tax incentives have never been greater. The opportunity comes from the Inflation Reduction Act (IRA) tax incentives for low-carbon renewable fuels under Section 45Z and for carbon capture, utilization, and sequestration (CCUS) under Section 45Q. The need comes from the overall push for decarbonization in the transportation sector expressed by government policies and consumers who provide advantages to the choice of electric over internal combustion passenger vehicles.

Ethanol producers with a clear decarbonization strategy are fortunate in today's low-carbon policy and consumer demand environment, which they see as an opportunity. Their focus is on completing the decarbonization projects in time to secure the 45Z tax advantages over the 2025-2027 tax years and the 45Q tax advantages on CCUS over 12 years. These producers seek to optimize IRA funding to help pay for decarbonization projects. Once qualified for 45Z or 45Q, these producers will likely continue to decarbonize as each carbon intensity (CI) point reduction improves their bottom line. As early adopters of low-CI production, they will have increased their net worth and ability to expand production compared to their higher-CI neighbors. Most importantly, they will set themselves up for long-term ethanol demand for low-CI vehicle markets and alcohol-to-jet (ATJ) projects.

In contrast, ethanol producers without a clear decarbonization strategy may consider themselves unfortunate in today's low-carbon policy and consumer demand environment, which they see as a risk. They may not be located near a CCS reservoir or carbon dioxide (CO_2) pipeline project. They may criticize the lack of clarity on how 45Z will be implemented and what projects will qualify. They may hope for long-term demand for their higher-CI ethanol in non-differentiated higher blend markets and their CO_2 in tightened industrial markets. They may disagree with the emphasis on decarbonization by policymakers and consumers and point to disadvantages placed on ethanol carbon scoring. They may disagree with the focus on electric vehicles (EVs) in passenger vehicles. These are valid perspectives that should be addressed. However, ethanol producers without a clear decarbonization strategy must consider themselves at risk when evaluating market preferences, higher prices, and tax and carbon removal incentives going to low-CI plants.

As the IRA 45Z window prepares to open from January 1, 2025, to December 31, 2027, this study analyzes the CI-reduction strategies that can be implemented to participate in the incentive program.

The analysis sets a baseline for an average combined ethanol (starch and fiber) of 52.2 kg CO_2e/MMBtu. It points producers toward the possible CI-reduction technologies they can implement to reach a US$0.10 per gallon (/gal) 45Z credit at 45.0 kg CO_2e/MMBtu. Technologies considered include combined heat and power (CHP), biogas, renewable electricity, waste heat capture, membrane dehydration, process improvements, and CCS.

The following specific recommendations are made for ethanol producers navigating their way toward lower-CI ethanol production:

- Establish a site-specific baseline CI score for your facility using Argonne National Laboratory's (ANL) Greenhouse gas, Regulated Emissions, and Energy use in Technologies (GREET) model.
- Consider unique site characteristics such as CCS, biomass-based heat, a CO_2 pipeline, and renewable electricity. Doing so may provide an implementation advantage at your facility.
- Consider the universal characteristics of your facility, including corn kernel fiber (CKF), CHP, and membrane dehydration.
- Make incremental improvements in yield and efficiency to reach the first credit generation threshold:
    - Cellulase applications for CKF ethanol when using a combined starch and fiber score.
    - Corn oil separation.
    - CHP applications
    - Thermal oxidizers and better waste heat recovery integration and optimization.
    - Fermentation and enzyme optimization, working with yeast and enzyme suppliers toward specific objectives.
- Consider opportunities requiring larger expenditures that deliver more considerable CI reductions:
    - Biogas from stillage and other locally accessible low-cost feedstocks (stillage waste, manure, food waste) into integrated CHP systems.
    - CCS opportunities.
    - CO_2 pipeline opportunities.
    - Renewable energy integration.
- Continue to watch for guidance on the following topics under 45Z:
    - CCU guidance on CI scoring related to displacement and permanence.
    - Guidance on qualifying sources of renewable energy.
    - General guidance on qualifications, calculations, and rounding.

Section 2: Introduction

As the global community grapples with the impacts of climate change, there is an increasing focus on developing sustainable low-carbon energy sources across industries. The U.S. ethanol industry is primed to meet the challenges of these climate impacts with the ability to significantly reduce carbon emissions from transportation by decreasing the CI of low-carbon fuels such as ethanol. The IRA marks the single largest investment in climate and energy in American history. Supporters tout the IRA as a means of tackling climate challenges, advancing environmental justice, securing America's position as a world leader in domestic clean energy manufacturing, and putting the U.S. in a position to achieve climate goals, including a net-zero economy by 2050. Criticisms to date include the lack of guidance on the qualification for the IRA incentives in time to implement the low-carbon strategies necessary to participate. This report aims to evaluate technology adoption and other steps that ethanol facilities can take to lower their CI to capture the IRA Clean Fuel Production Credit (45Z) value in the narrow available timeframe. This report is intended to provide specifics on the most impactful steps that can be taken through 2027.

The Clean Fuels Production Credit (CFPC or 45Z) is a tax-based production incentive to reduce the CI of transportation fuels further. The incentive is available from January 1, 2025, through December 31, 2027, for fuel producers that meet the program requirement of a CI threshold below 50 kg CO_2e/MMBtu (47.4 g CO_2e/MJ). This incentive has the potential to serve as a driver for the adoption of low-carbon technologies by providing a financial lever to absorb costs associated with implementation.

IRA 45Z creates incentives that scale with the magnitude of CI reduction with a maximum potential credit of $1.00/gal for fuels with a CI of 0 g CO_2e/MJ that fully meet prevailing wage and apprenticeship requirements. This scaling is driven by an emissions factor multiplier that rounds all emissions rates to the nearest multiple of 5 kg CO_2e/MMBtu, except for rates between 2.5 kg CO_2e/MMBtu and -2.5 kg CO_2e/MMBtu, which may be rounded to 0 kg CO_2e/MMBtu.[1] It is unclear at this time whether the rule will maintain the rounding to the "nearest" increment or if it will be revised to only round "up to" the nearest multiple.

shows sample credit breakdowns per ton of fuel produced by fuel type and compliance with the wage and apprenticeship requirements at assumed CO_2e emissions rates.[2] The reduction thresholds will be measured using a version of ANL GREET, although specific guidance has not yet been released.

The emissions factor for credit generation is determined using the following formula:

$$\text{Emissions Factor} = \frac{\left(50\ \frac{\text{kg CO}_2\text{e}}{\text{MMBtu}}\right) - \left(\text{Fuel}\ \frac{\text{kg CO}_2\text{e}}{\text{MMBtu}}\right)}{50\ \frac{\text{kg CO}_2\text{e}}{\text{MMBtu}}}$$

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[1] 26 U.S. Code § 45Z - Clean fuel production credit

[2] https://crsreports.congress.gov/product/pdf/IF/IF12502

Throughout this paper, the units for the emissions factor of kg CO_2e/MMBtu will be used interchangeably with g CO_2e/MJ. The following conversion can be used for reference:

$$1\ \frac{\text{g } CO_2e}{\text{MJ}} = 1.05505585\ \frac{\text{kg } CO_2e}{\text{MMBtu}}$$

Table 2.1: Estimated §45Z Clean Fuel Production Credit Values[3]

IRA CFPC Sample Thresholds for Credit Generation	Converted to Common Unit in Industry	Emissions Factor Multiplier	Base Incentive $/gal (Not Meeting Wage and Apprenticeship Measures)	Incentive $/gal with 5x Multiplier for Meeting Wage/Apprenticeship Measures
50 kg CO_2e/MMBtu	47.4 g CO_2e/MJ	0	0	0
40 kg CO_2e/MMBtu	37.9 g CO_2e/MJ	0.2	0.04	0.20
25 kg CO_2e/MMBtu	23.7 g CO_2e/MJ	0.5	0.10	0.50
10 kg CO_2e/MMBtu	9.5 g CO_2e/MJ	0.8	0.16	0.80
0 kg CO_2e/MMBtu	0 g CO_2e/MJ	1.0	0.20	1.00

In addition to the CI threshold requirement, federal prevailing wage and apprenticeship requirements must also be met to qualify for the entire 45Z tax incentive. This report does not attempt to include a detailed evaluation of tax law. Ideally, ethanol producers will engage a professional tax consultant well-versed in IRA incentives to support the qualification of any low-carbon project.

This report evaluates available technologies and related CI impacts through the lifecycle analysis of ethanol production. It discusses viable technology options to meet the IRA 45Z timeline and deliver a tax benefit.

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[3] Adapted from Table 1 of Congressional Research Service's Publication: The Section 45Z Clean Fuel Production Credit. IF12502 (congress.gov)).

Section 3: Ethanol CI Baseline

The ethanol industry has historically met economic challenges by increasing market demand and expanding into new markets for its co-product portfolio. However, the IRA has placed a direct relationship between CI and tax credit value for the first time. In other words, it is not just what you produce but how you produce it. This has the potential to impact the broader ethanol landscape by allowing low-CI producers to thrive and expand while legacy, high-CI producers face growing market headwinds. As such, 45Z presents a risk to legacy ethanol producers and an opportunity for progressive, forward-thinking ethanol producers with the potential to significantly assist in implementing low-carbon initiatives. Before considering low-CI technology adoption, it is critical to understand the current CI landscape of U.S. corn-based ethanol production and the magnitude of the challenge to meeting the requirements of 45Z.

A CI score for an ethanol production facility must be calculated using a certified and verifiable CI model. In the case of IRA 45Z, the U.S. Department of Energy (DOE) has developed, in conjunction with ANL, the GREET model. This tool examines the lifecycle impacts of technologies, products, and energy systems. It provides a transparent platform to calculate total energy consumption (non-renewable and renewable), air emissions, greenhouse gas (GHG) emissions, and water consumption. The GREET model was used by the U.S. Environmental Protection Agency (USEPA) to create the Renewable Fuel Standard (RFS) in 2005 and as the basis for the California Air Resource Board's (CARB) Low Carbon Fuel Standard (LCFS) program in 2009.

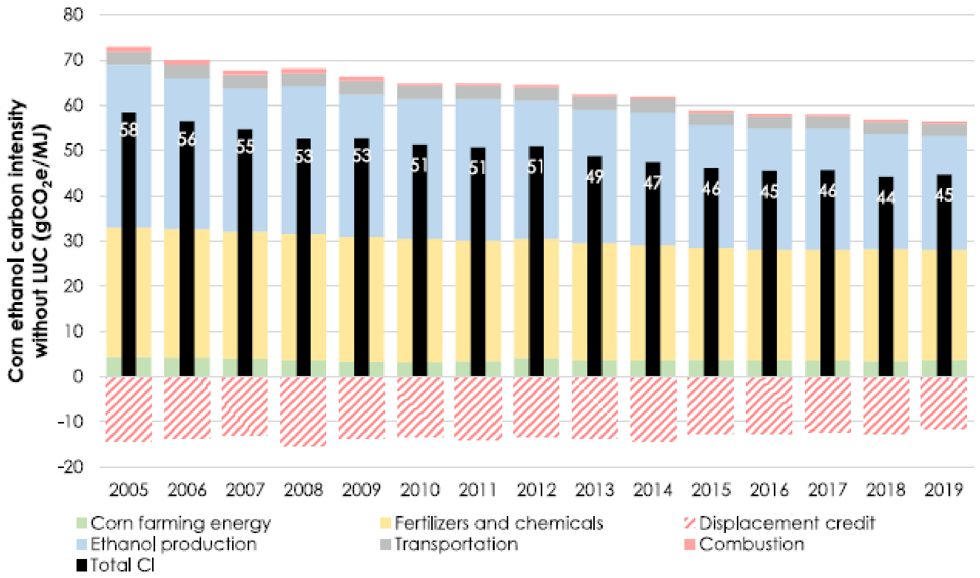
To discuss options for reducing the CI of ethanol and corn kernel fiber (CKF) ethanol, we first must establish the existing baseline and what operations and lifecycle stages fall within the current goal. For this report, technologies must fit within the existing footprint of the typical ethanol plant or one incorporated unit of operation. Developing attached assets, such as piping CO_2 from fermentation to a methanol or ethanol fermentation plant, is out of the scope of this report due to techno-economic feasibility and timing restrictions for credit availability. It may be worth further investigation if facilities can plan and deploy capital for projects of this magnitude in time to generate an additional 45Z credit.

The average or typical corn-based dry mill ethanol plant has reflected continual CI improvement since the beginning of the RFS deployment, as shown in Figure 3.1 from the Lee et. al. study.[4] IRA 45Z expected values will be generated from an ANL GREET model, the specific version of which will be included in the coming guidance.

In 2022, ethanol biorefineries captured roughly 2.8 million tons of CO_2, which was used for dry ice production, bottling, food processing, and other uses.[5] On average, one bushel of corn (56 lbs) run through a dry mill ethanol facility, the process of which is shown in Figure 3.2, results in:

- ~2.9 gallons of denatured ethanol
- ~15.1 lbs of distillers' grains animal feed at 10% moisture content
- ~16 lbs of biogenic CO_2[6]

Figure 3.1: CI of Corn Ethanol Without LUC from 2005-2019[4]



Although lifecycle emissions of ethanol production have decreased over time, reaching the qualifying CI threshold under 45Z will require a dedicated effort for most facilities.

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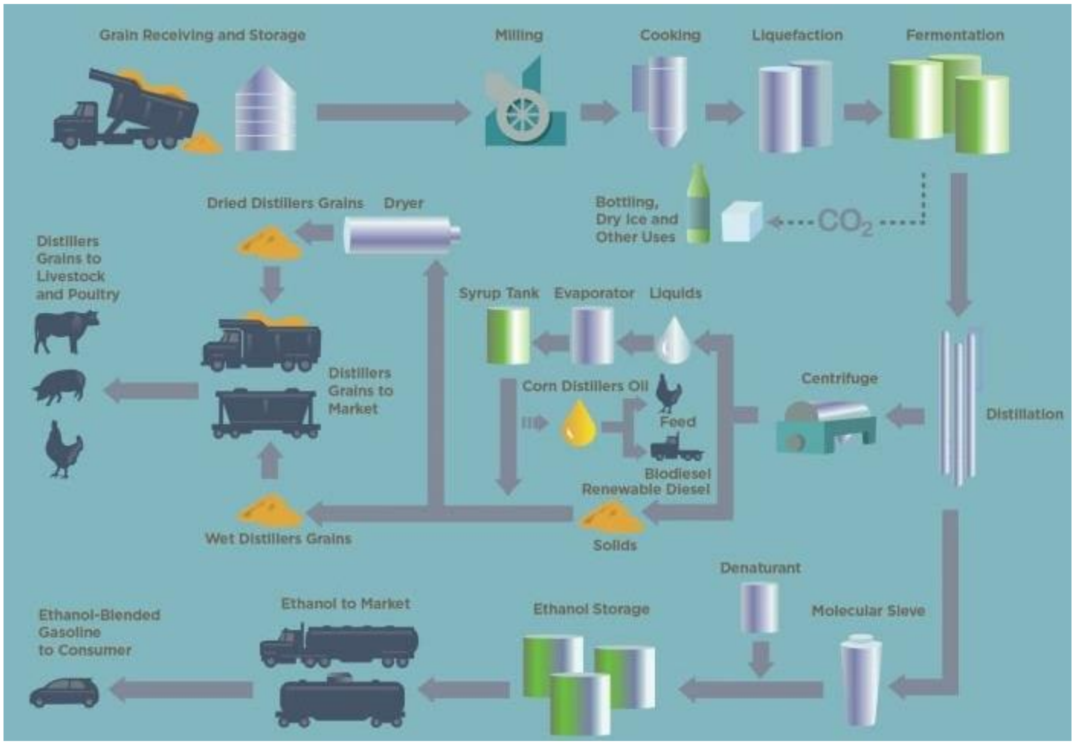
[4] U. Lee et al Biofuels, Bioprod. Bioref. 15:1318–1331 (2021); DOI: 10.1002/bbb.2225.

[5] RFA based on U.S. Department of Agriculture (USDA) data: How Ethanol is Made (ethanolrfa.org).

[6] Approximately 30% of U.S. dry mills capture CO2 from fermentation, per RFA: How Ethanol is Made (ethanolrfa.org).

Figure 3.2: Dry-Mill Ethanol Process[7]



Corn starch ethanol must drop from an average of 49.8 g CO_2e/MJ to at least 37.9 g CO_2e/MJ to generate a $0.04/gal credit. This represents a targeted 11.9 g CO_2e/MJ reduction for the lowest credit threshold. CKF with an average CI of 26.4 g CO_2e/MJ may already qualify for a $0.04/gal incentive and sits 2.7g CO_2e/MJ away from generating $0.10/gal. Note that the guidance provided may or may not recognize the CKF pathway, leaving the generation of credits in uncertain territory. Table 3.1 shows the lifecycle emission rates of ethanol production and use split into process stages and parameters.

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[7] How Ethanol is Made (ethanolrfa.org)

Table 3.1: Life Cycle Breakdown of Corn and Corn Fiber Ethanol Production and Use[8]

Parameter	Combined Ethanol CI g CO_2e/MJ	Combined Ethanol CI kg CO_2e/MMBtu
Corn Farming and Transport	25.6	27.0
Co-Product Credits	-13.5	-14.2
Ethanol Production	31.4	33.1
Ethanol Transport and Distribution	2.2	2.3
Combustion	0.5	0.5
Total Undenatured Ethanol Without Indirect Land-Use Change (ILUC)	46.2	48.7
ILUC	7.4	7.8
Total Undenatured Ethanol	53.6	56.6

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[8] Argonne National Laboratory. GREET 2020. GREET 1 Series (Fuel-Cycle Model): Argonne National Laboratory; 2020.

Section 4: Site Characteristics and Implementation Time

Ethanol producers face several challenges in meeting the 45Z CI threshold of 50.0 kg CO_2e/MMBtu, but the most significant hurdle is the three-year crediting period. The incentive is available from 2025 through 2027, so any low-carbon strategies producers invest in must meet a tight timeline. The due diligence required to research, adopt, integrate, and commission a low-carbon strategy could span two to three years, making it nearly impossible for ethanol producers to benefit from 45Z. Therefore, ethanol producers need to be mindful of focusing their efforts and investments on projects that meet associated timelines. Although IRA guidance is still forthcoming, it remains to be seen whether advocacy for an extension of the 45Z timeline will be successful.

When considering which low-CI technologies to pursue, ethanol producers will first want to consider the site-specific characteristics of their production facility, which may put them at an implementation advantage. Second, they will want to consider the time to implement compared to the 2025-2027 timeframe of 45Z. Table 4.1 provides an overview of low-CI technologies, site characteristics, category, and potential CI impact (High is >10 CI, Medium is > 5 CI points, Low is > 1 CI point) and time to implement (High is > 2 years, Medium is > 1 year, Low is > 6 months).

Table 4.1: Site Characteristics Impacting the Selection of Low-CI Technology[9]

Low-CI Technology	Site-Specific Characteristic	Category	Potential CI Impact	Time to Implement
CCS	Access to a suitable CO_2 sequestration reservoir near the site	Site-Specific	High	High
Biomass-Based Heat	Access to renewable biomass feedstocks for combustion or anaerobic digestion	Site-Specific	Medium	Medium-High
Low-CI Farm Practices	Areas with high yield and sustainable agricultural practices	Site-Specific	High	Medium-High
Renewable Electricity	Access to wind and solar	Site-Specific	Low-Medium	Medium
CCS	Access to CO_2 pipeline	Pipeline-Specific	High	High
Kernel Fiber Ethanol	Not applicable	Universal	Low-Medium	Low
CHP	Not applicable	Universal	Medium	Medium
Membrane Dehydration	Not applicable	Universal	Low-Medium	Medium
CCU	Not applicable	Universal	Unknown	Medium-High

With 45Z taking effect from January 1, 2025, through December 31, 2027, many projects with high implementation times cannot be completed within the short schedule. Some medium-time projects, like CHP, may achieve a window of 45Z participation. Some low-time project types, like kernel fiber, have time to begin and participate in 45Z on fiber gallons.

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[9] Developed by EcoEngineers

Section 5: Strategy, Partnerships, and Funding

Chapter 5.1: Strategy and Partnerships

Ethanol producers are actively engaged in a multifaceted approach to navigate the challenges associated with lowering carbon emissions that must be aligned with the timelines set forth by 45Z. Ethanol producers are investing heavily in cutting-edge technologies to optimize every stage of the ethanol production process. These include novel advancements in feedstock selection and processing, fermentation, energy inputs, and new product development, all aimed at enhancing efficiency and yields while reducing energy consumption. Many of these innovations require major plant or operational design changes, such as waste heat recovery systems and integrating sustainable energy sources like solar and wind. These internal R&D initiatives taken by ethanol producers are essential for both CI reduction and capturing future tax credits.

Ethanol producers are also forging strategic partnerships with research institutions, government agencies, and industry collaborators to leverage collective expertise and resources. Collaborative R&D efforts allow for pooling knowledge and exploring novel solutions to common challenges. For example, partnerships with agricultural researchers may focus on developing more sustainable and climate-resilient feedstocks, while collaborations with technology companies may explore implementing advanced monitoring and control systems to optimize ethanol plant performance. These external alliances enhance the industry's collective ability to meet the ambitious carbon emission-reduction targets required for the ethanol industry to take advantage of tax incentives like 45Z.

The following are examples of existing low-CI partnerships (from publicly available information):

- Western Plains Energy and Whitefox have announced the installation of membrane dehydration technology. Whitefox indicates a reduction in carbon emissions of up to 1.5 CI points.[10]
- Calgren Renewable Fuels and RONDO teamed up on a renewable fuel case study to evaluate the use of Rondo Heat Battery to capture renewable electricity and store it as process heat in brick materials.[11]

Chapter 5.2: Funding Mechanisms

Ethanol producers, recognizing the importance of R&D in achieving low-carbon emissions and alignment with 45Z incentives, are actively tapping into various funding mechanisms to support their innovative plans. These include government grants, private investments, tax incentives, and collaborations with academic institutions. One primary avenue for financial support is government grants and subsidies tailored to promote sustainable practices and carbon reduction in the biofuel industry.

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[10] "Western Plains to install Whitefox ICE-XL system" | *Ethanol Producer Magazine*; Whitefox ICE® - Membrane-based cartridge technology

[11] "Rondo Energy adds thermal energy storage at Calgren biorefinery" | *Biodiesel Magazine*; Calgren Renewable Fuels Case Study – Rondo Energy

Ethanol producers often apply for grants from agencies such as the DOE and the USDA, which offer funding programs dedicated to advancing clean energy technologies and supporting the development of biofuels with lower environmental impact. These grants provide crucial financial support for R&D projects and signify the government's commitment to incentivizing the transition to more sustainable energy sources.

Furthermore, ethanol producers are exploring partnerships with private investors, venture capital firms, and strategic industry collaborators to secure additional R&D funding. An example would be a private investment to evaluate nearby CCS storage reservoirs. Private sector involvement brings capital and valuable industry insights and networks, fostering an environment conducive to innovation. Joint ventures and collaborations allow ethanol producers to pool resources, share risks, and access expertise that can accelerate the development and implementation of low-carbon emission technologies. Private funding mechanisms often come with an expectation of a return on investment, highlighting the dual objectives of achieving sustainability goals while ensuring the economic viability of R&D initiatives.

Examples of existing grants and loans:

- USDA and Gevo signed a Climate-Smart Commodities grant agreement for up to $30 million.[12]
- USDA awarded a $25 million loan to Red Trail Energy LLC for its CCS project.[13]
- USDA awarded $177,635 in Rural Energy for America Program (REAP) grant funds to support a retrofit project that aims to boost ethanol production capacity by 8.1 MMgy.[14]

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[12] "Gevo, USDA sign agreement for climate-smart commodities grant" | *Biomass Magazine*

[13] "USDA awards $25M loan to Red Trail Energy for CCS project" | *Ethanol Producer Magazine*

[14] "USDA announces REAP awards, opens new funding round" | *Biodiesel Magazine*

Section 6: Low-CI Technologies

Chapter 6.1: Yield and Efficiency

Yield and efficiency are the initial areas for improvement affecting all ethanol producers. The goal is to get more ethanol from a bushel of corn and reduce process energy (primarily natural gas and grid electricity) in ethanol production. The use of specialized corn hybrids and advancements in enzymes and yeast may be included here, as well as improvements in electrical, mechanical, and heat recovery systems.

Chapter 6.2: Corn Kernel Fiber (CKF) and Cellulosic Ethanol Incorporation

The IRA incentives have great potential for cellulosic ethanol to improve ethanol and corn oil yield and plant operating efficiency by adding cellulase enzyme and co-processing CKF with starch ethanol. The IRA guidance has yet to make clear whether separate pathways will be allowed for CKF vs. starch, as California allows, or whether it will approve only combined pathways, as in Canada. If the regulation allows separate CKF pathways in the 20 CI range, virtually all producers may qualify based on part of their gallons and would be eligible for a $0.60/gal (CKF) benefit. If the regulation allows only combined pathways, CKF ethanol production will still be necessary as an incremental CI benefit.

Chapter 6.3: Carbon Capture and Storage (CCS) Technologies

Carbon capture technologies are mature technologies utilized in ethanol facilities for decades. A DOE report shows that ethanol plants account for 41 of the 104 U.S. industrial facilities currently capturing commercial CO_2.[15] Due to its high purity (>99%), capturing CO_2 from ethanol facilities does not require expensive post-processing (to remove sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter), depending on the specific process and setup – unlike other industrial sources (Figure 6.1). According to the DOE, an estimated 27 million metric tons per year (MMmt/year) of CO_2 could be captured via carbon capture technologies for $17.60/MT to $33.40/MT, with an average price of $27 per metric ton (/MT).[16] In November 2023, the average LCFS credit price was $70/credit (one LCFS credit equals one metric ton of avoided GHG emissions). This pricing suggests that CO_2 capture and storage from ethanol production is not only an affordable emissions abatement technique, but it could also provide potentially valuable tax credits through reduced ethanol CI.

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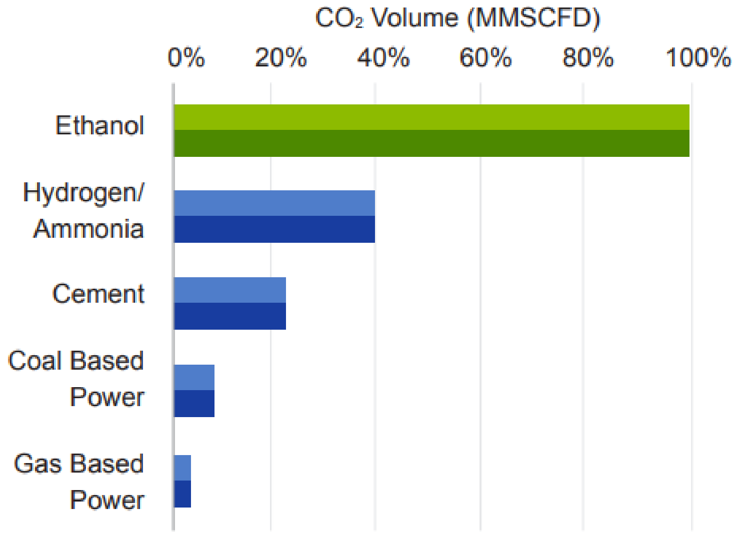
[15] https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

[16] https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf

Figure 6.1: CO_2 Concentration in Waste Gas from Industrial Processes[17]



Storing CO_2 in an underground geological formation is a new approach the ethanol industry is adopting to take advantage of the 45Z tax credits. As the credits significantly incentivize underground CO_2 sequestration, facilities near suitable geological formations can use the direct injection process. Around 65 ethanol plants have the potential for direct CO_2 injection without requiring pipeline transport. Figure 6.2 shows the location of saline storage, potential capacity, and potential industrial CO_2 sources.

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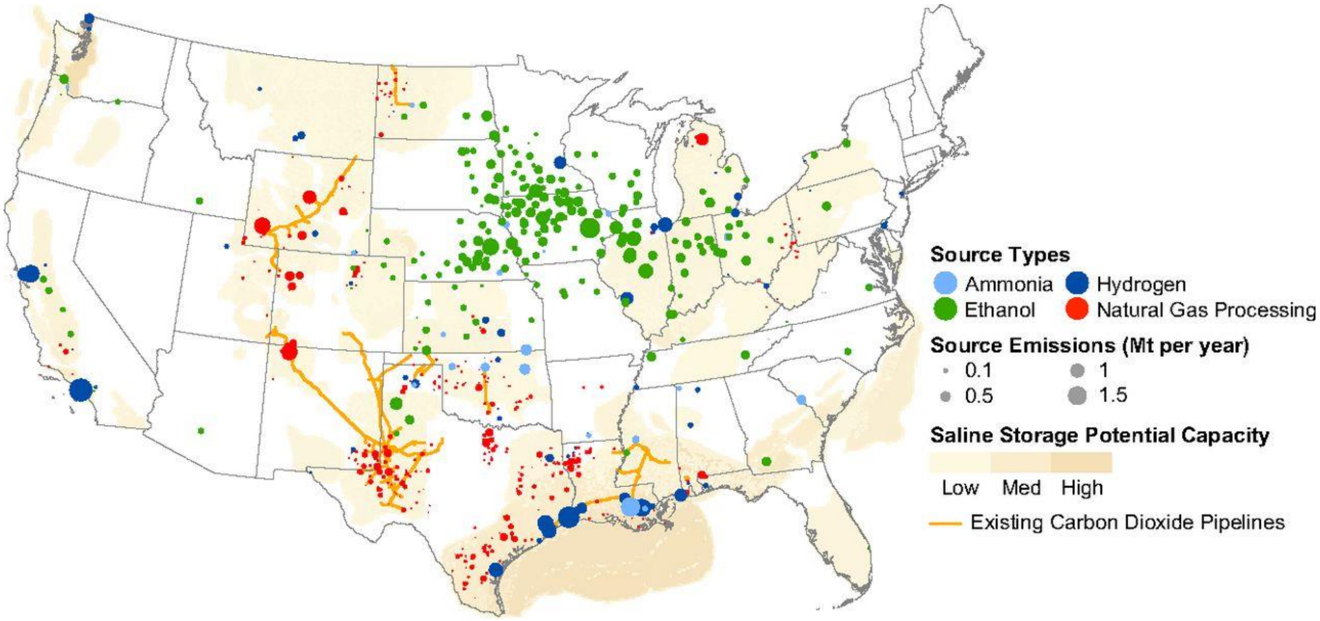
[17] CO_2-EOR Deployment Work Group, 2017

Figure 6.2: Low-Capture-Cost CO_2 Emissions in the U.S., Existing CO_2 Pipelines, and Potential Saline Storage Formations[18,19]



It is evident in Figure 6.2 that most Midwestern ethanol plants are not located near a geological formation or existing CO_2 pipeline and would require pipeline construction to transport captured CO_2 to the sequestration sites. The economy of scale for pipeline transport necessitates generating larger volumes of CO_2 from multiple ethanol plants to be cost-effective. Figure 6.3 shows the planned CO_2 transportation pipeline connecting midwestern regions with the geological formations. The Navigator CO_2 pipeline project has been canceled and some former Navigator plant partners have since joined the Summit Carbon Solutions pipeline project.

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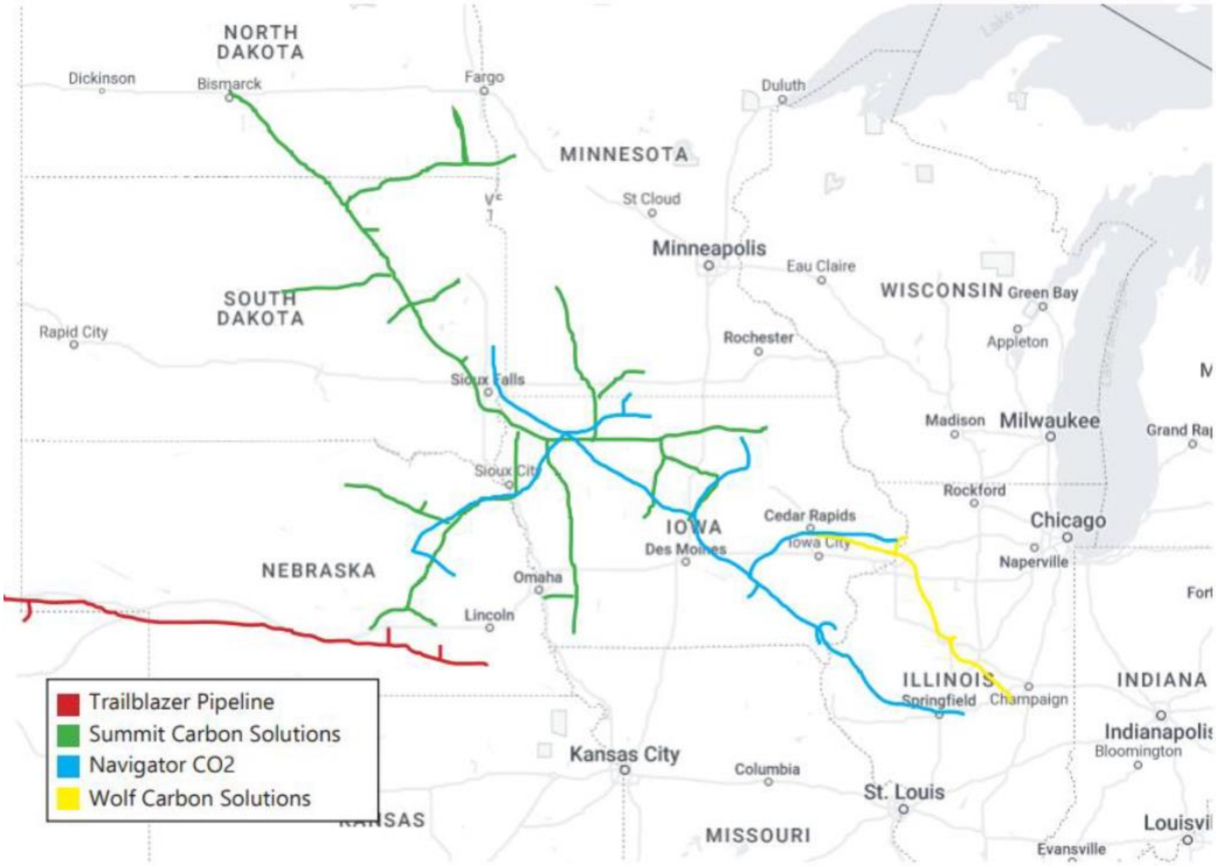
[18] Edwards, R. W., & Celia, M. A. (2018). Infrastructure to enable deployment of carbon capture, utilization, and storage in the United States. Proceedings of the National Academy of Sciences, 115(38), E8815-E8824. https://doi.org/10.1073/pnas.1806504115

[19] Co-located sources are summed so that the total emissions are observable.

Figure 6.3: Map of Proposed CO_2 Transportation Pipelines[20]



CCS technologies such as capture, transport, and injection are very mature and have been implemented by the oil and gas industry for decades for enhanced oil recovery (EOR). The underground storage can safely contain injected CO_2 and comply with environmental safety regulations.

The energy demand for the CCS from ethanol plants varies based on the plant production capacity. The estimated electricity demand for a 400 MT/day ethanol facility ranges between 135-142 kWh/MT of CO_2 produced, whereas a plant with 100-250 MT/day ethanol would require between 160-170 kWh/MT. The GREET 2022 default value is 180 kWh/MT CO_2 based on Red Trail Energy LLC's operational data.

The CI of an ethanol facility retrofitted with CCS depends on the efficiency of CO_2 capture and the energy demand for the CCS process. Based on the ANL GREET model, with a 97.5% capture efficiency and electricity demand of 198.6 kWh/MT of CO_2 captured, the total GHG reduction is 31.4 CO_2e/MJ (from a baseline of 52.2 g CO_2e/MJ). It includes CO_2 capture, liquefaction, pipeline transportation, and deep-well injection processes.

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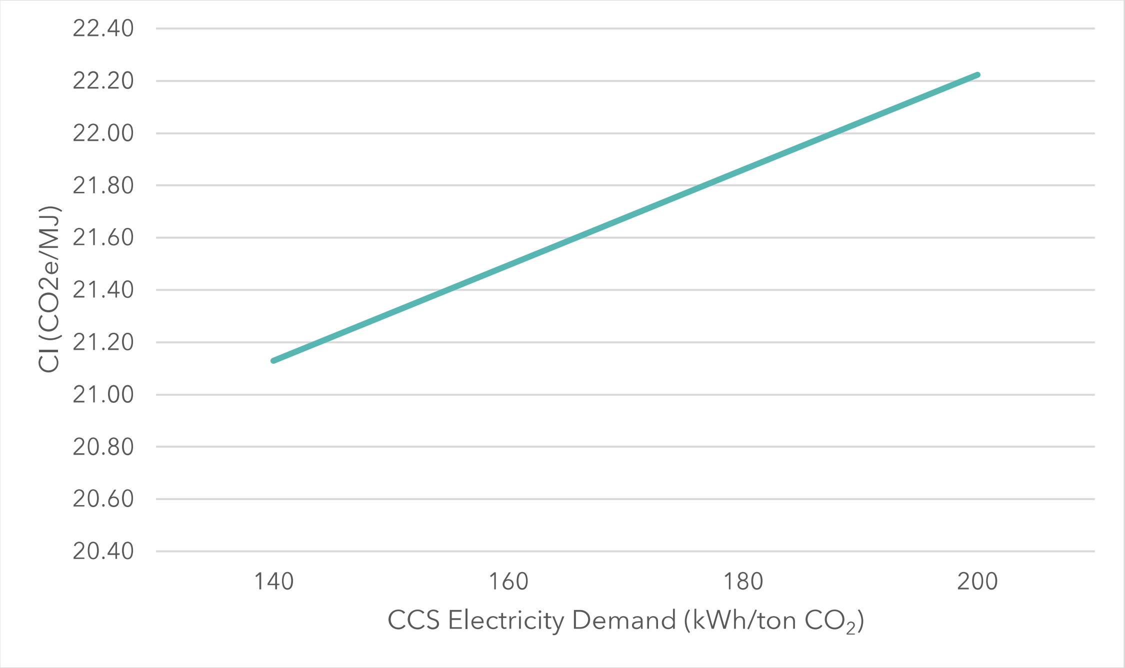
[20] The Latest Exciting Work from the DIS Team - Decision Innovation Solutions (decision-innovation.com).

Based on GREET 2022, the CI score increases proportionally with the CCS energy demand. Figure 6.4 gives an overview of the rate of change in CI regarding the CCS energy demand.

Figure 6.4: CI Score Relative to CCS Energy Demand[21]



Examples of existing projects:

- An Archer Daniels Midland (ADM) demonstration project stored 1 MT of CO_2 in Decatur, Illinois, between 2011–2014.
- Red Trail Energy captures 180,000 MT of CO_2 annually and stores fermentation CO_2 from its ethanol plant in Richardton, North Dakota in the Broom Creek Formation.
- The Blue Flint Ethanol facility in Underwood, North Dakota, has recently started injecting about 200,000 MT of CO_2 annually into the Broom Creek Formation.
- Two ethanol plants in Colorado—Sterling Ethanol LLC and Yuma Ethanol LLC[22] and one plant in Nebraska, Bridgeport Ethanol[23] have started implementing CCS in their respective facilities.

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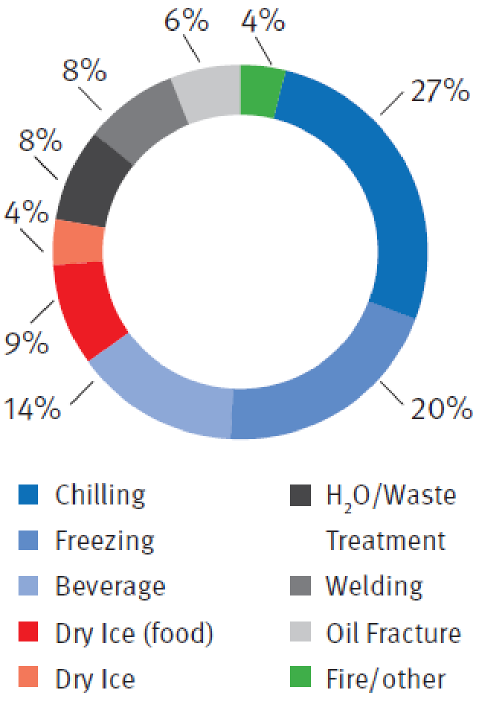
[21] Generated by EcoEngineers based on GREET 2022 values.
[22] *Ethanol Producer Magazine*, 2022
[23] *Biofuels International Magazine*, 2022

Chapter 6.4: Carbon Capture and Utilization (CCU) Technologies

Another promising opportunity for ethanol producers for CI reduction is the potential for utilizing captured carbon. Carbon utilization is a broad term to describe the many ways that captured carbon oxides – principally CO_2, and in some cases, carbon monoxide (CO) – can be used as is or to produce economically valuable products or services. Current uses for CO_2 in commercial markets are summarized in Figure 6.6. Ethanol production is the largest source (36%) of CO_2 produced from industrial sources and used for commercial applications in the U.S. These commercial applications do not result in permanent sequestration of CO_2. Note that although CO_2 is captured via photosynthesis, carbon storage via increased net biomass stocks and the conversion of plant-based biomass for fuels and other uses without subsequent carbon capture and sequestration are considered outside the scope of this report.

Ethanol facilities in the U.S. are major sources of pure CO_2 produced during fermentation, generating 2.85 kg of CO_2 for each gallon of ethanol. According to the DOE's "Industrial Decarbonization Roadmap", 210 ethanol plants located in the U.S. emit approximately 32 MMmt/year of biogenic CO_2, roughly 27 MMmt of which may be captured with existing CCS technologies.[24] Figure 6.6 illustrates the vast array of potential carbon utilization options (including those that result in emissions upon use).

Figure 6.5: U.S. CO_2 Demand by Application – 2020[25]



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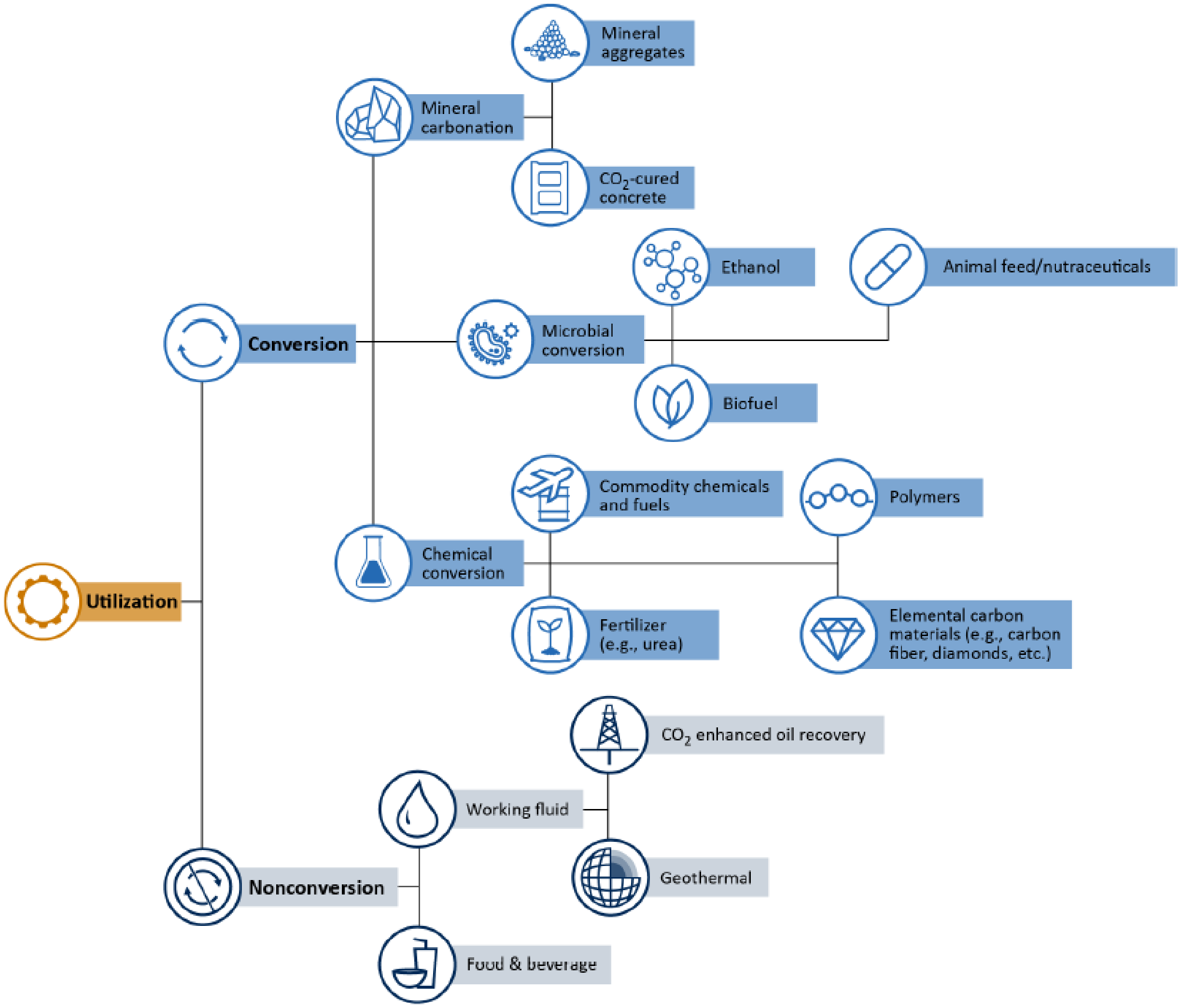
[24] Industrial Decarbonization Roadmap (energy.gov)
[25] Intelligas Consulting

Figure 6.6: CO_2 Utilization Options[26]



Each carbon utilization pathway has specific characteristics in terms of technical maturity, market potential, economics, societal impact, and lifecycle impact. Similarly, certain biological conversion technologies economically generate nutraceuticals at a relatively small scale. Utilization pathways differ in permanence or removing CO_2 from the atmosphere. Ongoing research seeks to improve cost and performance in existing markets and develop technologies capable of expanding into new markets. Technologies that produce fuels and chemicals are at earlier stages of development and require additional research and development to improve process efficiencies and drive down costs.

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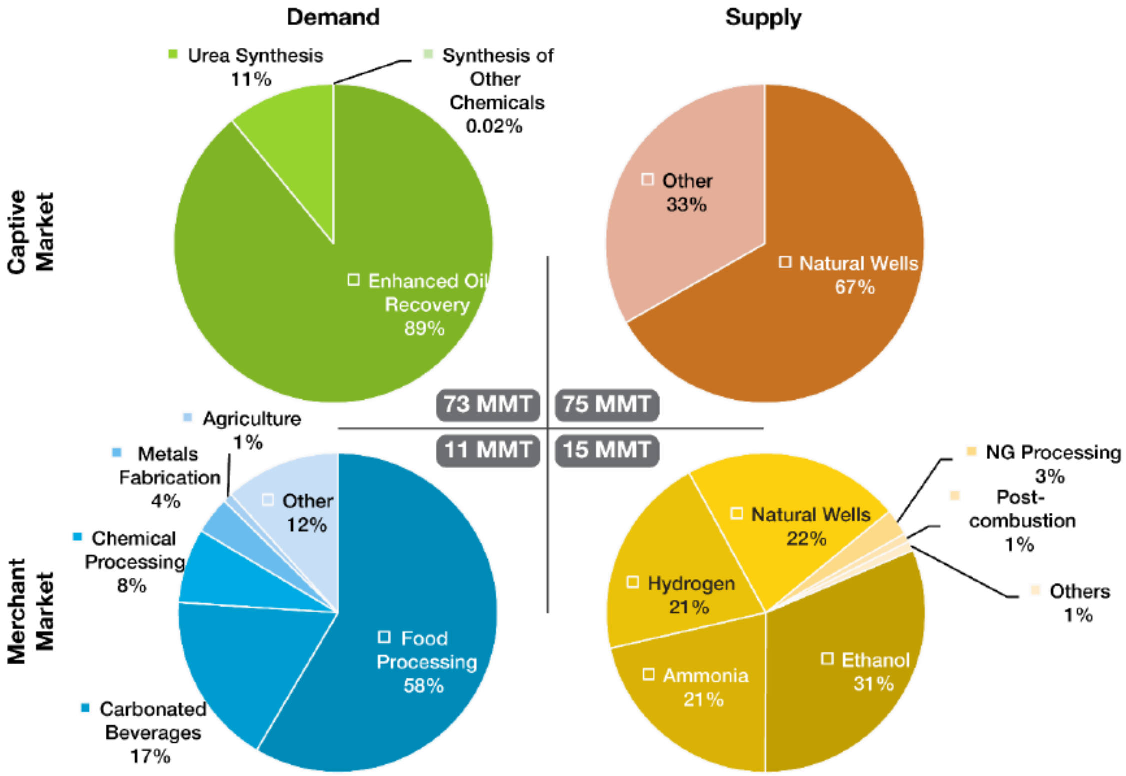
[26] GAO analysis of reports: GAO-22-105274.

Global industrial CO_2 utilization is over 230 MMmt, mostly in conventional industries, known as merchant markets, like fertilizer production, EOR processes, food and beverage production, metal fabrication, refrigeration, and plant growth in greenhouses. The major issue with diverting CO_2 to the merchant market is the concept of displacement and permanence. Some uses of CO_2 are transient, such as in beverages, where the CO_2 is utilized and quickly released into the atmosphere on consumption. Other uses of CO_2, such as in improved concrete weathering, result in more permanent storage, as demonstrated in Figure 6.7. The scientific community is divided on treating these displacement cases and whether capturing CO_2 should be considered equivalent to geological sequestration in terms of crediting. More work on the policy of CO_2 displacement in other markets is required to resolve this issue. That policy work needs to set guidelines for the LCA work to follow so developers can choose the best financial and environmental outcomes for CO_2 projects.

Figure 6.7: Recovered CO_2 Merchant and Captive Markets in the U.S. Broken Down by Source and End-Use Application[27]



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[27] https://www.researchgate.net/figure/Recovered- CO2-merchant-and-captive-markets-in-the-US-broken-down-by-source-and_fig2_280531742.

The CI score of an ethanol facility with CO_2 utilization is highly variable and significantly impacted by the energy intensity of the downstream CO_2-derived product. Based on the current technological status, most CO_2 utilization pathways for fuels or chemical production are highly energy-intensive. Utilizing a renewable energy source (i.e., wind, solar, etc.) to power CCU is the only option to achieve a lower CI.

Based on a study from ANL,[28] if the fermentation CO_2 is used for methanol production, the CI score reduction is 31.2 g CO_2e/MJ if the required electricity for hydrogen production and methanol synthesis comes from zero-emission renewable sources. Using the U.S. electricity mix would not provide CI-reduction benefits.

Chapter 6.5: Process Heat and Electricity

Energy use efficiency improvement technologies, such as co-generation and renewable energy integration, can significantly reduce ethanol CI.

6.5.1. Combined Heat and Power

Combined heat and power (CHP) is an established efficiency improvement to an ethanol facility. Natural gas is burned on-site to generate electricity for the facility and heat is captured from the process. This heat is typically used to generate steam for facility process heat. The CHP system is usually sized for the electricity load, resulting in additional natural gas to be supplied to the facility for process heat. Natural gas usage for the facility will increase to generate electricity, but the heat from the CHP system will help subsidize this increase. The lower electricity CI generated by CHP usually outweighs the increased natural gas use and improves the facility's CI score.

As shown in the CHP example, waste heat can be a source of low-CI energy to the facility. In the baseline example presented in this report in Table 4.1, natural gas can contribute up to 20 points of CI impact on a project. Capturing this waste heat to displace natural gas used for heating can reduce emissions and the amount of natural gas purchased. A CHP system could improve the facility score by 2 to 4 CI points.

6.5.2. Biomass-Based Process Heat

Another way to lower natural gas use is to operate a boiler using a low-CI feedstock, such as biomass-based waste diverted from a landfill.

6.5.3. Renewable Natural Gas (RNG)

RNG from low-CI feedstocks, such as landfill gas and livestock manure, can also be an alternative. Low-CI biogas can provide process energy to the facility and reduce process energy emissions by displacing fossil natural gas. Livestock manure can also generate methane avoidance credits that could further reduce the facility's CI score. The industry is considering using thin and whole stillage to produce low-CI biogas through anaerobic digestion. The use of whole stillage may require revision of D6 pathways under the RFS due to the impact on co-product credit from animal feed.

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[28] Xu, H., Lee, U. and Wang, M. (2022), Life-cycle greenhouse gas emissions reduction potential for corn ethanol refining in the USA. Biofuels, Bioprod. Bioref., 16: 671-681. https://doi.org/10.1002/bbb.2348.

The main requirement for this technology is having a physical connection to the RNG source. Book-and-claim delivery methods are invalid under CA-LCFS. However, treatment under IRA 45Z remains unknown.

6.5.4. Renewable Electricity

Solar, wind, and other sources of zero-CI electricity can also improve the CI score of ethanol by replacing electricity and thermal heat requirements from the grid. These technologies must be directly connected to the facility to ensure the zero-CI energy source is qualified under CA-LCFS. Until IRA guidance is issued, this remains a possible requirement for 45Z.

6.5.5. Advanced Feedstock Selection

Facilities can source higher-yielding or distinct characteristic feedstocks. Utilizing corn varieties optimized for high yields can increase the amount of ethanol produced per acre harvested, improving overall efficiency. Genetic advancements and crossbreeding techniques offer the continued improvement of strains with combinations of deep-rooting varieties for improved soil organic carbon (SOC) storage, disease resistance for reduced pest management chemical applications, high starch yield, and favorable knockdown characteristics for reduced grain drying needs. Genetically modified organism (GMO) breeds with favorable characteristics have sometimes had to face additional market challenges, potentially requiring costly physical segregation in the supply chain. Not all characteristic changes may favor other crop feed and chemical uses.

Feedstock selection and farming practices can impact the facility's CI score. Reducing fertilizer and pesticide consumption can reduce farming emissions. This topic is further discussed in EcoEngineers' report prepared for the RFA, titled "Farm-Level Carbon Intensity Improvements and the Inflation Reduction Act."

6.5.6. Variable Frequency Drives (VFDs)

Variable frequency drives (VFDs) and other continuous process monitoring can optimize the system based on key parameters, increasing efficiency, and minimizing waste. Process and technology improvements that increase efficiency, energy consumption, and ethanol production improve the CI score.

6.5.7. Advanced Process Technologies

Implementing advanced enzymatic processes for starch conversion can improve yields by enhancing sugar release efficiency during fermentation.

Using genetically modified yeast strains or advanced fermentation technologies can increase ethanol yield and reduce processing time. Yeast has been a target of advanced development and screening for several years. Further genetic modification or potential replacements with other microbial strains may be required for further advancements. Fermentation of higher-order alcohols such as isobutanol and bio-oils may result in better per-feedstock yield, but this has not been commercially viable for sector-wide deployment.

6.5.8. Waste Heat Recovery

Heat Integration can be used to optimize heat exchange systems and be integrated into the process to capture and reuse waste heat within the facility.

Process engineers consider this when possible during process design, but additional value could be derived from periodic reviews and ongoing process optimization. Heat/exhaust recovery and integration can reduce natural gas use by 10%-20%.

6.5.9. Energy-Efficient Distillation

More efficient distillation techniques reduce energy consumed and increase separation efficiency. Ethanol dehydration technologies can improve the dewatering of the ethanol and reduce the load on the distillation columns. Implementing more energy-efficient distillation processes, such as membrane-assisted vapor separation, offers the potential to reduce the energy intensity of ethanol separation. EcoEngineers has not modeled membrane-assisted vapor separation but expects it to result in a slight 2–3-point reduction in CI.

6.5.10. Use of Stillage to Generate Energy Through AD System

Table 6.1 details the CI impact and natural gas utilization across various types of corn ethanol plants. Depending on the plant type, between 22,812 Btu/gal and 34,372 Btu/gal of natural gas is required and the CI impact of natural gas ranges from 20.30 g CO_2e/MJ to 31.16 g CO_2e/MJ. Natural gas has a relatively high impact on the total CI of ethanol, ranging from 39%-41% of the total CI of ethanol in different plants. To reduce the overall CI of ethanol, alternative, and more sustainable heat sources can be employed in the production processes. Shifting from traditional natural gas to alternative sources such as renewable energy, biomass, or waste heat recovery can mitigate the environmental impact associated with heat generation, and ethanol plants can lower the CI impact attributed to the use of natural gas, subsequently contributing to a more environmentally friendly and sustainable ethanol production process.

Table 6.1: Natural Gas Use and Associated CI Impact in Different Corn Ethanol Plant Types[29]

	Ethanol CI (g CO_2e/MJ)	Natural Gas Use (Btu/gal)	CI Impact of Natural Gas (g CO_2e/MJ)	Contribution of Natural Gas in Total Ethanol CI (%)
Dry-Milling Corn Ethanol Without Corn Oil Extraction	52	22,812	20.68	40%
Dry-Milling Corn Ethanol With Corn Oil Extraction	52	22,386	20.30	39%
Wet-Milling Corn Ethanol	76	34,372	31.16	41%
Corn Ethanol: Combined Dry- and Wet-Milling Ethanol	55	23,604	21.40	39%

Currently, ethanol facilities recycle approximately 15% of thin stillage (TS) as backset process water for the subsequent starch bioethanol fermentation, with the remaining TS typically processed to produce dried distiller's grains with solubles (DDGS). These co-products, along with wet distiller's grains (WDG), serve as major by-products of ethanol production, contributing to the overall economics of an ethanol plant. Volumetrically, TS is produced at a rate of 15–20 gal TS/gal ethanol in a typical 50 MMgy starch ethanol plant.[30] Accounting for recycled backset, this still results in 750 million to 1 billion gallons of TS produced annually.

Alternatively, anaerobic digestion (AD) can be employed to convert TS into biogas, offering a sustainable energy source that offsets the gas and electricity requirements of the ethanol plant. The generation of bioenergy from TS in a corn ethanol mill provides a new perspective for using by-products to generate energy and reduce the CI of ethanol. In a previous case study, it was reported that stillage from the corn fiber ethanol process could be used for biomethane production, producing the gas equivalent of 9,000 Btu/gal that can partially meet the needs of the corn ethanol process.[31] Considering the details provided in Table 6.1, this could reduce the overall CI of ethanol by 8 g CO_2e/MJ. Using TS for energy generation through an AD system and CHP would produce 10.37 m^3 of biogas, which could generate 119.9 MJ (113,650 Btu) of heat and 24.7 kWh (84,284 Btu) of electricity in a CHP system from 1 ton of TS, favoring a greener energy scenario. The energy recovered from biogas returns to

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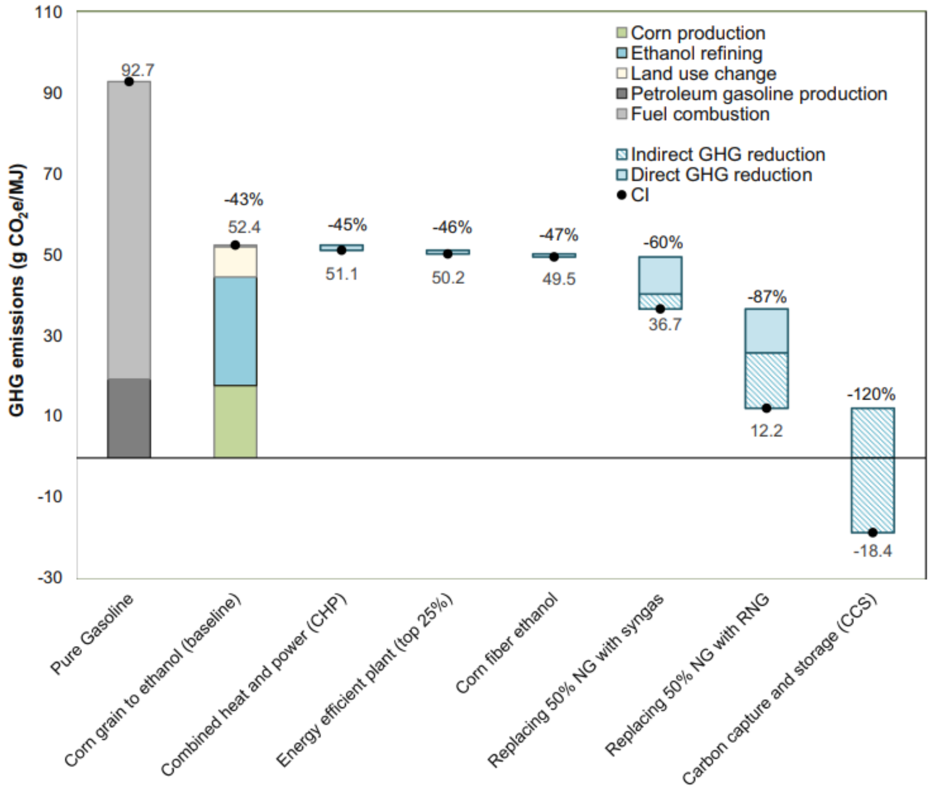
[29] This is based on the typical ethanol plant types, which are 5% dry milling without corn oil extraction, 86% dry milling with corn oil extraction, and 10% wet milling. (Source: ANL GREET 2023).

[30] Reis, C. E. R., Rajendran, A., and Hu, B. (2017). New technologies in value addition to the thin stillage from the corn-to-ethanol process. Rev. Environ. Sci. Biotechnol. 16, 175–206. doi: 10.1007/s11157-017-9421-6.

[31] Rathi, S. 2023. "Low Carbon Ethanol: Carbon Intensity Reduction through Advanced Technologies". Available at: https://www.biofuelsdigest.com/bdigest/2023/05/01/low-carbon-ethanol-carbon-intensity-reduction-through-advanced-technologies/.

the industry, supplying 7.15% of the heat required for steam production and 52.74% of the electricity requirement for industrial processing.[32] The significant contribution of alternative heat sources in reducing the CI of corn ethanol is also depicted in Figure 6.8.

Figure 6.8: CI of Corn Ethanol Production vs. Petroleum Gasoline, When Multiple Cleaner Fuel Production Technologies are Applied to the Ethanol Refining Stage[33]



6.5.11. Co-Product Optimization

Some ethanol plants extract corn oil from the stillage, a by-product of ethanol production. This corn oil is used in various applications, including animal feed and biodiesel manufacturing, providing an additional revenue stream for ethanol producers. In a typical dry-milling ethanol plant, corn oil is produced at a ratio of 0.27 bone-dry lb/gal ethanol, which can be considered a co-product. The extraction of corn oil requires additional energy consumption.

After ethanol production, the remaining grain residues, known as dried distiller's grains with solubles (DDGS), are often dried and used as high-protein animal feed. This practice reduces waste and creates a valuable by-product with economic benefits for the agricultural sector. In

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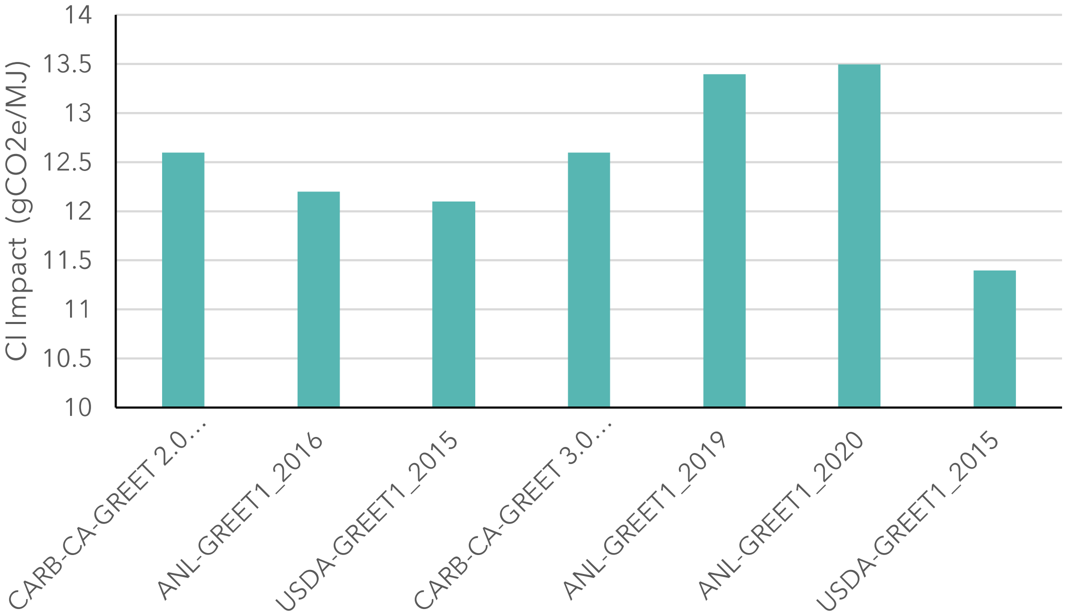
[32] Ziero, H.D.D.; Ampese, L.C.; Buller, L.S.; Costa, J.M.; Berni, M.; Forster-Carneiro, T. 2023. Corn ethanol production with thin stillage anaerobic digestion for bioenergy recovery: A technical and economic evaluation. Industrial Crops and Products. 206: 117618.

[33] Source: https://www.osti.gov/servlets/purl/1904178.

a typical dry-mill ethanol plant, dry DDGS is produced at a ratio of 3.25-3.43 dry lb/gal ethanol, and wet DDGS is produced at a ratio of 1.36-1.42 dry lb/gal ethanol.

The credit associated with corn oil and animal feed co-products depends on the allocation method applied and varies between programs. Figure 6.9 shows the average CI reduction associated with these co-products under different programs.

Figure 6.9: CI Impact of Ethanol Co-Products Under Different Programs[34]



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[34] Scully, M.J.; Norris, G.A.; Falconi, T.M.A., MacIntosh, D.L. 2021. Carbon intensity of corn ethanol in the United States: state of the science. Environmental Research Letters, 16 (4).

Section 7: Summary and Conclusions

Chapter 7.1: Summary

It is clear where average ethanol is in terms of CI evaluation by ANL GREET, as summarized in Table 7.1, based on combined, starch, and fiber ethanol. Table 7.1 also shows the net CI reduction required to reach a $0.10/gal 45Z credit at 45 kg CO_2e/MMBtu. Individual production facilities should have their site-specific baseline CI calculated by ANL GREET as a first step in pursuing CI reduction and qualification for 45Z. In addition, all producers should consider producing fiber gallons as a means of qualifying at least a small percentage of their ethanol production for 45Z.

Table 7.1: Summary of CI-Reduction Requirements to Realize 45Z[35]

Parameter	Combined Ethanol g CO_2e/MJ	Combined Ethanol kg CO_2e/MMBtu
Baseline Average of Undenatured Ethanol CI	53.6	56.6
Threshold CI for 45Z Qualification	47.4	50.0
Threshold CI to Achieve $0.10/gal 45Z Credit	42.7	45.0
Net CI Reduction Required to Reach $0.10/gal 45Z Credit at a CI of 45 kg CO_2e/MMBtu	10.9	11.6

Several facility-level options are available to reduce CI and qualify for CFPC/IRA 45Z credits, as summarized in Table 7.2. The most significant emission reductions rely on adding CCS or displacing the use of fossil natural gas for process heat. A facility could almost reach net-zero emissions by combining both zero-CI feedstock biogas and CCS. Major considerations include the cost of implementation and projected revenue from credit generation under the RFS, CA-LCFS, and other state-driven LCFS programs. Although IRA 45Z guidance is still pending, credit generation will begin in 2025 and end in 2027. To maximize credit generation, any CI improvement projects should be shovel-ready or deployable in 2024.

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[35] Source: EcoEngineers

Table 7.2: Summary of Available CI-Reduction Options for Corn-Ethanol Production[36]

Technology Deployed	Typical CI-Reduction Range of Application (g CO_2e/MJ) Used in CA-GREET	Typical CI-Reduction Range of Application (kg CO_2e/MMBtu) Used in ANL GREET
CHP	3-5	3.2-5.3
Zero-CI Feedstock Biogas	20.6	21.7
Zero-CI Electricity	3.8	4.0
Waste Heat Capture	3-4	3.2-4.2
Membrane Dehydration	1.5	1.6
Process and Technology Improvements	1-2	1.1-2.1
CCS	27-31	28.5-32.7

Chapter 7.2: Conclusions and Recommendations

With the IRA's 45Z tax incentive timeline targeted for inauguration on January 1, 2025, ethanol producers, industry technology suppliers, and other industry stakeholders are racing to implement R&D strategies to reduce the CI of ethanol production effectively. There are two strategies that ethanol producers can align themselves with (1) organic R&D efforts, and (2) R&D efforts that require external investment or resources.

Many examples of ethanol production benefiting from organic R&D positively benefit carbon reduction. One supporting example is ethanol producers conducting efficiency studies and applying strategies to enhance production efficiency, primarily lowering natural gas use, and/or electricity consumption, two major components of CI in ethanol production. Additionally, external low-carbon activities are growing vastly and as mentioned, require external partnerships. External partnerships come from significant financial investment and expertise outside a typical ethanol producer's repertoire.

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[36] Source: EcoEngineers

An example of an external R&D partnership might be an ethanol producer investing in a low-carbon technology like CHP or solar technology to lower energy inputs. External strategies typically are capital intensive, usually resulting in the adoption of innovative technology that changes the way the current production process has historically operated. Investing in strategic R&D programs aimed at process improvement, yield improvement, and operability improvement for ethanol producers can offer several potential benefits, especially when considering the use of incentives such as 45Z.

In conclusion, investing in strategic R&D programs for process improvement and cost reduction in the ethanol industry, coupled with the IRA 45Z Clean Producer Tax Credit, can lead to increased efficiency, cost savings, and competitive advantages. However, careful evaluation and alignment with industry dynamics and regulatory requirements are essential for maximizing the benefits of such investments.

The following specific recommendations are made for ethanol producers navigating their way toward lower-CI ethanol production:

- Establish a site-specific baseline CI score for your facility using ANL GREET.
- Consider unique site characteristics such as CCS, biomass-based heat, a CO_2 pipeline, and renewable electricity, which may provide an implementation advantage at your facility.
- Consider the universal characteristics of your facility, including CKF, CHP, and membrane dehydration.
- Make incremental improvements in yield and efficiency to reach the first credit generation threshold:
    - Cellulase applications for CKF ethanol when using a combined starch and ethanol score.
    - Corn oil separation.
    - CHP applications.
    - Thermal oxidizers and better waste heat recovery integration and optimization.
    - Fermentation and enzyme optimization, working with yeast and enzyme suppliers toward specific objectives.
- Consider opportunities requiring larger expenditures that deliver more significant CI reductions, such as:
    - Biogas from stillage and other locally accessible low-cost feedstocks (stillage waste, manure, food waste) into integrated CHP systems.
    - CCS opportunities.
    - CO_2 pipeline opportunities.
    - Renewable energy integration.

- Continue to watch for guidance on 45Z for the following topics:
    - CCU guidance on CI scoring related to displacement and permanence.
    - Guidance on consideration of CKF and starch pathways.
    - Guidance on consideration of methane avoidance.
    - Guidance on qualifying sources of renewable energy and the possibility of book and claim.
    - General guidance on qualifications, rounding, etc.

This paper has considered the LCA basis of U.S. ethanol to meaningfully participate in 45Z, defined here as reaching a $0.10/gal credit, which would generate $10 million/year in production tax credits (PTCs) for a 100 MMgy U.S. ethanol plant. This paper recommends that each facility establish its baseline CI according to ANL GREET to be prepared to consider the magnitude of CI reductions necessary and discusses the potential CI reductions from readily available technology. Work on this paper makes apparent the need for clear guidance from the U.S. Treasury Department on CI methodology. Also evident is the need for continued advocacy and policy supporting ethanol as a major platform for decarbonizing the transportation industry.

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