Office of the Chief Economist
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The California Low Carbon Fuel Standard: Incentivizing Greenhouse Gas Mitigation in the Ethanol Industry

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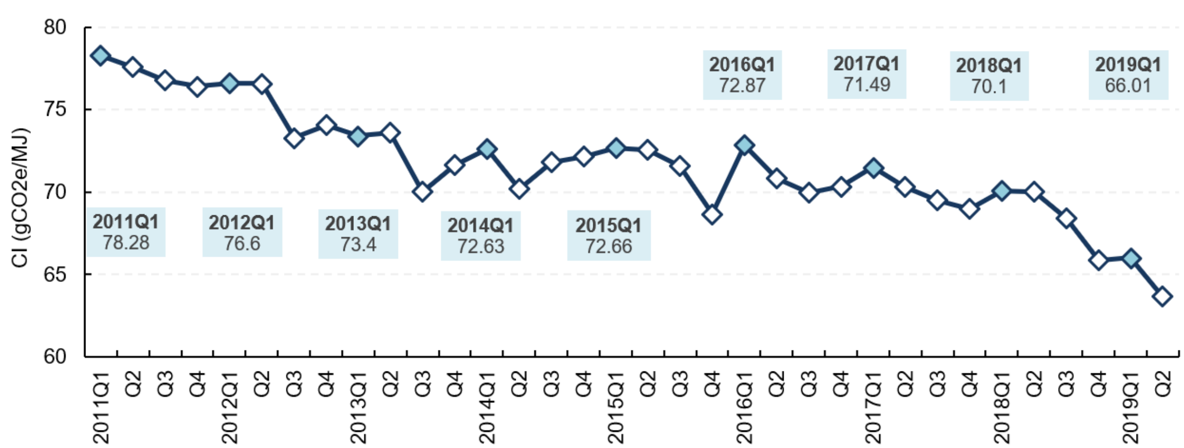
I. Introduction

Since 2010, Federal greenhouse gas (GHG) and renewable fuels policies have assumed substituting corn ethanol for gasoline in liquid transportation fuel reduces GHG emissions by 21 percent. Recent studies show the GHG benefits are much higher, between 39 percent and 43 percent.[1] Evidence from California's Low Carbon Fuel Standard (LCFS), administered by the California Air Resources Board (CARB), suggests that ethanol refineries can significantly improve their GHG profile through strategic modifications to their production processes. Currently, approximately 42 percent of U.S. ethanol production has registered and developed pathways to participate in the LCFS, making it one of, if not, the most influential policy when it comes to improving the GHG profile of ethanol fuel in the country.

Under the LCFS, renewable transportation fuels generate emissions reduction credits based on a comparison of their emissions with those of a reference (or standard) fossil fuel. For ethanol, the standard is gasoline. Credits are awarded such that renewable fuels with lower carbon intensities receive proportionally more credits. In order to receive CARB approval to sell ethanol as a renewable fuel in the LCFS, a refinery must submit documentation describing the technologies and practices it has put in place and quantify how much each technology/practice contributes to reducing GHG emissions.

Because there is a market for emissions reduction credits with prices currently fluctuating between $190 and $200 per ton of CO_2 equivalent, the LCFS provides a strong financial incentive for ethanol facilities to implement GHG reducing technologies and practices. Since the LCFS began in 2011, the average carbon intensity of ethanol fuel has decreased by approximately 25 percent,[2] due to changes in how ethanol plants are producing their fuel (Figure I-1).

Figure I-1. Average Low Carbon Fuel Standard (LCFS) Ethanol Carbon Intensity, 2011-2019Q2



Note: CI score is inclusive of all CI pathways, non-U.S. and U.S. pathways

[1] Lewandrowski, J, J. Rosenfeld, D. Pape, T. Hendrickson, K. Jaglo, & K. Moffroid. 2020. *The greenhouse gas benefits of corn ethanol – assessing recent evidence.* Biofuels, 11:3, 361-375, DOI:10.1080/17597269.2018.1546488.

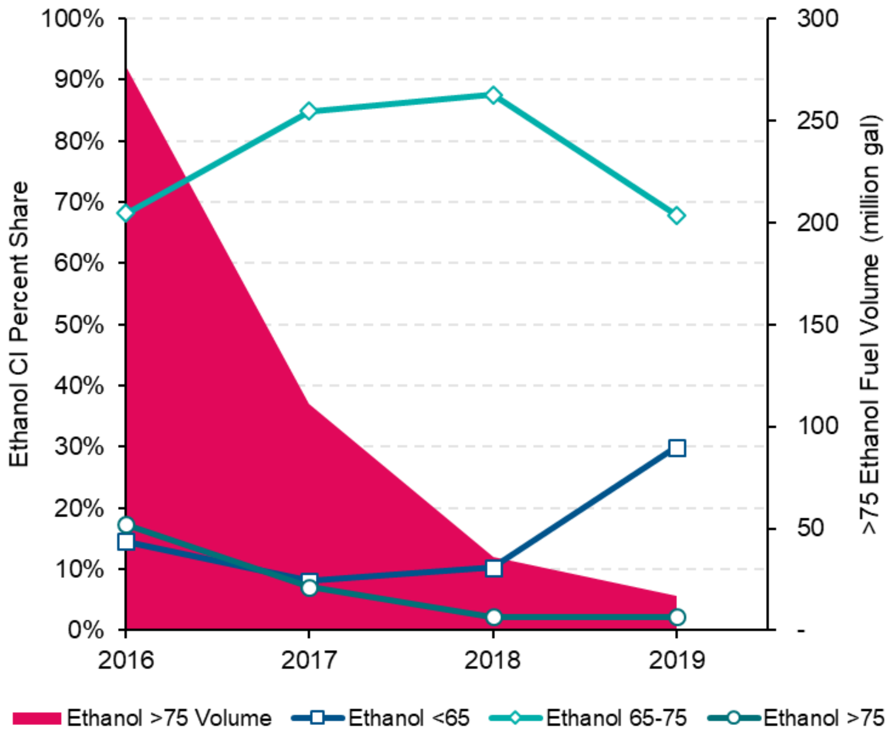
[2] Percent reduction based on modified 2011 carbon intensity with the current indirect land use change (ILUC) value.

It is anticipated that ethanol refineries can achieve continued emission reductions through facility improvements. Some examples of ethanol refinery plant modifications include utilizing biogas as a substitute for natural gas, installing combined heat and power (CHP) systems to displace natural gas used for industrial heating purposes, and replacing grid electricity with electricity generated by on-site solar or wind power systems. Our analysis has identified at least 89 corn ethanol refineries with certified LCFS production pathways; these pathways provide a rich data set for identifying technologies and practices that ethanol refineries are adopting to lower their GHG profile. Because the pathways are associated with specific refineries, it is also possible to assess the role of distance from California, refinery capacity, proximity to co-product markets, and other factors in the choice of which GHG mitigating technologies and practices refineries adopt. In addition, because ethanol sold under the LCFS commands a significant economic premium relative to ethanol sold in non-LCFS markets, the data allow us to look at how financial incentives have affected innovation in reducing GHG emissions within the ethanol industry.

CARB readopted the LCFS in 2015 and updated the indirect land use change (ILUC) values for corn ethanol pathways that took effect in 2016. Prior to 2016, corn ethanol pathways were assessed 30 carbon intensity (CI) points for emissions related to ILUC. Starting in 2016, this value was lowered to 19.8 g/MJ. As can be seen in Figure 1-2, the effects on the LCFS were substantial. Ethanol pathways with CI scores greater than 75 dropped from about 90 percent of all pathways at the start of 2016 to about 36 percent all pathways by the start of 2017.[3] In terms of ethanol fuel shares, pathways with CI scores greater than 75 accounted for 17.3 percent of all ethanol consumed in California in 2016; this has decreased to 1.1 percent of ethanol consumed in the first two quarters of 2019. Finally, in terms of volumes, ethanol from pathways with CIs over 75 has dropped from 277 million gallons in 2016 to approximately 16 million gallons (extrapolating from 8 million gallons during the first two quarters of 2019) in 2019 (Figure I-2). To limit the effects of the 2016 change in ILUC scoring, this analysis only looks at pathways approved in, and after, 2016.

[3] During the 2016 calendar year, all existing pathways from 2015 or earlier that applicants wanted to continue to use in 2016 and beyond were updated by California Air Resources Board. All pathways in place and able to be used in 2016 or later were updated.

Figure I-2. Ethanol Consumption in California by Carbon Intensity Category

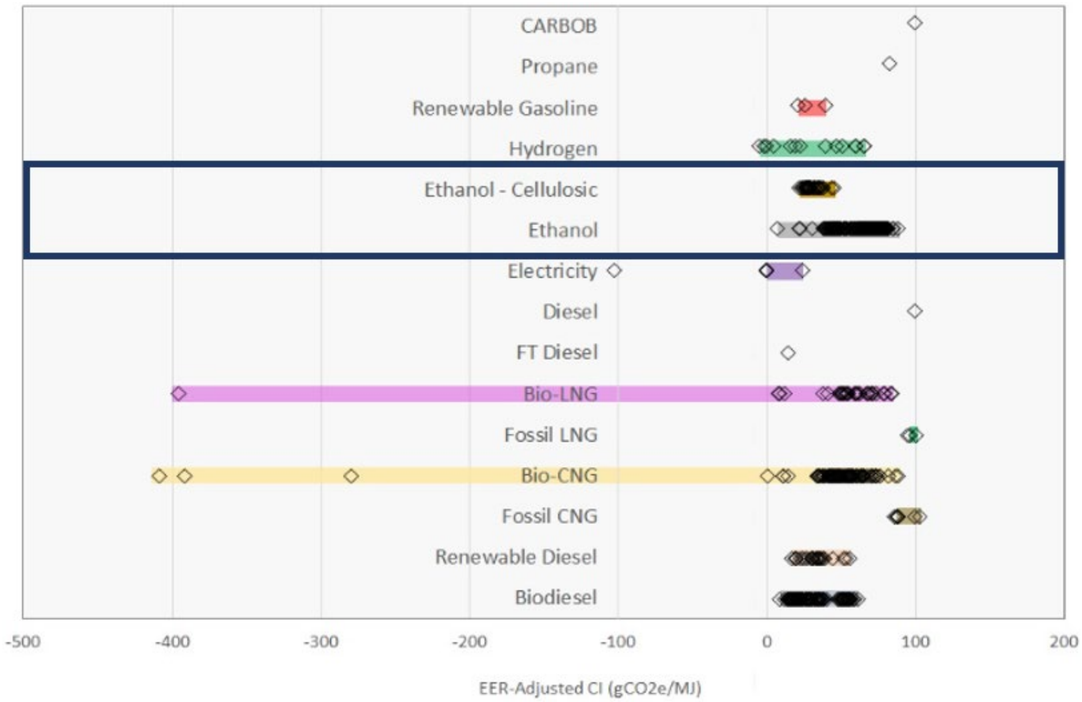


Note: 2019 ethanol pathways data was provided by CARB through Q2; an extrapolation was applied for Q3 and Q4.

Source: California Air Resources Board (CARB, 2019)

As of December 10, 2019, there were a total of 248 ethanol pathways registered with the LCFS, and approximately 89 facilities. Numerous factors can influence the CI of ethanol fuel, as will be described in more detail in the following section, and as such, ethanol pathways show a wide range of CIs from approximately 7 to 90 gCO_2e/MJ (Figure I-3).

Figure I-3. Carbon Intensity Scores of Current Certified Pathways, 2019[4]



The CI score of each ethanol pathway in the LCFS reflects a life cycle assessment (LCA) of its GHG emissions with variable emissions grouped into four source buckets: feedstock production, transport, co-product(s), and energy type and usage (see Table 1). The first bucket is based on the type of feedstock used and the emissions associated with its farming, including farm equipment use and fertilizer applications (particularly nitrogen). Each feedstock reflects a different emissions factor (EF). For example, according to CARB, corn has an EF of 6,442 grams of carbon dioxide equivalent per bushel of corn (gCO_2e/bushel), while sorghum has an EF of 7,268 gCO_2e/bushel.[5] The transport bucket of the LCA includes two components: the first is the emissions associated with transporting the feedstock to the ethanol plant, and second, the emissions associated with transporting the finished ethanol fuel to a distribution or fueling location. Fuel is transported by truck and/or rail. The third LCA bucket reflects emissions (typically savings) associated with co-products of ethanol production. Each co-product has a different emissions footprint. For example, dry distillers grain (DDG) and modified distillers grain (MDG) has a significantly higher EF relative to wet distiller grain (WDG) because the latter does not require energy to dry the co-product. The final bucket is the type of energy used during the ethanol production process. Natural gas, grid electricity, and renewable fuels (e.g., wind, solar, and biogas) have different EFs. These four categories are used to calculate the carbon intensity of the finished ethanol fuel, measured in gCO_2e/MJ.

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[4] California Air Resources Board. 2019. LCFS Pathway Certified Carbon Intensities. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm [accessed December 2019].
[5] California Air Resources Board. 2018. Summary of the Tier 1 Simplified Starch and Fiber Ethanol Pathway(s). https://www.arb.ca.gov/fuels/lcfs/ca-greet/tier1-sfe-calculator.xlsm [accessed December 2019].

Table 1. Ethanol LCA Stages

Feedstock		Co-Product	Energy Use	Transport
Standard	Nascent			
Corn	Corn stover	DDG	Natural gas	Truck
Sorghum	Wheat starch slurry	MDG	Grid electricity	Rail
Sugarcane	Waste wine	WDG	Biogas	
	Sugar beet	Syrup	Solar/wind	
	Wheat straw	Corn/sorghum oil		

II. Ethanol Facility Interviews

Distilling information from CARB's public database about specific ethanol facilities has its limitations, such as disaggregating the CI score of certain pathways to understand and breakdown what specific actions contributes to the total CI. In order to fill in data gaps, we conducted interviews with ethanol facilities to gain a better understanding of the motivations for making process improvements and the projected impacts for various process changes. Selection criteria were that facilities had to have more than five fuel pathways registered in the LCFS, nameplate capacity greater than 60 million gallons per year (MGY) and have implemented at least one innovative strategy to reduce ethanol CI. Conclusions based on interviews may not reflect all ethanol facilities, but can offer an idea of what, and why, decisions to implement certain strategies and processes were made.

The nameplate capacity of facilities interviewed were between 60 to 165 MGY and spanned States from the Midwest to the West Coast. In general, ethanol facilities implemented a diverse set of facility upgrades including process efficiency improvements, process energy modifications, changes to co-product production, enzyme enhancements, and more. We condensed and summarized qualitative interview questions and answers in Table 2.

Table 2. Ethanol Facility Interview Questions and Answers

Question	Answer
Was the decision to go forward with innovative facility upgrades driven, at least in part, by the LCFS or other goals (e.g., other regulatory driver, internal/company sustainability goals, RFS, grant funding requirements)?	In general, the LCFS and other regulations including the renewable fuels standard (RFS2) were large drivers. Reduction in energy costs were across the board large drivers for innovation. Internal sustainability goals had some impact but were not the primary driver for innovations.
Was there any push back or reluctancy internally to implement these changes?	Ethanol facility reluctancy was found in some instances but for the most part, company board of directors were in favor of implementing strategies especially when the economics were favorable.

Question	Answer
What were the primary arguments that ultimately greenlighted the facility upgrades?	Consensus around this question revolved around whether a particular upgrade achieved favorable capital returns. The degree of carbon intensity reductions was also a high priority for some ethanol plants.
Was there resistance from regulators?	In general, regulators were in favor of facility upgrades.

According to facility managers, utilizing a solid fuel boiler instead of a natural gas- powered boiler reduces the CI by approximately 10 points; switching from dry to wet distillers grain solubles (DDGS and WDGS) achieves a CI reduction of 8 to 10 points; installing a CHP system reduces CI depending on the fuel used, for example, biomass will reduce by approximately 3 to 4 points, and natural gas by 1 to 2; and using biogas as process energy will reduce the CI by approximately 3 points. For a list of facility improvements and the impact on fuel carbon intensity see Table 3.

Table 3. Facility Improvements

Improvement Type	Improvement Strategy	CI Impact (gCO_2e/MJ)
Energy efficiency and process steam generation	Combined heat-and-power (CHP): biomass and natural gas	Biomass = -3 to -4 Natural gas = -1 to -2
	CO_2 regenerative thermal oxidizer (RTO) system	
	Boiler heat recovery system	
	Solid fuel boiler: waste wood and landscape waste	-10 (relative to NG boiler)
	Dry to wet distillers grain solubles	-8 to -10 (depending on location)
	Oxidizer density meters	
Yield improvement	Distillation column modifications	
	Enzyme research/improvement	
Process energy	Biogas	-3

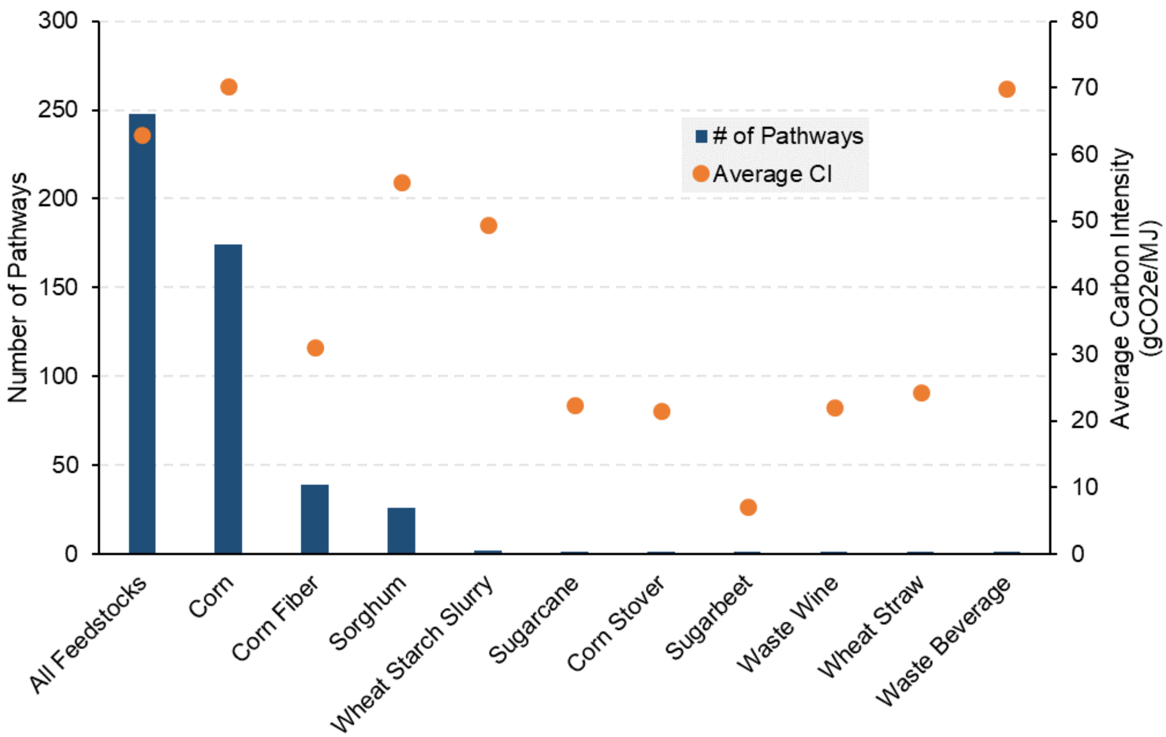
Understanding what has led ethanol plants to move forward with innovative facility upgrades can help uncover future opportunities and overcome challenges, whether internal to the company or external. Non-California ethanol plants did note that transportation costs were one barrier to sending ethanol to California. Additionally, there was confidence that as more LCFS type programs are implemented around the country that an increasing number of ethanol plants will be incentivized to achieve life cycle GHG emissions reductions.

III. CARB LCFS Data Research

The carbon intensity score is affected by numerous factors, from the type of process energy, to the associated indirect land use change emissions, to the emissions associated with transporting fuels to California, to the relative efficiency of the ethanol plant. ICF performed a thorough analysis of CARB's publicly available database – which keeps an up-to-date spreadsheet of registered LCFS fuel pathways – analyzing each pathway based on its pathway description, which included the type of feedstock, co-products produced, energy use type, and ethanol product.[6]

We can assess how on average different feedstocks effect the carbon intensity, keeping in mind that the transportation emissions are not being controlled (i.e., not normalizing based on the state of production). On average, conventional corn ethanol shows the highest CI among all feedstocks with an average CI score of 70.19 consisting of 174 pathways, followed closely by ethanol produced from 'waste beverage[7]' with a CI score of 69.82. Ethanol produced from sorghum, with 26 pathways, showed an average CI of 55.83, followed by wheat starch slurry with two pathways and an average CI score of 49.47. Corn fiber, with 39 pathways, shows an average CI of 30.98. The remainder of the feedstocks are only represented by one pathway each, including wheat straw, sugarcane, waste wine, corn stover, and sugar beet, with CIs of 24.20, 22.44, 21.58, and 7.18, respectively (Figure III-1).

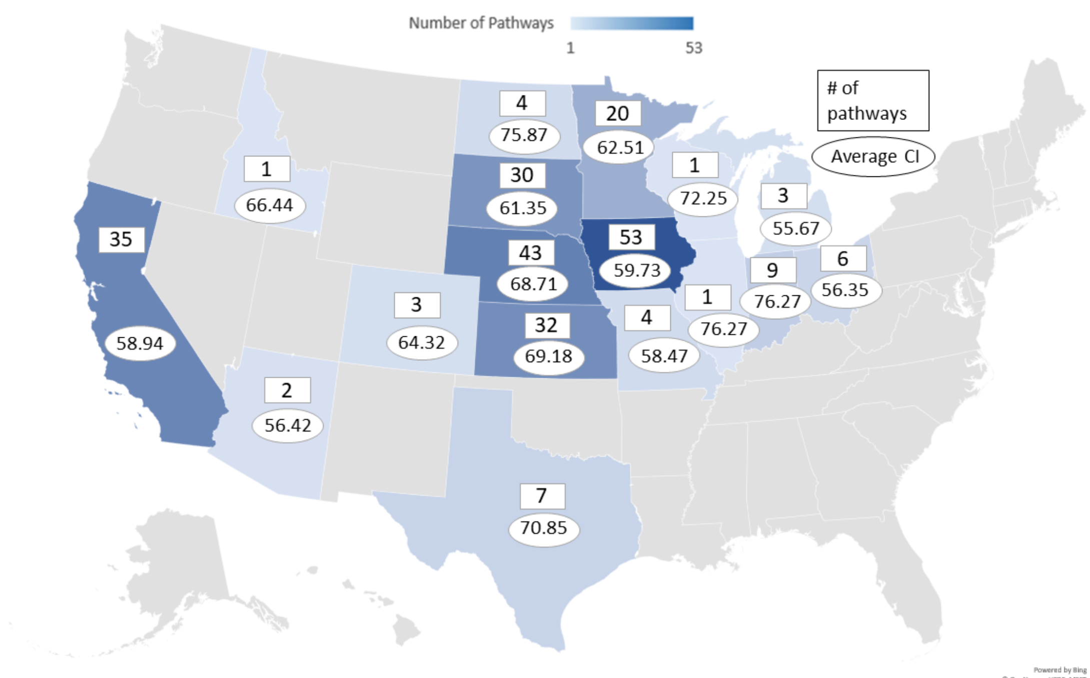
Figure III-1. CI Score by Feedstock



[6] California Air Resources Board. 2019. LCFS Pathway Certified Carbon Intensities. https://ww3.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm [accessed December 2019].
[7] There is only one ethanol pathway participating in the LCFS using waste beverage.

Like corn and ethanol production, refineries with LCFS approved ethanol fuel pathways are spread out around the country but are generally concentrated in the Midwest. Currently, Iowa has the highest number of registered ethanol fuel pathways with 53; these pathways have an average CI of 59.73. After Iowa, the States with the most approved pathways are Nebraska (43 pathways; average CI of 68.71), California (35 pathways; average CI of 58.94), Kansas (32 pathways; average CI of 69.18), South Dakota (30 pathways; average CI of 61.35), and Minnesota (20 pathways; average CI of 62.51). All other States have fewer than 10 ethanol fuel pathways. See Figure III-2 for a complete list on U.S. States with LCFS ethanol fuel pathways and the average CI of their fuel.

Figure III-2. Ethanol Pathways by State and Average CI Score



One key objective of this analysis was to gain a better understanding of what specific actions refineries have taken to achieve CI reductions in their ethanol. This was partly accomplished through interviews with ethanol facility managers but was also explored using CARB's LCFS fuel pathways database. CARB's LCFS database provides a snapshot of a fuel pathways current characteristics but omits prior details relating to the fuel pathways coproducts and facility operational energy source(s). Without having the ability to see a fuel pathway's CI before and after a production process change, we instead looked at the average of all fuel pathways that have implemented a given emissions reducing action. While this methodology does not capture how a given action explicitly lowers the CI of ethanol, it does make it possible to analyze the broader effect that action has on fuel pathway CIs in general. We applied this methodology for two process improvements (co-generation[8] and biogas) and four co-products (DDGS, WDGS, corn oil, and corn syrup) and observed the following:

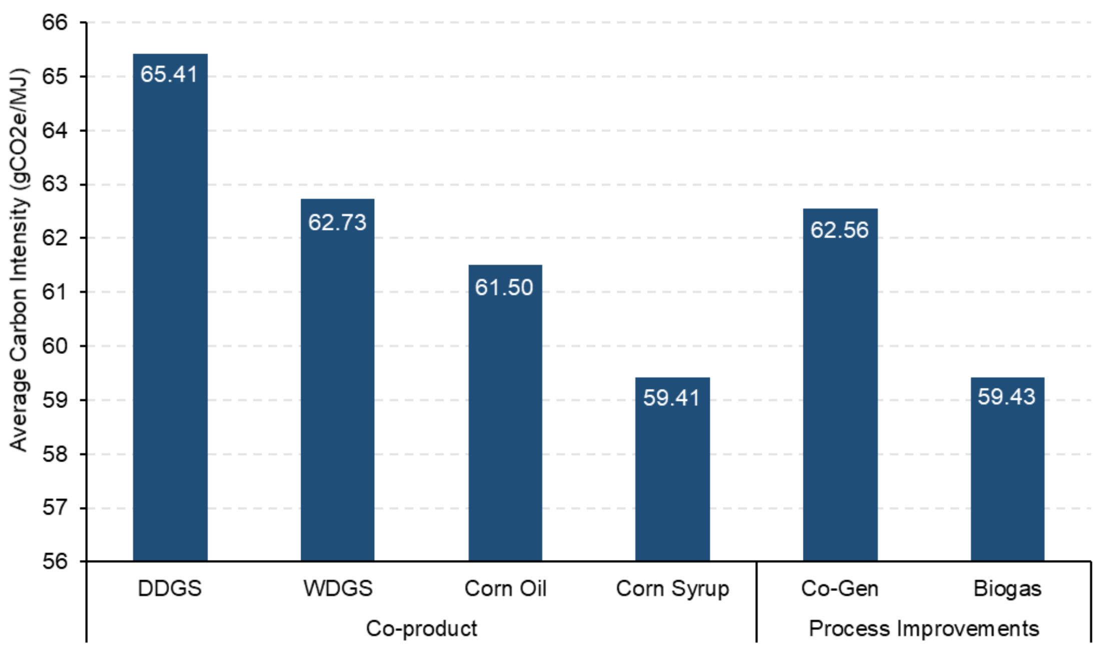
[8] Also, referred to as combined heat and power (CHP).

First, consider the effect of co-products in the CIs of ethanol pathways generally. As shown in Figure III-3, among fuel pathways with co-products, those with DDGS showed the highest average CI, due to the energy requirements of drying DGS, which is in line with literature on the topic.[9] DDGS was followed by pathways with WDGS, corn oil, and corn syrup pathways with the lowest CI. In addition, results show that pathways with additional co-products streams have lower CIs, especially when energy intensive DDGS is not in the pathway.

Looking at the process improvements, pathways with co-generation – which was not distinguished by the type of fuel used – reflected a higher CI compared to fuel pathways utilizing biogas. Co-generation is typically powered using natural gas to produce electricity and steam; however, some facilities utilize biomass. The life cycle emissions associated with co-generation powered by natural gas is significantly higher compared to biomass, and even higher relative to biogas. Unfortunately, we were unable to obtain the substrates used to produce the biogas, which dictates the GHG profile of the finished biogas. It is safe to assume that facilities utilizing biogas generated from anaerobically digested cow manure would see the most favorable CI reductions to their ethanol fuel.

These results, although limited by the available data, show that increasing a plant's energy efficiency, sourcing renewable fuels and electricity, and switching from dry to wet DGS will achieve a plant's goals of reducing the CI of their ethanol fuel. Quantitative results for the facility and fuel pathway modifications described previously can be viewed in Figure III-3.

Figure III-3. Average CI Score Associated with Facility Modifications



Note: DDGS = Distiller's Dried Grains with Solubles; WDGS = Wet Distillers Grains with Solubles

[9] Kraatz, S., J. C. Sinistore, D. J. Reinemann. 2013. *Energy intensity and global warming potential of corn grain ethanol production in Wisconsin (USA)*. Food and Energy Security, 2(3): 207-219. https://onlinelibrary.wiley.com/doi/full/10.1002/fes3.27 [accessed September 2020].

IV. Carbon Capture and Sequestration

In the last decade, Federal and State policies have sought to incentivize carbon capture and sequestration (CCS) projects. One notable program at the national level is the 45Q tax credit and at the State level is the LCFS's CCS protocol. These policies have been modified (45Q) or created (CCS protocol) to encourage CCS projects related to fuel production. This section will discuss the details of each policy and the possible ramifications on the CI of ethanol fuel.

1. Section 45Q Tax Credit Implications

The Section 45Q tax credit was originally enacted in 2008 by the Department of Treasury (Treasury Department) and the Internal Revenue Service (IRS) with the policy objective of increasing the prevalence of carbon capture projects around the country. In its original form, 45Q eligibility was based on projects that captured 500,000 or more metric tons of carbon dioxide per year ($MTCO_2$/year). In addition, Q45 originally had a total cap of 75 million tons, which was a deterrent for interested entities investing in projects that could become obsolete once the cap was reached. Due in large part to the eligibility threshold, the overwhelming majority of ethanol plants did not qualify for the original 45Q.

In 2018, legislation to extend and expand the Q45 tax credit was passed, and it is now viable for many ethanol facilities to qualify for this policy. From a refinery perspective, the two modifications were the lowering of the carbon capture threshold from 500,000 to 100,000 $MTCO_2$/year and the elimination of the cap. Moreover, projects that qualify and begin construction within the next 6 years are able to claim credits for 12 years once the project is underway. The new credit values are based on the type of storage and are as follows:

- Saline storage = \$22.66 to \$50/$MTCO_2$
- Product utilization (fuels, chemicals, products, etc.) = \$12.83 to \$35/$MTCO_2$
- Enhanced oil recovery = \$12.83 to \$35/$MTCO_2$[10]

Ethanol plants considering carbon capture should take advantage of this tax credit given that the ethanol fermentation process emits a fairly pure stream of carbon dioxide. The widescale use of 45Q is contingent on the geographic location of ethanol plants. The 45Q, however, could make an interconnected pipeline viable and would increase opportunities for poorly located ethanol plants to take advantage of the tax credit.[11]

2. LCFS CCS Protocol

In 2018, CARB amended the LCFS regulation to permit carbon capture and sequestration projects to receive credits so long as transportation fuel is sent to California. Ethanol plants that currently, or will, send ethanol to California and receive LCFS credits have an opportunity to improve the economics of their operations and increase their long-term relevance in the LCFS

[10] Internal Revenue Service. 2019. Request for Comments on Credit for Carbon Oxide Sequestration – Notice 2019-32. https://www.irs.gov/pub/irs-drop/n-19-32.pdf [accessed September 2020].
[11] Gibson, L. 2018. Enhanced Oilfield Opportunities. Ethanol Producer Magazine. http://www.ethanolproducer.com/articles/15185/enhanced-oilfield-opportunities [accessed December 2019].

program by receiving credits for capturing and storing the carbon dioxide generated in the ethanol production process. Eligible projects for the CCS protocol include direct air capture, CCS at oil and gas production facilities, CCS at refinery projects, and other applications of CCS, including at ethanol refineries (Figure IV-1). Qualification for the CCS protocol hinges on a sequestration site that has undergone certification by a geologist in order to meet permanence requirements, including:

- Site characterization and risk assessment;
- Well construction and corrective action;
- Operation;
- Testing and monitoring;
- Well plugging and abandonment; and
- Post-injection site care and site closure.

Figure IV-1. LCFS Eligible CCS Projects[12]

	Direct Air Capture Projects	CCS at Oil & Gas Production Facilities	CCS at Refineries Projects	All Other CCS Projects (e.g., CCS with Ethanol)
Location of CCS project	Anywhere in the world	Anywhere, provided they sell the transportation fuel in California	Anywhere, provided they sell the transportation fuel in California	Anywhere, provided they sell the transportation fuel in California
Storage site	Onshore saline or depleted oil and gas reservoirs, or oil and gas reservoirs used for CO_2-EOR			
Credit method	Project-based	Project-based, under the Innovative Crude Provision	Project-based, under the Refinery Investment Credit Program	Project-based or fuel pathway
Earliest date which existing projects eligible	Any	2010	2016	Any
Requirements	Project must meet requirements specified in the CCS Protocol			
Additional restrictions	None	Must achieve minimum CI or emission reduction	None	None

Similar to 45Q, ethanol plants are strongly positioned to utilize the LCFS CCS protocol. Ethanol facilities can benefit from both the 45Q and LCFS CCS protocol so long as the project meets qualification requirements for both policies, as previously outlined.

3. Carbon Intensity Implications of CCS

To estimate the potential carbon intensity implications from CCS, we need to review the overall chemical formula for alcoholic fermentation shown in **Figure IV-2** below.

[12] Adapted from: Havercroft, I. & A. Townsend. n.d. California's LCFS and CCS Protocol. Global CCS Institute. https://www.globalccsinstitute.com/wp-content/uploads/2019/06/2019-06_LCFS-and-CCS-Protocol.pdf [accessed December 2019].

Figure IV-2. Chemical Formula for Alcoholic Fermentation

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2\ CO_2$$

Assuming a stoichiometric reaction, one molecule of ethanol is made for every molecule of carbon dioxide. Considering the energy density of ethanol and mass of carbon dioxide, maximum potential carbon dioxide capture is approximately 35 gCO_2/MJ ethanol. When taking into account the energy requirements to capture, transport, and inject carbon dioxide into storage reservoirs, the net impact is likely a CI reduction of 20-25 gCO_2/MJ of ethanol.