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**FULL REPORT**
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# Pathways to Net-Zero Ethanol:

## Scenarios for Ethanol Producers to Achieve Carbon Neutrality by 2050

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## Executive Summary

The commitments of corn ethanol producers to achieve emissions reductions of 70% compared to gasoline by 2030 and net zero emissions by 2050 are ambitious. Though the industry has succeeded in reducing emissions by 22% from 2005 to 2019 and further opportunities to improve the carbon intensity (CI) of ethanol exist, continued innovations in biorefinery technologies and farming practices over the coming decades will be necessary to meet these targets. By surveying over two dozen potential emissions reduction actions throughout the corn ethanol supply chain and prioritizing them by technical feasibility, scale of emissions reduction, and cost, this study presents a series of pathways to net zero CI corn ethanol by 2050.

Updated life cycle emissions forecasts of corn ethanol from 2020 through 2050 show that the industry can achieve net negative CI ethanol by adopting near-term technologies and expanding best practices in corn farming. Although baseline emissions improvements may stall without continued improvements in biorefinery technology and farm management, industry-average net emissions of -5 g $CO_2$e/MJ are feasible (Figure 1). This core pathway to below net zero applies:

1) Renewable electricity at 50% of ethanol facilities in 2030, up to 90% in 2050
2) Corn kernel fiber fermentation at 20% of dry mills by 2030, up to 50% by 2050
3) 'Better-than-business-as-usual' industry-wide efficiency improvements and ethanol yields based on the historical trends of industry leading producers
4) Adoption of renewable electricity by 25% of corn suppliers in 2030, up to 90% in 2050
5) Installation of carbon capture and sequestration (CCS) technology at 40% of ethanol facilities by 2030, up to 90% by 2050
6) Sourcing of bio-methane from manure biogas at 28% of ethanol facilities in 2030, up to 78% by 2050
7) Expansion of reduced tillage practices to an additional 7.5% of corn farmers in 2030, 30% by 2050.

The core pathway avoids the potentially higher costs of green ammonia and biomass-fueled combined heat and power infrastructure. Instead, renewable electricity purchases, improved energy efficiency, corn kernel fiber fermentation, and reduced tillage are used to meet emissions targets while limiting producer and farmer costs. One key technology, CCS, may require high capital investment, but has been shown to be cost efficient at capturing emissions. Moderate subsidies or active carbon markets could lead to rapid CCS adoption. Only bio-methane (likely from manure) is expected to have a high cost that may not be easily overcome by policy incentives.

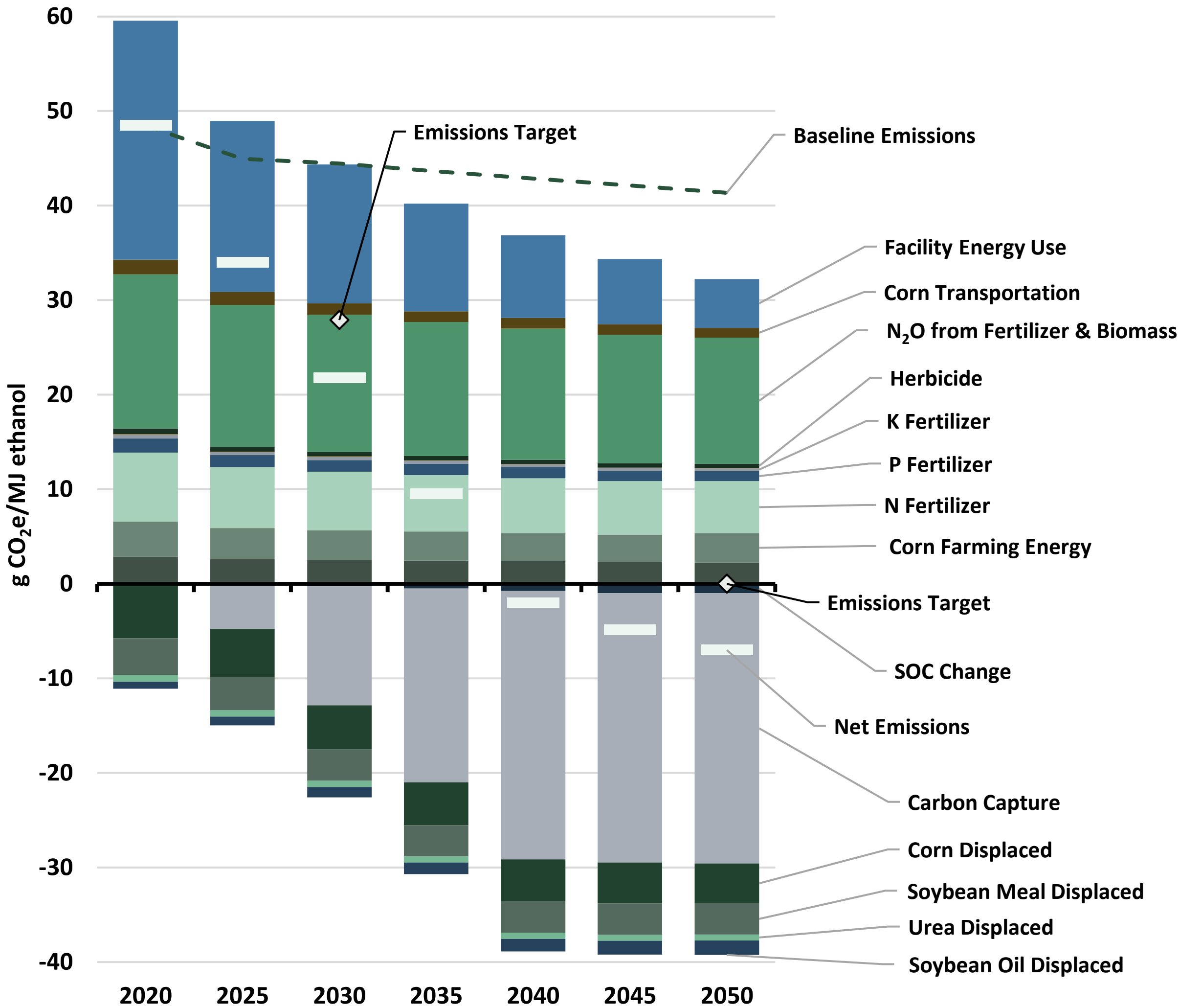


*Figure 1: Core pathway results achieving RFA target emissions reductions across the ethanol industry (shown are average emissions from dry mills with corn oil extraction).*

Beyond the stark climate benefits of capital-intensive actions like biomass-fueled CHP or CCS of fermentation $CO_2$, working with farmers to expand cost-effective conservation practices can facilitate an extremely low CI for corn ethanol. Together, improved fertilizer management, reduced tillage, and cover crops have the potential to reduce the industry average CI of corn ethanol by 16 g $CO_2$e/MJ. Producers in some regions could see twice as great a benefit from practices that enhance soil carbon storage. Investments in efficiency improvements across the industry, from developing technologies like very high gravity fermentation and improved yeast strains to identifying new markets for existing coproducts like WDGS, are also likely to play an important role in facilitating lower ethanol emissions across the industry.

Alternative pathways prioritizing low-cost emissions reductions avoid bio-methane in favor of a variety of lower-cost actions by farmers and higher-risk technical developments like improved yeast strains. An ethanol producer in a region suitable for higher adoption rates of strip-till/no-till and cover cropping, and with corn suppliers willing to enact strict '4R' fertilizer management practices, could meet the 2030 emissions target without installing a carbon capture system. These pathways lead to ethanol CIs between -10 and -20 g $CO_2e$/MJ by 2050 using actions expected to cost no more than $50/t $CO_2e$.

Renewable energy expansion and land management changes in line with current US goals to halve emissions by 2030 and reach net zero by 2050 (White House, 2021) have dramatic benefits for ethanol producers. Corn ethanol emissions drop below 20 g $CO_2e$/MJ by 2050 in this 'climate action future' - less than half the emissions in the baseline scenario. With technological advancements in fermentation efficiency, access to fuel from an established renewable bio-methane industry, and CCS, a producer could generate ethanol with a CI as low as -15 to -40 g $CO_2e$/MJ.

Achieving the UN Paris Agreement climate targets of limiting global warming to 1.5°C will require rapid and ambitious action, including improvements by the agriculture sector. This presents an unprecedented opportunity for corn ethanol producers to lead the biofuels and bioenergy industries to implement large-scale climate solutions. By investing in low-carbon process innovations and establishing a market for low-carbon agricultural products, the pathways in this study demonstrate than ethanol producers can achieve extremely low corn ethanol emissions and fill a critical need in tomorrow's zero-carbon economy.

## Contents

# 1. Introduction

The members of the Renewable Fuels Association (RFA) recently announced their commitment to reduce the carbon intensity (CI) of corn ethanol to 70% lower than petroleum gasoline in 2030 and become net carbon neutral by 2050 (RFA, 2021). Achieving such ambitious targets is critical to avoiding severe climate change. The UN Intergovernmental Panel on Climate Change (IPCC) has warned that rapid reductions in greenhouse gas (GHG) emissions will be necessary to limit global temperatures to the Paris Agreement targets of 1.5 to 2.0°C by the year 2100 (IPCC, 2021). Evidence suggests that climate change is already increasing the rate and severity of weather-related disasters and starting to affect crop yields in the United States (IPCC, 2021; Ray et al., 2019).

Large-scale reductions in GHG emissions in the United States will require changes in the nation's fuel mix and transportation system, which is the highest-emitting sector at 29% of US GHG emissions (Environmental Protection Agency (EPA), 2021). As the highest-volume alternative fuel in the US, ethanol can play a major role in transportation emissions reductions. Already, from 2005 to 2019, ethanol substitution for gasoline prevented 544 million metric tons (MMT) of $CO_2$-equivalent GHG emissions ($CO_2e$) (Lee et al., 2021). These benefits have been achieved by a rapid increase in ethanol production volumes (from 3.8 billion gallons in 2005 to 16 billion gallons per year in 2019) and a continuing improvement in the emissions differential between ethanol and gasoline. A recent study by Argonne National Laboratory reported that the life-cycle GHG emissions of corn ethanol, including all stages of corn production, transportation, fermentation, and combustion, decreased 22% between 2005 and 2019 (Lee et al. 2021). The authors concluded that corn ethanol reduces GHG emissions by 52% compared to gasoline (or 44% when including emissions from land use change; Lee et al., 2021).

Reductions in the CI of corn ethanol have the potential to drive substantial changes in US transportation emissions. Meeting RFA members' 2030 target of reducing corn ethanol's emissions to 70% lower than gasoline could provide an additional annual GHG reduction of 22 MMT. Achieving net zero emissions would expand the benefit to 58 MMT per year at current ethanol volumes, over 3% of total US transportation emissions (EPA, 2021). Increasing the percentage of ethanol blended with gasoline would provide a multiplicative effect. A blend rate of 15% instead of the current 10%, for example, combined with net zero carbon ethanol could reduce transportation emissions by an additional 59 MMT, doubling the climate benefits of corn ethanol.

Most of the carbon that flows through a biorefinery comes from the corn itself (figure 2). This carbon is biogenic – it is part of the short-term cycle of carbon from the atmosphere to the growing crops and back to the atmosphere within a few months or years. Because it flows back and forth between the atmosphere and crops, biogenic carbon is usually considered 'carbon neutral' when assessing the carbon footprint or carbon intensity of products. The carbon intensity of ethanol comes primarily

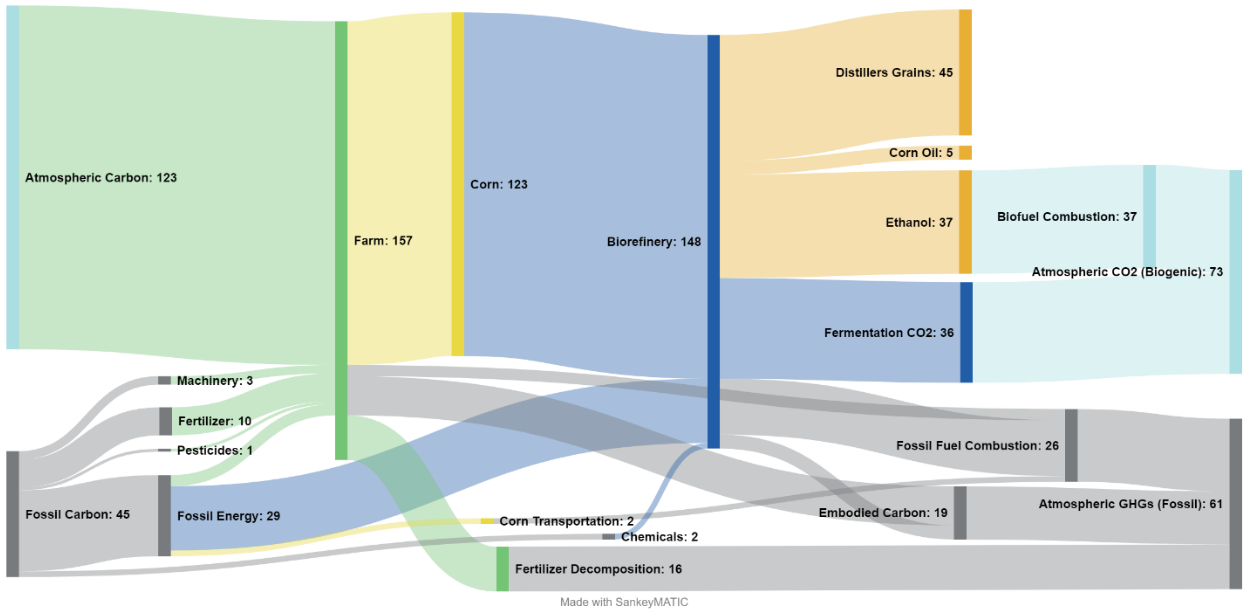


*Figure 2: Carbon flows and GHG emissions in the corn ethanol supply chain. Line widths and values indicate the relative sizes of carbon flows (values in g $CO_2$e/MJ ethanol). Carbon flows controlled at the farm stage are shown in green. Carbon flows controlled at the biorefinery are shown in blue. GHG emissions from the upstream production of fertilizers, machinery, and electricity are shown as 'embodied carbon.' Carbon flows through soils, crop residue, and the fate of coproducts are excluded for clarity, and the resulting values are therefore not comparable to life cycle assessment results.*

from the use of fossil fuels to power the biorefinery and manufacture chemicals and machinery used on the farm. Because this 'fossil carbon' is naturally stored in geologic formations for hundreds of millions of years, releasing it to the atmosphere increases the greenhouse effect and disrupts climate patterns which operate on cycles of thousands of years.

Meeting RFA members' emissions reduction targets will require addressing the two largest sources of fossil GHG emissions in the ethanol supply chain: energy use at the biorefinery and fertilizer use at the farm. These two factors represent two-thirds of the fossil fuels used in the corn ethanol life cycle. Including the emissions from fertilizer decomposition to $N_2O$, they account for 49 g $CO_2$e/MJ ethanol (not accounting for co-product credits). A range of technological and management tools exist to mitigate these emissions. Renewable energy, including wind or solar-generated electricity and renewable methane from biogas, can substitute for fossil fuels in fertilizer manufacturing and at the biorefinery. Changes in the types and application methods of fertilizers used can reduce $N_2O$ emissions on the farm.

Ethanol producers also have an opportunity to capture a quarter of the biogenic carbon that flows through the biorefinery. Fermentation converts about half of the carbon in corn starch to ethanol, with the other half (36 g $CO_2$e/MJ) lost as biogenic $CO_2$. Capturing and storing $CO_2$ from fermentation can offset GHG emissions elsewhere in the supply chain and creates an opportunity for carbon-negative ethanol.

Many other emissions-reducing actions can mitigate or eliminate other emissions sources. Improvements in biorefinery efficiency will further lower the fossil carbon contribution to net GHG emissions. Utilizing bioenergy throughout the supply chain, whether as biodiesel in farm equipment and corn transportation or biomass-fueled combined heat and power at the biorefinery, can help to shift the life cycle carbon flow from fossil to atmospheric carbon. Expanding the corn ethanol system to include soil carbon provides further opportunities for farmers and ethanol producers to build a more resilient and climate-friendly fuel supply chain by integrating conservation practices, precision management, and soil amendments that recycle nutrients from the broader agricultural and urban environment.

## 1.1. Goal of the Study

The goal of this study is to identify and assess the tools available to mitigate the life-cycle emissions from corn ethanol and develop a series of pathways by which producers, and the industry as a whole, can achieve a net zero carbon intensity by 2050. By examining the energy and materials sources available to ethanol producers and corn farmers, current and future technologies available to improve biorefinery efficiency, and the potential for changes in land management to improve yields and store carbon in agricultural soils, this study assembles a toolkit of emissions reduction actions along the corn ethanol supply chain. By prioritizing these actions by cost, feasibility, and effectiveness, sequences of innovations and supply chain decisions are assembled into pathways leading to net zero carbon – or carbon negative – corn ethanol.

## 2. Methods

This study develops a series of pathways for ethanol producers to achieve net zero GHG emissions by 2050 by assessing the current state of the industry, mapping a business-as-usual baseline case, and applying combinations of emissions reduction actions to improve the carbon intensity (CI) of corn ethanol. These pathways are built on a set of updated life cycle inventory parameters used to model corn ethanol life cycle emissions from 2020 to 2050 using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) and associated tools from Argonne National Laboratory (https://greet.es.anl.gov/). GREET is a leading platform for modeling GHG emissions from biofuels and bioenergy sources and is used to estimate the CI of ethanol for the EPA Renewable Fuels Standard (RFS) and the California Air Resources Board Low-Carbon Fuel Standard (CARB LCFS). Pathway targets were set based on the RFS standard for gasoline GHG emissions (93 g $CO_2e$/MJ, EPA, 2010) and using an emissions accounting framework that includes all major supply chain materials (including farm equipment) but excluding emissions from land use change. (See section 3.3 for a discussion of the role of land use change emissions in ethanol emissions targets.)

Contributions of many individual processes and materials to baseline GHG emissions were used to inform the selection of emissions reduction actions. Additional actions were selected to assess the potential for carbon storage and sequestration in soils and underground reservoirs. Actions were assembled into pathways achieving net zero CI for corn ethanol by 2050 on the basis of their technical feasibility, effectiveness (size of the emissions reduction), and financial cost. The technological readiness level (TRL) scale (table 1) is used to guide the selection of emissions reduction actions for the net zero emissions pathways.

The financial costs of each emissions reduction action are not intended to represent the actual net costs of implementation for ethanol producers. Depending on the action being assessed, they provide a snapshot of the gross system costs (i.e. for installing wind turbines) or changes in core expenses (i.e.

*Table 1: The technological readiness level (TRL) scale.*

| ***TRL*** | **Stage** | **Definition** |
|---|---|---|
| *9* | Systems Operation | Actual system operated over full range of expected conditions |
| *8* | System Commissioning | Actual system completed and qualified through demonstrate tests |
| *7* | System Commissioning | Full-scale, similar prototype demonstration in relevant environment |
| *6* | Technology Demonstration | Engineering / pilot scale prototype testing in relevant environment |
| *5* | Technology Development | Lab-scale validation in relevant environment |
| *4* | Technology Development | Component or system validation in lab environment |
| *3* | Research to Prove Feasibility | Analytical / experimental test of critical function - proof of concept |
| *2* | Basic Technological Research | Technology concept and/or application formulated |
| *1* | Basic Technological Research | Basic principles observed and reported |

for improved energy efficiency). But they do not include the full life cycle costs. Unknown or highly uncertain values like facility upgrading capital costs are excluded. Some potential sources of revenue, such as from credits associated with sales of lower-carbon ethanol (i.e. through the CARB LFCS), are also not considered. Because the true costs and benefits of implementing each action will differ for each biorefinery operator, readers are encouraged to use the action costs summarized in table 10 as a general guide to solutions with higher or lower financial barriers.

## 2.1. Electricity Generation

An electricity generation mix representative of US Midwestern corn ethanol production was assembled based on the US Energy Information Administration (EIA) 2021 Annual Energy Outlook (EIA, 2021a). Projected 2020 – 2050 electric generation mixes for selected North American Electric Reliability Corporation (NERC) regions were weighted by approximate corn grain ethanol production (see table 2). EIA-reported electricity sources were matched with GREET electricity generation categories, resulting in a set of GREET-compatible electricity generation factors for 2020 – 2050 specific to corn grain ethanol production. This generation mix was applied in GREET for all stationary electric consumption in the ethanol production model.

The EIA US electric power projections for 2050 include roughly 56% renewable energy sources (primarily solar, wind, and hydroelectric power). A future with substantial policy or economic pressure to reduce fossil fuel consumption (i.e. to meet the United Nations Paris Agreement climate targets to limit global warming to a maximum of 2.0°C by 2100) would likely have substantially faster growth in renewable energy production. An alternative electric generation mix compatible with substantial climate action by 2050 was created based on the '95% by 2050' National Renewable Energy Laboratory (NREL) national electricity generation scenario (Cole et al., 2021). Electric generation projections from the '95% by 2050' scenario (compatible with a 95% reduction in GHG emissions from the electricity sector by 2050) for 2036 and 2050 were matched with GREET electricity generation categories. GREET-compatible electricity generation factors for 2020 – 2050 were generated by linear

*Table 2: Baseline ethanol-production-weighted electricity generation mix for corn ethanol production.*

| ***GREET Categories*** | | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|---|
| *Residual Oil* | *%* | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% | 0.2% |
| *Natural gas* | *%* | 11.6% | 8.7% | 10.4% | 11.1% | 11.4% | 12.2% | 12.0% |
| *Coal* | *%* | 45.2% | 35.8% | 37.4% | 36.8% | 36.0% | 34.6% | 33.4% |
| *Nuclear* | *%* | 12.6% | 10.3% | 4.1% | 3.0% | 3.0% | 2.9% | 2.7% |
| *Biomass* | *%* | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| *Hydroelectric* | *%* | 4.9% | 5.1% | 5.2% | 5.0% | 4.9% | 4.8% | 4.6% |
| *Geothermal* | *%* | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| *Wind* | *%* | 24.1% | 33.3% | 33.9% | 33.2% | 32.7% | 31.7% | 30.7% |
| *Solar PV* | *%* | 1.1% | 6.3% | 8.5% | 10.4% | 11.5% | 13.2% | 15.9% |
| *Others* | *%* | 0.3% | 0.3% | 0.3% | 0.4% | 0.4% | 0.4% | 0.4% |

*Table 3: Climate action scenario electricity generation mix for corn ethanol production.*

| GREET Categories | | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| *Residual Oil* | % | 0.2% | 0.1% | 0.1% | 0.0% | 0.0% | 0.0% | 0.0% |
| *Natural gas* | % | 11.6% | 16.7% | 21.9% | 27% | 20.4% | 13.9% | 7.3% |
| *Coal* | % | 45.2% | 32.8% | 20.4% | 8.0% | 5.6% | 3.1% | 0.7% |
| *Nuclear* | % | 12.6% | 13.7% | 14.9% | 16% | 14.7% | 13.3% | 12% |
| *Biomass* | % | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| *Hydroelectric* | % | 4.9% | 5.6% | 6.1% | 6.6% | 6.6% | 6.2% | 5.3% |
| *Geothermal* | % | 0.0% | 0.1% | 0.2% | 0.4% | 0.4% | 0.4% | 0.4% |
| *Wind* | % | 24.1% | 25.1% | 24.7% | 23.0% | 28.5% | 34.1% | 40.0% |
| *Solar PV* | % | 1.1% | 5.6% | 11.6% | 19.0% | 23.7% | 28.7% | 34.0% |
| *Others* | % | 0.3% | 0.3% | 0.2% | 0.0% | 0.1% | 0.2% | 0.3% |

interpolation between the historical 2020 ethanol production-weighted generation mix, the 2036 NREL '95% by 2050' scenario projection, and the 2050 NREL '95% by 2050' scenario projection (see table 3).

## 2.2. Corn Farming

Corn yield projections to 2050 were generated by extending the USDA long-term field grains forecast from 2030 to 2050, combined with a factor for yield loss due to climate change. The USDA Feed Grain Projections to 2031 include a 2 bushel per acre per year increase in corn grain yields from 2021-2031 (USDA, 2021a; USDA, 2021b). Climate change is expected to have detrimental effects on corn yields in most regions of the United States, including in key ethanol producing regions (Yu et al., 2021; Hatfield et al., 2011). Increases in daily minimum temperature, precipitation, and other factors may result in a substantial reduction in corn yields compared to a scenario without climate change. While climate change impacts are likely to negatively affect corn yields in the US Midwest, there is substantial uncertainty in the magnitude of these effects – both on their own and relative to the expected yield-increasing effects of continued crop breeding and genetic modification. A review of recent studies provided a range of 3% to 68% drop in corn grain yields due to climate change between a baseline of 2010-2021 and 2040-2060, due to a temperature increase of 1–2°C (table 4; Lobell & Field, 2007; Hatfield et al., 2011; Leng & Huang, 2017; Tigchelaar et al., 2018; Wing et al., 2021; Yu et al., 2021).

*Table 4: Climate change yield penalty for corn grain from reviewed studies.*

| Yield Penalty | Scenario | Region | Source |
|---|---|---|---|
| 39% to 68% | 2050 vs. 2013-2017 | USA | Yu et al. 2021 |
| 3% to 12% | 2041 – 2060 vs. 2000 | Global | Wing et al. 2021 |
| 17.4% to 18.3% | 2°C Increase vs. 2000 | USA | Tigchelaar et al. 2018 |
| 20% to 40% | 2050 vs 2021 | USA | Leng & Huang 2017 |
| 2% to 3% | 0.8°C Increase vs. 2010 | US Midwest | Hatfield et al. 2011 |
| 4.0% to 12.2% | 1°C Increase | Global | Lobell & Field 2007 |
| 15% | 2050 vs 2015 | USA | This study |

*Table 5: Long-term corn yield forecasts and assessed climate change yield penalty. *Historical data from USDA NASS. **Extended projection of the USDA long-term forecast.*

| ***GREET Categories*** | | **2020** | **2025** | **2030** | **2035** | **2040** | **2045** | **2050** |
|---|---|---|---|---|---|---|---|---|
| *USDA Long-Term Grains Forecast* | *bu/ac* | 171.4* | 187 | 197 | 207** | 217** | 227** | 237** |
| Temperature Anomaly | °C | 1.26 | 1.40 | 1.53 | 1.66 | 1.78 | 1.89 | 2.00 |
| Yield Penalty | % | 0.0% | -1.9% | -4.0% | -6.4% | -9.1% | -11.9% | -15.0% |
| *Yield Penalty* | *bu/ac* | 0.0 | -3.1 | -6.6 | -10.7 | -15.2 | -19.8 | -25.1 |
| *Baseline Model Yield Forecast* | *bu/ac* | 171.4 | 183.9 | 190.4 | 196.3 | 201.8 | 207.2 | 212.0 |

Based on these findings and aiming to set a conservative but reasonable yield forecast, this study applies a maximum yield penalty of 15% (from a 2015 baseline of 167 bu/acre) to account for the likely negative impacts of climate change on corn yields through 2050.

The magnitude of the yield penalty in years between 2020 and 2045 was interpolated based on the forecast temperature anomaly. The negative impacts of climate change are expected to become increasingly severe at higher temperatures, and so the magnitude of the corn yield penalty was fit to the cube of the difference in the temperature anomaly for each 5-year period between 2020 and 2050. The estimated temperature anomaly, yield penalty (% baseline), and yield penalty (bushels per acre) are shown in table 5.

Parameters for corn farming operations, including energy use, fertilizer application rates, and chemical (herbicide) application rates were sourced from a recent report on US corn ethanol production and GHG emissions by Argonne National Laboratory (Lee et al., 2021). Lee et al. reviewed state-specific corn farming data to generate a national weighted average of farming inputs to corn ethanol production (Lee et al., 2021). Lacking additional, reliable forecast data for potential changes in farming energy use and fertilizer applications over the next several decades, this study applied the current (2019) values for farming inputs through 2050 (table 6). Because GREET assesses fertilizer, herbicide, diesel, and gasoline inputs on a per-acre basis, the relative contribution of these inputs per unit of corn will decrease over time as corn yields increase. Conversely, LPG, natural gas, and

*Table 6: Fertilizer use and farming energy inputs to the GREET model.*

| | | |
|---|---|---|
| Nitrogen | lb/ac | 158.3 |
| $P_2O_5$ | lb/ac | 59.4 |
| $K_2O$ | lb/ac | 60.1 |
| Lime | lb/ac | 542.1 |
| Herbicide | lb/ac | 2.5 |
| Diesel | gal/ac | 6.80 |
| Gasoline | gal/ac | 1.25 |
| LPG | gal/bu | 0.011 |
| Natural Gas | $ft^3$/bu | 0.453 |
| Electricity | kWh/bu | 0.292 |

electricity use were assessed per bushel and their impacts remained constant on a corn yield basis through 2050. This conservative assumption regarding energy use on the farm and at grain elevators may overstate the emissions from these stages in the ethanol supply chain between 2025 and 2050 (and conversely, overemphasize the influence of emissions reductions at those stages).

## 2.3. Ethanol Production

Modeling parameters for ethanol facility operations, including energy use and ethanol yields were sourced from Lee et al. 2021. Lee et al. reviewed facility survey data from Argonne National Laboratory (Wu, 2019) and Christianson, a consulting firm which has corn ethanol facility benchmarking data from 2005 to 2019 (www.christiansoncpa.com). Aggregated national-average facility energy use and ethanol yields reported by Lee et al. were disaggregated into estimates for wet and dry mills based on the proportion of wet and dry mill facilities and the difference in their efficiencies in the default GREET model.

The proportion of natural gas, coal, and electricity used by corn ethanol facilities were sourced from the GREET default model, except that the proportion of energy from coal in wet mills (27.5% in the GREET default model) was reduced to 6.2% to reflect the average energy mix reported by Lee et al. (2021). Model inputs for chemicals, materials, and co-product yields were sourced from the GREET default model. Average energy use between 2025 and 2050 was determined for each facility type by adjusting the GREET default forecast data proportionally to the new 2020 model input values. For "1.5 gen" dry mill facilities capable of fermenting the carbohydrates in corn kernel fiber, GREET contains a separate module to estimate facility energy use based on inputs for conventional dry mills with corn oil extraction, expected energy use in corn kernel fiber extraction and fermentation, and changes in the balance of coproducts. See table 7 for a complete list of forecast facility parameters.

Industry average ethanol yields, defined as gallons of 200-proof undenatured ethanol per bushel (gal/bu), were estimated for 2020 and 2025 using the same data set and process as other ethanol facility parameters (Lee et al., 2021). The 2020 value of 2.85 gal/bu for dry mills with corn oil extraction

*Table 7: Forecast GREET input parameters for ethanol yields and energy use at ethanol facilities and the proportion of wet mills to all ethanol production. Ethanol is undenatured and 200-proof. COE = Corn oil extraction. CKF = Corn kernel fiber ethanol.*

| | **Ethanol Yield (gal/bu)** | | | | **Facility Energy Use (Btu/gal)** | | | | **Coal Energy Use (%)** | | **Wet mills (%)** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Dry Mill | Dry Mill + COE | Dry Mill + CKF | Wet Mill | Dry Mill | Dry Mill + COE | Dry Mill + CKF | Wet Mill | Dry Mill | Wet Mill | |
| **2020** | 2.85 | 2.85 | 3.12 | 2.75 | 23,175 | 22,800 | 21,363 | 44,800 | 0.4% | 6.2% | 9.0% |
| **2025** | 2.88 | 2.90 | 3.16 | 2.75 | 22,962 | 22,591 | 21,217 | 44,800 | 0.0% | 6.2% | 9.0% |
| **2030** | 2.90 | 2.92 | 3.17 | 2.75 | 22,841 | 22,471 | 21,176 | 44,800 | 0.0% | 6.2% | 9.0% |
| **2035** | 2.90 | 2.92 | 3.17 | 2.75 | 22,841 | 22,471 | 21,176 | 44,800 | 0.0% | 6.2% | 9.0% |
| **2040** | 2.90 | 2.92 | 3.17 | 2.75 | 22,841 | 22,471 | 21,176 | 44,800 | 0.0% | 6.2% | 9.0% |
| **2045** | 2.90 | 2.92 | 3.17 | 2.75 | 22,841 | 22,471 | 21,176 | 44,800 | 0.0% | 6.2% | 9.0% |
| **2050** | 2.90 | 2.92 | 3.17 | 2.75 | 22,841 | 22,471 | 21,176 | 44,800 | 0.0% | 6.2% | 9.0% |

is equivalent to 2.92 denatured gal/bu (assuming 2.5% denaturant). Yields in the baseline scenario plateau in 2030 at 2.92 gal/bu (3.00 gal/bu denatured ethanol) as they near the theoretical maximum yield.

The theoretical maximum yield of ethanol from corn grain is determined from the stoichiometric conversion of corn starch to glucose (1 g starch produces 1.11 g glucose) and glucose to ethanol (1 g glucose produces 0.511 g ethanol). A bushel of corn with the US average 72.9% starch has a theoretical maximum ethanol yield of 2.99 gal/bu. Many factors, particularly imperfect starch separation during milling, yeast growth, and production of byproducts during fermentation, lead to maximum feasible ethanol yields that are below the theoretical maximum yield. Future improvements in milling technology and yeast cultivation and genetics could potentially push average yields above 2.92 gal/bu, and some of the most efficient facilities report yields above that level today. Those innovations are explored in the 'better-than-BAU efficiency' and 'improved yeast' actions.

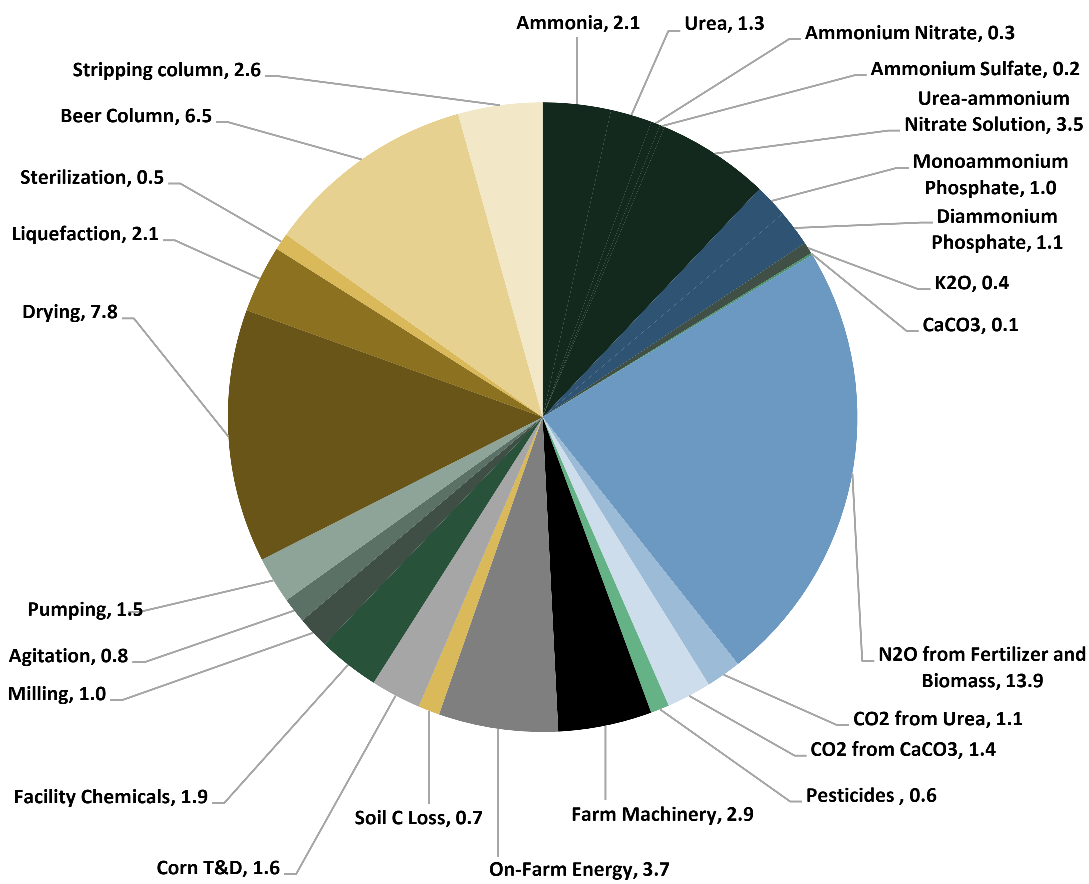


*Figure 3: Breakdown of life cycle GHG emissions from ethanol production at an average US dry mill facility (g $CO_2e$/MJ). Biorefinery processes are color-coded by energy source with electricity in shades of green and natural gas in shades of gold.*

The total 2020 baseline GHG emissions for corn ethanol from an average US dry mill are shown in figure 3. The values shown are adjusted for coproduct credits. Emissions were allocated among fertilizers according to average US fertilizer use following the GREET model. Process emissions within the ethanol facility were estimated based on relative energy demand (Saffy et al., 2015).

## 2.4. Emissions Reduction Actions

Emissions reduction pathways meeting RFA member targets of 70% lower GHG emissions than gasoline by 2030 and net zero carbon by 2050 were generated by assembling a series of actions by ethanol producers, farmers, and elevators. Each action represents a purchase decision or process improvement that reduces the overall life cycle emissions of corn ethanol.

### 2.4.1. Ethanol Producer Actions

#### 2.4.1.1. Renewable Electricity Purchase

Renewable power purchases (wind or solar photovoltaic electricity generation) are often a reliable and low-cost tool for reducing industrial GHG emissions.

Renewable energy purchase at corn grain ethanol facilities was modeled outside of the GREET model. Because GREET applies the same electricity mix to all supply chain processes, including machinery manufacture, on-farm electricity use, and fertilizer and chemical manufacturing, simply replacing the Midwestern ethanol production-weighted electricity mix developed for this study with an all-renewable electric generation mix would exaggerate the effect of renewable electricity purchases on total life cycle ethanol GHG emissions. Instead, the emissions benefit of renewable power purchases was assessed as a credit to the GREET model emissions results.

The renewable energy emissions credit was determined for each facility type (wet mill, dry mill, dry mill with corn oil extraction, and dry mill with corn kernel fiber fermentation and corn oil extraction) at each model run. The credit was calculated as the difference in emissions between the carbon intensity of the electric mix in the model run and the emissions intensity of solar photovoltaic electric generation and supply (Wernet et al., 2016), applied to the electricity fraction of total energy use by the facility type in the given model run. This approach allows GREET to apply the appropriate emissions intensity of electricity to upstream processes while giving ethanol producers credit for purchasing low-carbon electricity.

Costs of renewable power purchases vary depending on the energy system and the type of purchase agreement. For the purposes of assessing the range of potential renewable energy costs, this study included two purchase vehicles: renewable energy credits (RECs) and power purchase agreements (PPAs). REC premiums have historically been less than $1/MWh but over the past two years climbed to over $6/MWh (Heeter et al., 2021). PPAs, on the other hand, can provide cost savings compared to conventional electricity purchases with an obligation to a long-term contract. Prices for wind PPAs in the Midwest region over the past 3 years have ranged from $15 to $40/MWh thanks in part to Federal tax incentives (Wiser et al., 2021). This study applies a cost of $30/MWh for PPAs, substantially lower than the $72.50/MWh 2020-2021 average grid electric price (EIA, 2021b).

#### 2.4.1.2. Renewable Electricity Generation & Storage

Integrated on-site wind or solar electric generation is another approach to supplying renewable energy. This action includes the installation of on-site power generation and 24-hour battery storage to improve resilience to both grid and on-site system disruptions as well as periods of low solar or wind resource availability. Equipment emissions and costs were assessed based on the baseline electricity requirements of a dry mill facility producing 100 million gallons per year and an electricity demand of 62,000 MWh/yr (5,170 MWh/month). Solar resource availability was determined using the NREL PVWatts calculator for a photovoltaic system with 1-axis tracking in central Iowa (NREL, 2021a). To ensure year-round electricity supply, the solar photovoltaic system was sized to meet demand during December, the month of lowest solar radiation. The resulting 92 MW solar PV system would generate an average of 78,000 MWh/year of excess electricity sold to the grid and occupy nearly 250 acres, not including the associated transformer and battery system.

Wind resource availability also varies seasonally. A wind capacity factor of 21.0%, rather than the annual average of 34.5%, was applied based on the lowest monthly median wind plant capacity factors for the Upper Plains region (occurring in July and August; EIA, 2015). The resulting 34 MW wind power system would generate an average 39,000 MWh/year in excess electricity sold to the grid and require a 1,500-acre wind farm. However, the direct footprint of the wind power system (the wind turbines and service roads) would occupy only 16 acres, leaving the remaining area available for farming, the battery storage system, and other uses.

Emissions reductions from on-site renewable energy production and storage were modeled based on a review of life-cycle emissions from current solar and wind generation technology and battery storage (NREL, 2013; IEA, 2020). Total estimated life cycle emissions are 0.063 kg $CO_2$e/kWh for on-site solar plus energy storage, and 0.048 kg $CO_2$e/kWh for on-site wind power plus storage. Net emissions were estimated by subtracting the life cycle emissions of the generation and storage system, applied to the total annual electric generation of the solar and wind power systems, from the carbon intensity of electricity supplied by the ethanol-production-weighted grid mix described in section 2.1. The large scale of these on-site energy systems, designed to meet ethanol plant demand during low-capacity months, result in large emissions credits for offsetting grid electricity – up to 8.9 g $CO_2$e/MJ ethanol (solar PV) or 6.6 g $CO_2$e/MJ (wind).

Costs of installing on-site renewable power generation were estimated independently based on recent assessments of the capital and operational costs of commercial wind turbines (Stehly et al., 2020) and solar panels (NREL, 2021). Energy storage costs for up to 24 hours of facility energy requirements was estimated based on reported costs of similar installations in Europe between 2018 – 2020 (NREL, 2021). Energy storage increased system costs by 24% and 40% for wind and solar systems. The current average commercial grid energy price ($72.50/MW) was used to calculate the revenue from electricity generation in excess of ethanol plant requirements.

#### 2.4.1.3. Bio-methane Purchase

Natural gas is the primary process fuel in ethanol production and is the source of most of an ethanol facility's direct GHG emissions. Substituting renewable methane from biological sources, such as manure or municipal waste, for fossil methane is one of an ethanol producer's largest opportunities for emissions reduction.

Emissions reductions from bio-methane use in ethanol facilities was modeled outside of the GREET model, as GREET does not contain a bio-methane pathway for stationary (facility) use. And as with renewable electricity, substituting bio-methane emissions factors for natural gas parameters in GREET would also apply bio-methane to all upstream processes, including fertilizer manufacturing. Following the same method as the renewable electricity emissions credits, bio-methane emissions credits were calculated for each facility type at each model run based on the difference between energy supply from bio-methane and fossil natural gas. Bio-methane emissions were estimated at 11.0 g $CO_2$e/MJ based on relevant Ecoinvent LCA database sources (Wernet et al., 2016), compared to the 68.7 $CO_2$e/MJ GREET emissions factor for fossil natural gas. Final scenario results were then adjusted from the GREET output to include a credit for the bio-methane substitution for fossil natural gas based on the total gas consumption per gallon of ethanol for each facility type.

The cost of substituting bio-methane for fossil natural gas was estimated at $7.90/MMBtu based on recent prices of bio-methane at $13.90/MMBtu (IEA, 2020b) and approximately $6.00/MMBtu for natural gas (EIA, 2021c).

#### 2.4.1.4. Combined Heat and Power from Biomass

Rather than substituting renewable energy sources for electricity and heat separately, an ethanol facility could utilize a biomass-fired combined heat and power system to become independent of fossil fuels. Biomass-fueled combined heat and power systems for ethanol facilities are integrated into the GREET model, and so no additional external modeling is necessary for this action. Although this report refers to corn stover-fueled CHP systems (due to the wide availability of corn stover near ethanol facilities), the emissions benefits of biomass-fueled CHP are not limited to corn stover. A test of CHP scenarios in GREET showed that the emissions benefits for ethanol producers are nearly identical, regardless of whether the biomass source is corn stover, switchgrass, or poplar.

The operating costs of a biomass-fired CHP system ($16 million per year; Sokhansanj et al., 2010) are substantially higher than current natural gas boiler operating costs. This study estimates an added cost of roughly $0.18/gallon ethanol at current natural gas prices.

#### 2.4.1.5. Better-than-BAU Efficiency

Ethanol producers will likely have access to many process improvements and energy efficiency modifications over the next three decades. These may include a reduction in DGS drying, simultaneous saccharification and fermentation (SSF), very-high-gravity fermentation, high-efficiency boiler or heat recirculation systems, or other unforeseen process improvements (Tse et al., 2021). Rather than attempting to predict the feasibility or likelihood of each potential technological or economic shift in the corn ethanol industry, the 'better-than-BAU' efficiency action extrapolates from the past decade of facility energy efficiency gains by the most efficient corn ethanol producers (Christianson, 2020). The advantages of unexpected or technically challenging process improvements are assessed by assuming that these advancements allow the industry as a whole to "catch up" to the most efficient producers, who in turn are also forecast to continue reducing their energy use and improving ethanol yields per bushel.

Emissions reductions for better-than-BAU facility efficiency improvements were estimated by applying the lower energy use and faster rate of efficiency improvements of a group of high-performing dry mill facilities to the dry mill average with a 5 year delay. Extrapolating from the historical improvements in ethanol production efficiency (Btu/gallon ethanol) of the "US Leaders" group of ethanol producers reported by Christianson from 2010 to 2019 (Christianson, 2020), the average improvement in energy efficiency over a 5-year period was applied to the 2020 dry mill facility energy use parameters (described above). A 15% decline in the rate of efficiency improvements every 5-year period was applied to reflect diminishing returns and increasing costs or complexity of future efficiency improvements.

In addition to energy efficiency improvements, the improved efficiency action includes more rapid and greater progress in corn oil extraction and ethanol yield. Improved efficiency corn oil extraction rates for 2025-2050 were forecast from historical improvement rates using the same method as the energy use improvement forecast. Ethanol yields by the "US Leaders" group of producers was matched at a 5 year delay, with maximum ethanol yields increased by 0.03 gal/bu (i.e. a 1%

*Table 8: Facility energy use, ethanol yield, and corn oil yield by dry mill ethanol producers under the BAU and Improved Efficiency actions.*

| | BAU Energy Use (Btu/gal) | Improved Efficiency Energy Use (Btu/gal) | BAU Ethanol Yield (gal/bu) | Improved Efficiency Ethanol Yield (gal/bu) | BAU Corn oil Yield (lbs/gal) | Improved Efficiency Corn Oil Yield (lbs/gal) |
|---|---|---|---|---|---|---|
| *2020* | 22,800 | 22,800 | 2.85 | 2.92 | 0.27 | 0.27 |
| *2025* | 22,591 | 19,687 | 2.90 | 2.93 | 0.31 | 0.35 |
| *2030* | 22,471 | 18,466 | 2.92 | 2.95 | 0.35 | 0.42 |
| *2035* | 22,471 | 17,428 | 2.92 | 2.95 | 0.39 | 0.47 |
| *2040* | 22,471 | 16,545 | 2.92 | 2.95 | 0.44 | 0.52 |
| *2045* | 22,471 | 15,795 | 2.92 | 2.95 | 0.48 | 0.56 |
| *2050* | 22,471 | 15,158 | 2.92 | 2.95 | 0.52 | 0.59 |

improvement vs the maximum theoretical ethanol yield). Emissions reductions from the improved energy efficiency and ethanol yield were assessed in GREET using the input parameters shown in table 8.

The financial costs and benefits of the improved efficiency action were estimated based on the added ethanol revenue and reduced fuel costs in 2030 compared to BAU and a 25% increase in the total facility investment cost (Ou et al., 2014).

#### 2.4.1.6. WDGS Focus

Though dried distillers' grains are a more valuable coproduct than wet distillers' grains, the high energy cost of the drying process leads to a higher GHG footprint for DDGS production. Ethanol producers who can find a larger market for WDGS have an opportunity to reduce their energy use and emissions. The 'WDGS Focus' action reflects a reversal of the roughly 2:1 DDGS:WDGS production ratio in the current market to 1:2 DDGS:WDGS. This allows ethanol producers to reduce DGS drying energy by roughly 50%, cutting facility-wide heat use by about 25%.

Emissions benefits from a higher WDGS production ratio were assessed in GREET by reducing facility energy use and changing the ratio of coproducts, which affect the emissions credits from offset corn and soybean production for animal feed. This action was implemented for single-facility scenarios as a case study for energy efficiency improvements.

Costs of switching to a higher WDGS co-product mix were estimated applying the market prices of DDGS and WDGS to the coproduct quantities before and after the switch. Natural gas savings at current prices were subtracted from the change in coproduct value.

#### 2.4.1.7. Corn Kernel Fiber Fermentation

The GREET pathway for "1.5 Gen" ethanol production was used to assess the emissions of ethanol from a facility capable of fermenting the carbohydrates in corn kernel fiber. Although producers may be able to sell this additional ethanol as higher-value cellulosic biofuel under the RFS, this study does not differentiate between ethanol produced from corn starch and fiber. Instead, the average emissions (g $CO_2$e/MJ ethanol) from the facility are reported. This simplifies the comparison of ethanol facilities with and without fiber fermentation and reflects the average emissions benefit of additional ethanol production.

Due to limited data on the capital costs of corn kernel fiber ethanol production, estimated pathway costs reflect only the value of additional ethanol production, changes in energy purchases, and the lost revenue due to reduced coproduct sales volumes.

#### 2.4.1.8. Improved Yeast Strains

Key ethanol production parameters, including fermentation rate, ethanol yield, and ethanol concentration are determined in part by the capabilities and limitations of the active yeast strain. Development of yeasts with higher tolerances to ethanol and other chemical stressors and higher conversion efficiency of glucose to ethanol has been an active area of research for decades. New bioengineering tools and increases in understanding the *Saccharomyces cerevisiae* genome and metabolism will likely allow continued breakthroughs and efficiency improvements (Tse et al., 2021). Without focusing on a single potential yeast strain or breakthrough in metabolic engineering, this study used the improved yeast strain action to represent a range of possible improvements in yeast performance and the likely benefits for corn ethanol producers.

Improved yeast strains were expected to result in some combination of (1) higher ethanol yields, (2) higher fermentation ethanol concentrations, and (3) reductions in enzymatic and chemical fermentation aids. Emissions benefits from an improved yeast strain were modeled in GREET by applying a roughly 2% increase in ethanol yield (an added 0.05 gal/bu, achieving up to 99.3% the theoretical maximum ethanol yield), a 10% reduction in beer column energy use, and a 66% reduction in enzyme use.

The costs to ethanol producers of utilizing an improved yeast strain were estimated by doubling yeast costs to the biorefinery, adding $0.015/gal ethanol.

#### 2.4.1.9. Carbon Capture and Sequestration

Ethanol fermentation creates a remarkably high-purity stream of $CO_2$, which many facilities already utilize as an added-value coproduct. Sequestering this carbon in geological formations is one of the largest and most effective actions producers can take to reduce the carbon intensity of corn ethanol. The core 'CCS' action in this study addresses this biological source of $CO_2$. Another option for producers is to capture the $CO_2$ from on-site power generation. This study assesses the potential for producers to sequester additional biological $CO_2$ from biomass-fueled combined heat and power systems as a further step that facilities can take to maximize bioenergy carbon capture and sequestration (i.e. BECCS).

Emissions from CCS of $CO_2$ from fermentation are assessed using the built-in modeling tools available in GREET. GREET estimates a production rate of 2.85 kg $CO_2$/gallon ethanol, with 100% efficient capture, at an energy cost of 180 kWh/ton $CO_2$ (Red Trail Energy, 2019; Wang et al., 2020). This study also assesses an emissions rate of 1.9 g $CO_2e$/MJ ethanol to account for the energy used in transportation and deep well injection of captured carbon (Kaliyan et al., 2011). CCS from biomass-fueled CHP is modeled outside of GREET for each facility type and year of operation using GREET-calculated estimates of the biological fraction of $CO_2$ emissions from the CHP system and the GREET default energy cost of carbon capture. The same emissions rate for transportation and sequestration are included and the final total emissions reduction added to the GREET output and other adjustments for each scenario.

A review of technology and economic assessments of carbon capture and sequestration at fossil energy and bioenergy facilities shows likely costs between $20 and $70 per ton of $CO_2$ (Herzog et al., 2005; Kim et al., 2020; Sanchez et al., 2018; Schmelz et al., 2020). This study applies a mid-range estimate of $50/ton to establish the cost ranking factors for CCS.

### 2.4.2. Supply Chain Actions

#### 2.4.2.1. Renewable Fuels Use

Transportation of corn grain from the farm to the ethanol facility generates roughly 1.5 g $CO_2$e/MJ ethanol from fuel combustion. Substituting renewable fuels for conventional diesel in the corn supply chain can assist ethanol producers in reducing the total emissions from ethanol. This study assesses the potential for soybean biodiesel to replace fossil diesel in corn grain transportation.

Emissions from soybean biodiesel substitution for conventional diesel in corn grain transportation was modeled outside of GREET. GREET-reported corn grain transportation emissions were adjusted by the ratio of life-cycle emissions from 100% soybean biodiesel to conventional diesel for each facility type and in each model run. This had the effect of reducing corn grain transportation emissions by roughly 63%.

The cost of renewable fuels use in corn transportation was estimated according to the difference in fuel prices for biodiesel and conventional diesel on an energy basis ($3.73 and $3.10 per gallon gasoline equivalent, respectively) and the quantity of fuel used in corn grain transportation (Alternative Fuels Data Center (AFDC), 2021).

### 2.4.3. Farming Actions

#### 2.4.3.1. Renewable Fuels Use

Liquid fuels use on the farm generates roughly 3 g $CO_2$e/MJ ethanol. Substituting renewable fuels for conventional diesel and gasoline in farm equipment could be an effective way of reducing the life cycle GHG emissions of corn ethanol. This study assesses the potential for soybean biodiesel to replace petroleum fuels in corn farming operations.

Emissions from soybean biodiesel substitution for conventional diesel in corn farming was modeled outside of GREET. GREET-reported corn farming fuel emissions were adjusted by the ratio of life-cycle emissions from 100% soybean biodiesel to conventional diesel for each facility type and in each model run. This had the effect of reducing corn farming fuel emissions by roughly 63%.

The cost of renewable fuels use in corn farming was estimated according to the difference in fuel prices for biodiesel and conventional diesel on an energy basis ($3.73 and $3.10 per gallon gasoline equivalent, respectively; AFDC, 2021).

#### 2.4.3.2. Renewable Electricity Purchase

Electricity use in grain drying and other on-farm activities creates a small but measurable quantity of GHG emissions, representing approximately 0.22 g $CO_2$e/MJ from corn ethanol. Utilizing solar or wind energy through RECs or PPAs is a straightforward and reliable way to reduce the carbon intensity of corn used for ethanol production.

The GHG emissions benefits of purchasing wind or solar-generated electricity on the farm were calculated using the same method as renewable energy purchases by ethanol producers (above). The quantity of GHG emissions from on-farm electricity use was estimated in each model run for each facility type. An emissions credit was applied to the GREET model results for the difference in GHG emissions for renewable energy generation and the electric mix used in the given model run.

Costs of on-farm renewable electricity use were estimated using the recent cost of RECs ($6/MWh; Heeter et al., 2021) and the quantity of on-farm electricity use in the base ethanol production case.

#### 2.4.3.3. Reduced Tillage

The effects of tillage changes on soil carbon can vary depending on a wide range of factors that vary within and between farms, including soil type and both long-term and recent land use histories. Tillage changes also have interactive effects with other land management decisions, such as fertilizer type and the use of cover crops. This study uses the Argonne Feedstock CI Calculator (FD-CIC) to model county-scale changes in tillage practices and cover crop adoption (Wang et al., 2021). The FD-CIC takes inputs from the GREET model and a database of soil carbon responses to farming practices generated with a custom parameterized version of the CENTURY model (Dunn et al., 2017) to generate estimates of the 30-year average soil carbon costs or benefits of changes in farming practices per unit of feedstock (i.e. corn grain) produced. Results from the FD-CIC can be used to assess the difference between current practices and a uniform test case at the county level. In other words, the tool can provide the difference in soil carbon storage in a particular county between current practices (a mix of conventional tillage, reduced till, and strip till or no tillage) and uniform conventional, reduced, or no-till farming across all corn-producing acres in the county.

As the FD-CIC results are county-specific and it is beyond the scope of this study to compile soil carbon results for all corn-producing counties in the US for each tillage scenario, six counties across the Midwest were selected as case studies. Counties were selected according to three criteria: (1) one county from each of the top six ethanol-producing states; (2) counties with multiple ethanol biorefineries within a roughly 50 mile radius; (3) counties among the highest total corn-producing states by volume in each state. The current average tillage practices in each state were retrieved from the USDA NASS QuickStats database (USDA NASS, 2021). Finally, the FD-CIC tool was used to estimate changes in soil carbon for each county for each combination of tillage practices and cover crops (see table 8).

*Table 9: County details for tillage and cover crop case studies. County properties from USDA NASS. Soil carbon change results from the Argonne FD-CIC tool. Negative values indicate carbon storage, positive values indicate carbon emissions. CT = Conventional tillage; RT = Reduced Tillage; ST/NT = Strip till/no-till; CC = Cover crop.*

| ***County*** | **Corn Production** | **CT** | **RT** | **ST/NT** | **Cover Crop** | **CT** | **RT** | **ST/NT** | **CT + CC** | **RT + CC** | **ST/NT + CC** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **(Million bu)** | **%** | **%** | **%** | **%** | **ΔSOC (g $CO_2$e/bu)** | | | | | |
| *Kossuth, IA* | 73.3 | 44% | 52% | 3% | 2% | 505 | 34 | -1135 | -1770 | -2881 | -4393 |
| *Bureau, IL* | 61.8 | 33% | 41% | 26% | 3% | 327 | -197 | -1257 | -5352 | -6263 | -7898 |
| *Renville, MN* | 60.4 | 66% | 32% | 2% | 7% | 354 | -484 | -2044 | -3682 | -5052 | -6913 |
| *York, NE* | 54.1 | 13% | 58% | 28% | 3% | 688 | 241 | -562 | -7358 | -8128 | -9210 |
| *Brown, SD* | 54.0 | 6% | 43% | 51% | 1% | 554 | 45 | -1274 | -6098 | -6529 | -6851 |
| *White, IN* | 30.2 | 42% | 42% | 16% | 2% | 296 | -26 | -779 | -5338 | -6168 | -7147 |
| | | | | | | | | | | | |
| *Production-weighted average* | | 35% | 45% | 20% | 3.0% | 464 | -73 | -1220 | -4708 | -5638 | -6925 |

Using the modeled county-level changes in SOC, this study assessed two approaches to reduced tillage. One approach implements RT (without cover crops) on all corn acres in place of current practices. As shown in table 8, the production-weighted results from the FD-CIC tool show a net soil carbon benefit of 73 g $CO_2$e/bu of corn, or 0.3 g $CO_2$e/MJ ethanol at current ethanol yields. These values are small in part because the benefits of converting conventionally tilled fields to RT are balanced by SOC losses from converting strip till and no-till (ST/NT) fields to RT as well. Strip till and no-till management are expected have similar emissions profiles, both leading to more soil carbon storage than other reduced-tillage practices (Liu et al., 2021).

Unfortunately, these tools do not accommodate selective changes in land management practices (i.e. converting only conventionally tilled soils to RT). Because converting lands under ST/NT management to RT is an undesirable outcome, a second approach was identified to assess the conversion of CT fields to RT without loss of carbon from ST/NT fields. The second approach models an expansion of RT area from 45% to 75% of farmland (representing a two-thirds increase in RT adoption based on the production-weighted average in table 8). To isolate the benefits of CT conversion to RT in the FD-CIC tool, the county-wide gain from expanding RT in Kossuth and Renville counties were used, as those counties contain limited ST/NT cropping area. Soil carbon changes from the two counties were adjusted to exclude RT area (since a RT-to-RT "transition" will presumably lead to no long-term changes in soil carbon). The total change in SOC from a 50% increase in RT area was then assessed by applying the CT-to-RT transition factor (-340 g $CO_2$e/bu) to 30% of total acres.

In addition to changes in SOC, reduced tillage has the benefit of reducing on-farm fuel use. A review of farm-side factors affecting corn ethanol GHG emissions found that the transition from CT to RT can save 0.23 gallons of diesel per acre, representing about 0.07 g $CO_2$e/MJ. Applying this benefit to the fraction of farms expanding RT leads to additional emissions benefits in both of the RT approaches (100% RT and expansion of RT from 45% to 75% of farmland).

The costs of expanding RT were estimated from the difference in 2021 corn production costs between CT and RT systems for a corn-soybean rotation in Iowa (Plastina, 2021).

#### 2.4.3.4. No-till

Emissions from the transition of cropland to ST/NT were modeled using a similar approach as the reduced tillage actions. Two approaches to expanding no-till farming were assessed. The first approach models 100% ST/NT adoption across all corn ethanol suppliers, using the production-weighted average of SOC gain from the FD-CIC model shown in table 8 (1,220 g $CO_2$e/bu, or about 5.4 g $CO_2$e/MJ).

The second approach models 50% ST/NT adoption across corn ethanol suppliers, assessing the production-weighted SOC change for each of the six case study counties. Reaching 50% ST/NT adoption evenly across all counties requires large changes in some counties (49% of corn farmers in Renville, MN) and small changes in others (Brown, SD has already achieved at least 50% ST/NT adoption). The weighted average change in emissions for the second approach is about 2.1 g $CO_2$e/MJ. It is worth noting that these estimates, intended as representative average values for Midwestern ethanol production, will not be accurate for individual corn farmers or biorefinery operators. Within the six counties selected as case studies, the county with the largest carbon benefit of no-till has over three times the soil carbon storage rate as the county with the smallest benefit. Efforts to reduce emissions through soil carbon storage will require a concerted effort to accurately estimate soil carbon across farms and regions in emissions models of ethanol and other farm products.

As with RT, ST/NT practices also reduce farm fuel use. An emissions credit from reduced farm diesel use was applied based on the estimated diesel savings of 1.59 gal/acre (Liu et al., 2020) and the proportion of farms adopting ST/NT.

The costs of expanding ST/NT were estimated from the difference in corn production costs between strip tillage and CT systems for 2021 production costs for a corn-soybean rotation in Iowa (Plastina, 2021).

#### 2.4.3.5. Cover Crops

Changes to GHG emissions from cover crop adoption were modeled using GREET and the Argonne FD-CIC tool. Because the integrated GREET cover crop module assigns cover crop-related emissions and credits only to corn stover and not to the corn grain ethanol pathway, changes to farming energy and emissions due to cover crop farming were calculated separately and used to adjust core corn ethanol input values. Farming energy use for a mix of rye and hairy vetch are assumed to be similar to the GREET default values for rye cover crop farming. The yield, nitrogen content, and herbicide use rates for rye and hairy vetch were sourced from the Penn State Extension office (Duiker, 2010). Half of the cover crop biological N was assumed to be available to the following crop, reducing chemical fertilizer application rates by 38 lbs/acre. Following GREET standard assumptions, a rate of 1.53% of cover crop

N to $N_2O$ was applied, increasing total field $N_2O$ emissions by about 3.8 g $N_2O$/bu at 2020 corn yields (Kwon et al., 2021).

Changes in SOC accumulation were modeled using the Argonne FD-CIC tool following the same procedure as the tillage actions. The weighted average of SOC changes under cover cropping and the mix of tillage practices in each of the six case study counties was used to estimate the annual average SOC accumulation of corn ethanol suppliers between 2020 and 2050. Soil carbon gains were estimated at about 4,800 g $CO_2e$/bu at 2020 corn yields.

The costs of cover crop establishment were estimated as $37/acre in added farm operations costs, with a credit for $10/acre in reduced fertilizer purchases (Myers et al., 2019).

#### 2.4.3.6. Green Ammonia

Producing “green” ammonia by using low-carbon electricity to produce and recombine N2 and H2 (rather than through the fossil fuel-intensive steam reforming of natural gas) has the potential to reduce the carbon intensity of nitrogen fertilizers (Liu et al., 2021). Changes in GHG emissions from green ammonia adoption on corn farms were estimated using the Argonne FD-CIC tool and added separately to each relevant GREET model run. It was assumed that, among farms using green ammonia, all of the nitrogen previously sourced from conventional ammonia and urea-ammonium nitrate solution (99.5 lbs/acre out of a total 158 lbs N/acre) were replaced with green ammonia. Total N fertilizer emissions in 2020 using green ammonia were 9.7 g $CO_2e$/MJ, a reduction of 10.5 g $CO_2e$/MJ from the baseline 2020 scenario.

The cost of adopting green ammonia was estimated from current fertilizer prices (Plastina, 2021) and the ratio of green ammonia to conventional ammonia prices (Brown, 2020).

#### 2.4.3.7. 4R: Right time, Right place, Right form, and Right rate

‘4R’ approaches to fertilizer management encompass many individual actions to optimize for a combination of various outcomes: economic return, nitrogen use efficiency, reduce nutrient runoff, and odor control (Grant & Flaten, 2019). The actions themselves can include monitoring soil nutrient levels, GPS-guided precision application, modeling of crop yield responses, variable timing of nutrient applications to adjust for precipitation and field conditions, among others (Banger et al., 2020; Rogers, 2019). Though not addressed explicitly in this model, some 4R practices are likely to play a role in maintaining steady fertilizer rates per acre as corn yields continue to increase over the next few decades under the baseline scenario.

This study follows the approach of the GREET modeling team by representing the impact of a concerted adoption of 4R practices among farmers as an improvement in pollution control. The emissions benefits of 4R are represented by a reduction in the loss of N as $N_2O$. That emissions rate is reduced by up to ⅓ depending on the adoption rate among farmers in the corn ethanol supply chain

(Liu et al., 2021). This study also assumes that additional field passes are needed for precision application of fertilizer, which results in emissions from 1 gal/acre additional diesel consumption.

4R is expected to result in no additional costs to the farmer beyond the additional fuel and labor for precision fertilizer application (about $3.50/acre).

#### 2.4.3.8. Enhanced Efficiency Fertilizers

Enhanced efficiency fertilizers (EEFs) are a group of chemically-modified or supplemented fertilizers that are more stable than conventional chemical nutrients. Increased stability means that more nutrients may be available to crops, rather than decomposing in the environment, and emissions associated with fertilizer losses are reduced. Like 4R fertilizer management, EEFs can reduce the loss of N as $N_2O$ (Thapa et al. 2016). Changes in GHG emissions were modeled with the Argonne FD-CIC tool and used to adjust GREET outcomes for each facility type in each model run. Under baseline 2020 conditions, EEFs reduced fertilizer $N_2O$ emissions by 2.2 g $CO_2$e/MJ.

Enhanced efficiency fertilizers were estimated to cost twice that of conventional nitrogen fertilizers (Ozores-Hampton, 2018).

#### 2.4.3.9. Soil Amendments

Soil amendments can refer to a wide range of products, from conventional fertilizer to manure, compost, lime, and specialty products. This study defines soil amendments as products used to improve soil fertility and soil organic matter, regulate moisture, extend nutrient availability, or store carbon in agricultural soils. These services are in addition to, and do not replace, use of conventional fertilizers. A variety of soil amendments, including animal byproducts, hydrothermal treated manure, and food manufacturing waste have been shown to have short-term benefits to soil physical characteristics and crop yield (Sisouvanh et al., 2021; Olayemi et al., 2020; Spargo et al. 2016; Jackson & Mazour, 2020). Though some of these materials are currently widely used by organic farmers, relatively little long-term data is available the benefits of their use (Brock et al., 2021).

Because livestock manure is already widely used by both conventional and organic corn farmers and significant concerns exist about common application rates (Long et al., 2018) and the safety of spreading untreated manure (Goss et al., 2013), this study focuses on the potential benefits of three other types of soil amendments: treated organics (i.e. highly processed manure or byproducts from food manufacturing), municipal compost, and biochar.

Emissions from processed, manure-based soil additives were modeled based on an 9% corn yield increase, additional fuel use for transportation and spreading of the soil additive equivalent to 1.4 gal/acre, direct emissions of $N_2O$ from the N fraction of added organic material using the GREET emissions factors for manure, and assumed long-term additional soil carbon storage of 25% of added carbon. Some of these parameters are highly uncertain, particularly the attributable fraction of $N_2O$ emissions and soil carbon storage. However, the assessed GHG emissions from addition on processed manure-based soil additives are driven by the improvement in corn yield, with direct emissions and soil carbon playing only minor roles.

Emissions from municipal organic compost addition to corn-growing soils were estimated for a best-case scenario, including offsetting of landfill methane emissions and the full life cycle of compost production, addition, and soil improvement according to DeLonge et al. 2013. Because of the limited supply of high-quality municipal compost that could be credited with avoided landfill emissions, a maximum farmer adoption rate of 10% was set for this action.

Emissions from the addition of biochar were modeled based on a combination of review and field studies of corn production (Drawdown, 2020; Xiao et al., 2016; Xu et al., 2019). Biochar amendment of roughly 10 tons/acre every 10 years was expected to increase corn yields by 10%, reduce $N_2O$ emissions from fertilizer and biomass by 10%, and sequester soil carbon at an effective rate of 0.95 lbs $CO_2$e/lb biochar. Additional on-farm diesel use of 2 gal/acre during application years was added to GREET model inputs alongside the yield addition and $N_2O$ emissions rate adjustment to model the total effects of biochar addition on corn ethanol GHG emissions. Soil carbon storage was added to the GREET results to generate the final emissions reduction figure.

Soil amendments can carry high costs to farmers, often as much as $20-$100/acre in addition to core NPK fertilization (Brock et al., 2021; McBride et al., 2015), while biochar prices are estimated at $200/ton, or approximately $2,000/acre for an initial 10-ton/acre application (Drawdown, 2020). Municipal organic compost, where available, may be substantially more affordable at approximately $30/ton (Duffy, 2019).

#### 2.4.3.10. Deep-rooting Corn

Deeper and more plentiful root systems are a primary advantage of many prairie species over corn and other grain crops in accumulating soil carbon. Corn varieties with more substantial root systems could play a role in stabilizing and rebuilding SOC, if such varieties could be bred without a loss in grain yield (Paustian et al., 2019).

According to one bounding study of soil carbon accumulation under a hypothetical deep-rooting corn variety, corn with a 50% greater root mass and a strong shift to a deeper root system could store about one metric ton of $CO_2$e soil carbon per acre per year (Paustian et al., 2019). Accounting for additional emissions from added fertilizer production and $N_2O$ losses, emissions benefits to ethanol producers could reach 18 g $CO_2$e/MJ under baseline 2020 ethanol producer parameters.

As no cost estimates for hypothetical deep-rooting corn varieties are available, this study assumes a doubling in seed costs to account for intensive breeding and crop development efforts.

## 2.5. Pathway Development

The emissions reduction potential, financial cost, and feasibility of all 29 emissions reduction actions are summarized in table 10. GHG emissions and financial costs are listed on a per-MJ-ethanol basis. Costs are also reported on an emissions-reduction basis ($/t $CO_2$e reduced). The ranking of actions by emissions magnitude (MAG) and cost are used in combination with the TRL to guide the selection of actions for each pathway to net zero carbon ethanol. Because not all actions are compatible with all scenarios, and not all actions are compatible with each other, the pathway rankings were not used strictly, but rather as guidelines to inform the preferred emissions reductions strategies for each pathway.

### 2.5.1. Core Pathway to Net Zero Ethanol

The core pathway for ethanol producers to meet RFA member goals of 70% lower emissions than gasoline by 2030 and net zero by 2050 was developed from an adjusted ranking of the available actions by technological readiness, magnitude of the emissions reduction, and cost of the emissions reduction:

$$R_P = (R_M + R_{CC}) \times (10 - T_R)$$

Where $R_P$ is the core pathway ranking factor of the emissions reduction action, $R_M$ is the magnitude rank of the action, $R_{CC}$ is the cost-of-carbon rank of the action, and $T_R$ is the technological readiness level of the action. Actions were then ranked from the lowest-to-highest scoring according to the core pathway ranking factor. This formula prioritizes high-magnitude and low-cost actions, while heavily weighting the role of technological readiness (i.e. feasibility) of each action.

For the core pathway model of individual facilities, the selected actions were:

1. Facility Renewable power (PPAs) (by 2030)
2. Fermentation CCS: deep-well injection (by 2030)
3. On-farm Renewable power (RECs) (adoption by 75% of supplying farmers by 2050)
4. Reduced tillage adoption: 45% to 75% (by 2050)
5. Corn Kernel Fiber Utilization (by 2050)
6. Increased WDGS:DDGS ratio (by 2050)
7. Bio-methane from manure (by 2050)

For the industry-wide core pathway, the selected actions were:

1. Facility Renewable power (PPA) (incremental adoption rate of 5%/yr from 25% in 2025)
2. Corn Kernel Fiber Utilization (incremental adoption rate of 5%/yr from 15% in 2025)
3. Better-than-BAU Facility Efficiency
4. On-farm Renewable electricity (RECs) (incremental adoption rate of 5%/yr starting in 2026)
5. Fermentation CCS: deep-well injection (incremental adoption rate of 5%/yr from 15% in 2025)
6. Bio-methane from manure (incremental adoption rate of 5%/yr from 20% in 2025)
7. Reduced tillage adoption: 45% to 75% (incremental adoption rate of 5%/yr starting in 2026)

*Table 10: Available actions to reduce emissions for corn ethanol. Shown are total emissions reductions under baseline conditions, estimated costs of implementation (per MJ ethanol and per ton of $CO_2e$ emissions reduced), technological readiness level (TRL), and rankings of action by the size of potential emissions reductions (MAG Rank), cost of emissions reductions per MJ (MJ Cost Rank), cost of emissions reductions per t $CO_2e$ (GHG Cost Rank), and according to the core pathway system (CORE Rank). Pathway ("Path") columns show which actions are used to achieve RFA Member GHG targets in each scenario. 'FAC' and 'IND' indicate whether each pathway applies to a single hypothetical facility (FAC) or to the ethanol industry as a whole (IND). 'CAF' refers to the Climate Action Future scenario. Pathways with actions marked 'X' include those actions by default.*

| Process Stage | Action | Emissions Reduction (g $CO_2e$/MJ) | Cost ($/MJ) | Cost ($/t $CO_2e$) | TRL | MAG Rank | MJ Cost Rank | GHG Cost Rank | CORE Rank | Path: CORE FAC | Path: CORE IND | Path: COST (MJ) FAC | Path: COST (GHG) FAC | Path: MAG FAC | CAF BASE | Path: CAF IND |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Facility Operations** | **Renewable power (RECs)** | 4.29 | $0.00012 | $27 | 9 | 17 | 12 | 10 | 3 | | | | | | | |
| **Facility Operations** | **Renewable power (PPA)** | 4.29 | -$0.00034 | -$78 | 9 | 17 | 7 | 7 | 1 | **1** | **1** | **3** | **4** | | | **1** |
| **Facility Operations** | **On-site solar PV + storage** | 3.98 | $0.00106 | $267 | 8 | 9 | 20 | 20 | 11 | | | | | | | |
| **Facility Operations** | **On-site wind + storage** | 4.10 | $0.00075 | $183 | 8 | 10 | 16 | 14 | 7 | | | | | | | |
| **Facility Operations** | **Bio-methane from manure** | 13.63 | $0.00204 | $150 | 8 | 6 | 26 | 25 | 13 | **7** | **6** | | | | **5** | **X** |
| **Facility Operations** | **CHP from corn stover** | 24.23 | $0.00227 | $93 | 8 | 3 | 28 | 19 | 5 | | | | | **2** | | |
| **Facility Operations** | **Increased WDGS:DDGS ratio** | 4.66 | $0.00061 | $131 | 9 | 16 | 18 | 21 | 4 | **3** | | **10** | | | | |
| **Facility Operations** | **Better-than-BAU Facility Efficiency** | 4.13 | -$0.00092 | -$223 | 8 | 19 | 4 | 6 | 9 | | **3** | | | | | **3** |
| **Facility Operations** | **Corn Kernel Fiber Utilization** | 1.80 | -$0.00250 | -$1,388 | 9 | 24 | 1 | 2 | 2 | **2** | **2** | **1** | **1** | | | **2** |
| **Facility Operations** | **Improved Yeast** | 1.57 | -$0.00007 | -$45 | 3 | 25 | 8 | 8 | 29 | | | **4** | **3** | | | |
| **Carbon Capture** | **Fermentation CCS: deep-well injection** | 31.73 | $0.00159 | $50 | 7 | 1 | 23 | 15 | 7 | **5** | **5** | **12** | **7** | **1** | | **4** |
| **Carbon Capture** | **CCS from stover CHP: deep-well injection** | 27.82 | $0.00127 | $50 | 7 | 2 | 21 | 15 | 10 | | | | | **3** | | |
| **Corn Transportation** | **Biodiesel substitution** | 0.87 | $0.00008 | $134 | 8 | 26 | 10 | 23 | 21 | | | **8** | | | **1** | **X** |
| **Corn Farming Energy** | **Biodiesel substitution** | 2.39 | $0.00017 | $134 | 8 | 20 | 14 | 23 | 19 | | | **9** | | | **1** | **X** |
| **Corn Farming Energy** | **Renewable electricity (RECs)** | 0.21 | $0.00002 | $90 | 9 | 29 | 9 | 18 | 6 | **4** | **4** | **5** | | | **X** | **X** |
| **N Fertilizer** | **Green ammonia substitution** | 5.71 | $0.00186 | $325 | 6 | 12 | 24 | 28 | 25 | | | | | 5 | | |
| **N Fertilizer** | **Green Ammonia + 4R** | 10.54 | $0.00194 | $184 | 6 | 8 | 25 | 26 | 24 | | | | | | | |
| **$N_2O$ from Fertilizer & Biomass** | **4R (Right time, Right place, Right form, and Right rate)** | 4.83 | $0.00009 | $18 | 7 | 15 | 11 | 9 | 15 | | | **6** | **5** | | **3** | **X** |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **$N_2O$ from Fertilizer & Biomass** | **Enhanced Efficiency Fertilizer** | 2.24 | $0.00044 | $196 | 6 | 21 | 18 | 27 | 26 | | | | | | | |
| **Farm Management** | **Reduced tillage adoption: 45% to 75%** | 0.85 | -$0.00060 | -$715 | 8 | 27 | 5 | 3 | 12 | **6** | **7** | | **2** | | **2** | **X** |
| **Farm Management** | **Reduced Tillage: 100% adoption** | 0.32 | -$0.00181 | -$4,649 | 7 | 28 | 3 | 5 | 20 | | | | | | | |
| **Farm Management** | **No-till: 50% adoption of ST/NT** | 2.15 | -$0.00050 | -$233 | 7 | 22 | 6 | 1 | 18 | | | | | | | |
| **Farm Management** | **No-till: 100% adoption of ST/NT** | 5.36 | -$0.00200 | -$343 | 6 | 13 | 2 | 4 | 14 | | | **2** | | | | |
| **Farm Management** | **Cover Crop adoption: 25%** | 5.34 | $0.00016 | $31 | 7 | 14 | 13 | 11 | 17 | | | **7** | **6** | | | |
| **Farm Management** | **Cover Crop adoption: 50%** | 10.68 | $0.00033 | $31 | 6 | 7 | 17 | 11 | 15 | | | **11** | **8** | **4** | **4** | **X** |
| **Farm Management** | **Soil Amendment: processed manure** | 2.14 | $0.00221 | $1,033 | 6 | 23 | 27 | 29 | 27 | | | | | | | |
| **Farm Management** | **Soil Amendment: municipal organic compost** | 5.94 | $0.00020 | $34 | 5 | 11 | 15 | 13 | 23 | | | | | | | |
| **Farm Management** | **Soil Amendment: biochar** | 20.62 | $0.00135 | $65 | 5 | 4 | 22 | 17 | 22 | | | | | | | |
| **Farm Management** | **Deep rooting corn** | 18.32 | $0.00241 | $131 | 2 | 5 | 29 | 22 | 28 | | | | | | | |

### 2.5.2. Cost-priority Pathways

Two cost-priority pathways were developed to highlight the opportunities to meet RFA member emissions reduction goals at least cost. Both pathways were developed for individual facilities (not the ethanol industry as a whole). Like the core pathway, both cost-priority pathways use the action rankings as guidelines to inform a selection of actions by ethanol producers and supplying farmers to meet the targeted emissions reduction. While the cost rankings are the primary guide to the selected actions, technological readiness is also considered when determining the order and rate of adoption (by farmers) of certain actions. For the 'cost-per-MJ' priority pathway, the selected actions were:

1. Corn Kernel Fiber Utilization (by 2030)
2. No-till: 100% adoption of ST/NT (adoption rate of 50% by 2030, 100% by 2050)
3. Facility Renewable power (PPA) (by 2030)
4. Improved Yeast (by 2030)
5. On-farm Renewable electricity (RECs) (adoption rate of 100% by 2030)
6. 4R (Right time, Right place, Right form, and Right rate) (adoption rate of 100% by 2030)
7. Cover Crop adoption: to 25% (by 2030)
8. Biodiesel substitution in corn transportation (adoption rate of 100% by 2030)
9. Biodiesel substitution in corn farming (adoption rate of 100% by 2030)
10. Increased WDGS:DDGS ratio (by 2030)
11. Cover Crop adoption: to 50% (by 2050)
12. Fermentation CCS: deep-well injection (by 2050)

For the 'cost-per-$CO_2$' priority pathway, the selected actions were:

1. Corn Kernel Fiber Utilization (by 2030)
2. Reduced tillage adoption: 45% to 75% (by 2030)
3. Improved Yeast (by 2030)
4. Renewable power (PPA) (by 2030)
5. 4R (Right time, Right place, Right form, and Right rate) (100% adoption by 2030)
6. Cover Crop adoption: to 25% (by 2030)
7. Fermentation CCS: deep-well injection (by 2030)
8. Cover Crop adoption: 50% (by 2050)
9. Soil Amendment: municipal organic compost (10% adoption by 2050)
10. Soil Amendment: biochar (10% adoption by 2050)

### 2.5.3. Magnitude-priority Pathway

An alternative pathway was developed to highlight the effectiveness of the highest-magnitude emissions reduction actions to drive very-low-carbon corn ethanol. This pathway applied the five actions with the largest potential emissions reductions and high technological readiness:

1. Fermentation CCS: deep-well injection (by 2030)
2. Cover Crop adoption: to 50% (10% adoption by 2030, 50% adoption by 2050)
3. Green Ammonia (25% adoption by 2030, 75% adoption by 2050)
4. CHP from corn stover (by 2050)

5. CCS from stover CHP: deep-well injection (by 2050)

#### 2.5.4. Climate Action Future Pathway

Two additional scenarios were developed to assess the effects of a broader policy and/or economic drive to reduce GHG emissions from energy and agriculture by 2050. First, a new Climate Action Future baseline scenario was created to thematically match the Biden Administration commitment to "reaching net zero emissions economy-wide by no later than 2050 (White House, 2021)." This alternative baseline assumed a more rapid transition to renewable electricity sources (see table 2), a transition toward renewable fuel (i.e. soybean biodiesel) in place of diesel, integration of bio-methane from manure into the energy system, and expansion of conservation practices by corn farmers. Corn yields from 2030 through 2050 were increased by eliminating the climate change yield penalty and using the extended USDA yield forecast (table 4). In addition to applying the climate action scenario electric mix to background processes in GREET, the actions in this revised baseline include:

1. Biodiesel substitution in corn farming (incremental adoption rate: 2%/yr from 2026)
2. Biodiesel substitution in corn transportation (incremental adoption rate: 2%/yr from 2026)
3. Reduced tillage adoption: 45% to 75% (incremental adoption rate: 2%/yr from 2020)
4. 4R (Right time, Right place, Right form, and Right rate): (incremental adoption rate: 5%/yr from 10% in 2025)
5. Cover Crop adoption: to 50% (incremental adoption rate: 2%/yr from 2026)
6. Bio-methane from manure (incremental adoption rate: 2%/yr from 2026)

Building on the Climate Action Future baseline, a pathway to meet RFA member target GHG emissions was designed. This pathway prioritizes direct substitution for fossil energy sources, energy efficiency, and carbon capture, actions which might be subsidized or otherwise made more attractive through climate policy (such as a carbon price). The action sequence for this industry-wide pathway to net zero by 2050 was:

1. Facility Renewable power (PPA) (incremental adoption rate: 5%/yr from 25% in 2025)
2. Corn Kernel Fiber Utilization (incremental adoption rate: 5%/yr from 25% in 2025)
3. Better-than-BAU Facility Efficiency
4. Fermentation CCS: deep-well injection (incremental adoption rate: 1%/yr from 25% in 2030)

## 3. Results

The baseline scenario for corn ethanol GHG emissions to 2050 represents a world in which modest progress is made toward reducing carbon intensity of the broader energy sector and farmers continue current land management practices while working to improve corn yields and fertilizer efficiency. Ethanol producers are also expected to make advancements in energy efficiency and ethanol yields from today's values, though improvements are slow compared to the previous two decades.

Results highlight the likely gains from these continued improvements in electricity decarbonization and facility efficiency, from 48.5 to 41.4 g $CO_2$e/MJ between 2020 and 2050, a decrease of 7.1 g $CO_2$e/MJ (figure 4). The largest emissions benefits under the baseline scenario accrue to dry mill operations, particularly those capable of separating corn oil (table 11). These values include the full life cycle of corn ethanol production, from fertilizer manufacturing and farming activities (including farm equipment manufacturing and maintenance), direct emissions from combustion and fertilizer loss, chemical and energy supply to the biorefinery, and credits for co-products (DGS and corn oil) but exclude emissions from land use change. Land use change emissions, and their role in long-term estimates of ethanol CI in 2050 and beyond, are discussed separately in section 3.4.

Under the baseline scenario, the leading sources of emissions from corn ethanol are the same in 2050 and 2030 as 2020. Facility operations (primarily energy use), on-field $N_2O$ emissions from fertilizer and biomass decomposition, and fertilizer manufacturing are major contributors. Credits from DGS and other coproducts supplied by ethanol producers that offset additional demand for corn and soybeans continue to be important factors as well. Without coproduct credits, ethanol emissions would remain above 50 g $CO_2$e/MJ in 2050.

*Table 11: Ethanol GHG emissions by facility type, industry average, and % reduction vs gasoline for the baseline scenario, 2020-2050. Reductions vs gasoline estimated against the 93 g$CO_2$e/MJ RFS baseline. COE = corn oil extraction. CKF = corn kernel fiber ethanol production. (CKF facilities are not included in the baseline industry averages.)*

| | **Wet Mill** | | **Dry Mill** | | **Dry Mill + COE** | | **Dry Mill + CKF** | **Industry Average** | **Reduction vs Gasoline** |
|---|---|---|---|---|---|---|---|---|---|
| | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | (g$CO_2$e/MJ) | % |
| *2020* | 64.7 | 9% | 49.0 | 4.6% | 48.5 | 86.5% | 47.3 | 49.9 | 46% |
| *2025* | 62.8 | 9% | 47.5 | 4.6% | 44.9 | 86.5% | 43.8 | 46.7 | 50% |
| *2030* | 62.2 | 9% | 46.8 | 4.6% | 44.5 | 86.5% | 43.4 | 46.2 | 50% |
| *2035* | 61.5 | 9% | 45.7 | 4.6% | 43.6 | 86.5% | 42.6 | 45.3 | 51% |
| *2040* | 61.0 | 9% | 45.1 | 4.6% | 42.9 | 86.5% | 41.9 | 44.6 | 52% |
| *2045* | 60.6 | 9% | 44.5 | 4.6% | 42.1 | 86.5% | 41.1 | 43.9 | 53% |
| *2050* | 60.1 | 9% | 43.8 | 4.6% | 41.4 | 86.5% | 40.4 | 43.2 | 54% |

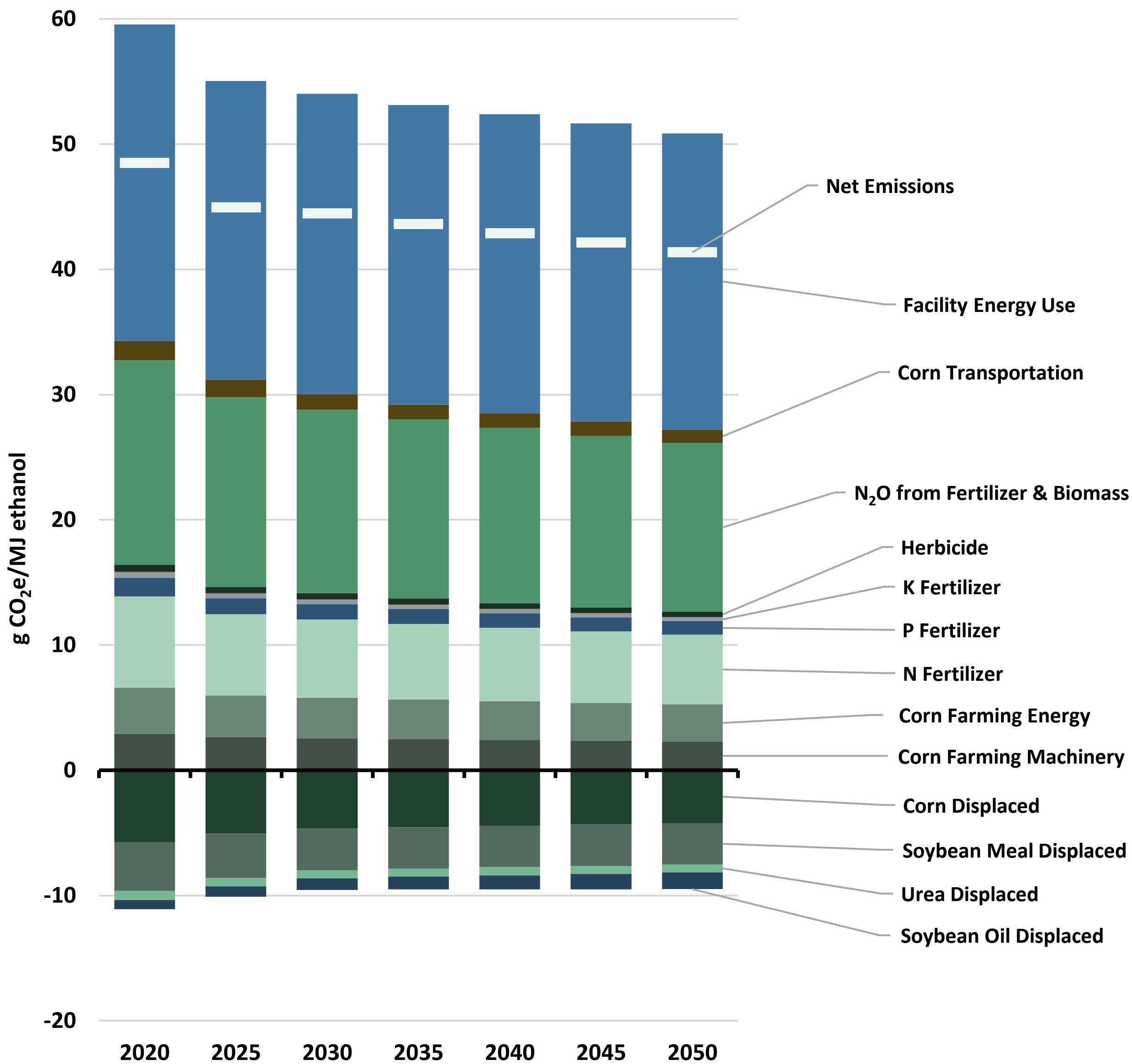


*Figure 4: Baseline GHG emissions from an average dry mill ethanol producer.*

## 3.1. Core Pathways to Zero Carbon Ethanol

The core pathways to meet RFA member emissions targets of a 70% reduction vs gasoline by 2030 and net carbon neutral by 2050 use renewable electricity, bio-methane, better-than-BAU efficiency improvements, and corn kernel fiber fermentation to minimize fossil fuel-related emissions per gallon of ethanol at the biorefinery. These actions reduce facility operations emissions by 42% by 2030 and nearly 80% by 2050 (see Figure 5). Working with corn suppliers to encourage broader adoption of reduced-till practices (expanding RT from 45% to 75% of participating acres) provides a 1.0 g $CO_2e$/MJ SOC credit in 2050.

Rather than relying on farmers to make sufficient additional changes in fertilizer use or land management practices to mitigate the remaining 22 g $CO_2e$/MJ in ethanol life cycle emissions, the core pathway relies on carbon capture and sequestration of the biogenic carbon dioxide from fermentation tanks. At an estimated cost of roughly $50/ton $CO_2$, CCS is expected to become one of the most cost-effective methods for ethanol producers to meet carbon reduction goals. Capture of $CO_2$ from fermentation also has an advantage of scale. Implementing CCS can offset more GHG emissions than are emitted by all of a facility's energy use and non-corn input purchases operations combined.

With CCS and substitution of renewable electricity and bio-methane for fossil energy at the biorefinery, the industry-average core pathway achieves net zero GHG emissions before 2050, by 2045. This gives the industry some leeway in the adoption rate of key technologies. This pathway uses a maximum CCS adoption rate of 90% by ethanol producers and could still meet the 2050 net zero target with adoption as low as 80%. If a high CCS adoption rate is achieved, other actions like wind power purchase agreements or bio-methane use could be allowed more flexibility. The industry could potentially meet the net zero 2050 target with a bio-methane adoption rate as low as 40%, rather than the 78% maximum adoption rate in 2050 modeled here.

As in the baseline scenario, emissions in the core pathway vary between facility types. Due to higher energy use and lower ethanol yields at wet mills, those facilities continue to average roughly 20 g $CO_2e$/MJ higher than dry mills (table 12). The reliance of wet mills on process energy (primarily natural gas), those facilities cannot benefit from the relatively simple emissions benefits of renewable electricity. However, they do gain large benefits from bio-methane, and have the potential advantage of being able to become powered completely by renewable energy by making only a single change in fuel type.

*Table 12: Ethanol GHG emissions by facility type, industry average, and % reduction vs gasoline for the industry-average core emissions reduction pathway, 2020-2050. Reductions vs gasoline estimated against the 93 g $CO_2e$/MJ RFS baseline. COE = corn oil extraction. CKF = corn kernel fiber ethanol production.*

| | **Wet Mill** | | **Dry Mill** | | **Dry Mill + COE** | | **Dry Mill + CKF** | | **Industry Average** | **Reduction vs Gasoline** |
|---|---|---|---|---|---|---|---|---|---|---|
| | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % |
| *2020* | 64.7 | 9% | 49.0 | 4.6% | 48.5 | 86.5% | 47.3 | 0% | 49.9 | 46% |
| *2025* | 54.6 | 9% | 35.4 | 4.6% | 34.3 | 71.5% | 33.0 | 15% | 36.0 | 61% |
| *2030* | 43.2 | 9% | 23.4 | 4.6% | 22.4 | 66.5% | 21.0 | 20% | 24.0 | 74% |
| *2035* | 32.0 | 9% | 11.1 | 4.1% | 10.4 | 62.0% | 7.7 | 25% | 12.1 | 87% |
| *2040* | 21.0 | 9% | 0.0 | 3.6% | -0.9 | 57.5% | -4.1 | 30% | 0.9 | 99% |
| *2045* | 18.2 | 9% | -2.5 | 3.1% | -3.5 | 53.0% | -6.5 | 35% | -2.0 | 102% |
| *2050* | 15.6 | 9% | -4.7 | 2.6% | -5.8 | 48.5% | -8.5 | 40% | -4.9 | 105% |

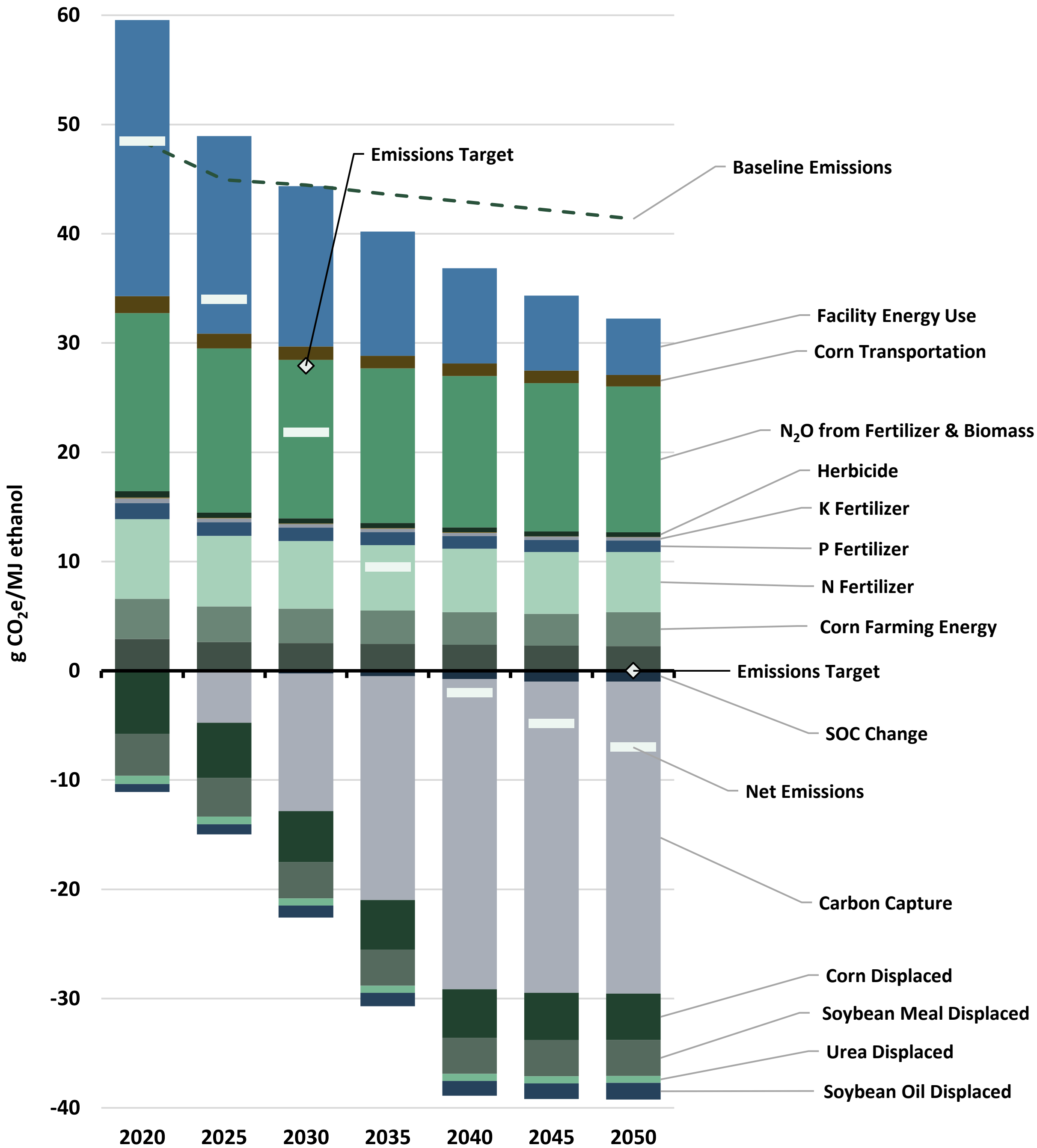


*Figure 5: Core pathway results for achieving RFA target emissions reductions across the ethanol industry (shown are emissions from an average dry mill with corn oil extraction).*

Based on the relative costs, technological readiness, and magnitude of the emissions reduction actions identified in this report, the core pathway for individual facilities uses renewable electricity and CCS to meet the 2030 emissions target. Together, these technologies provide a 90% emissions reduction vs gasoline, exceeding the 70% target (figure 6). Though a facility using CCS could meet the

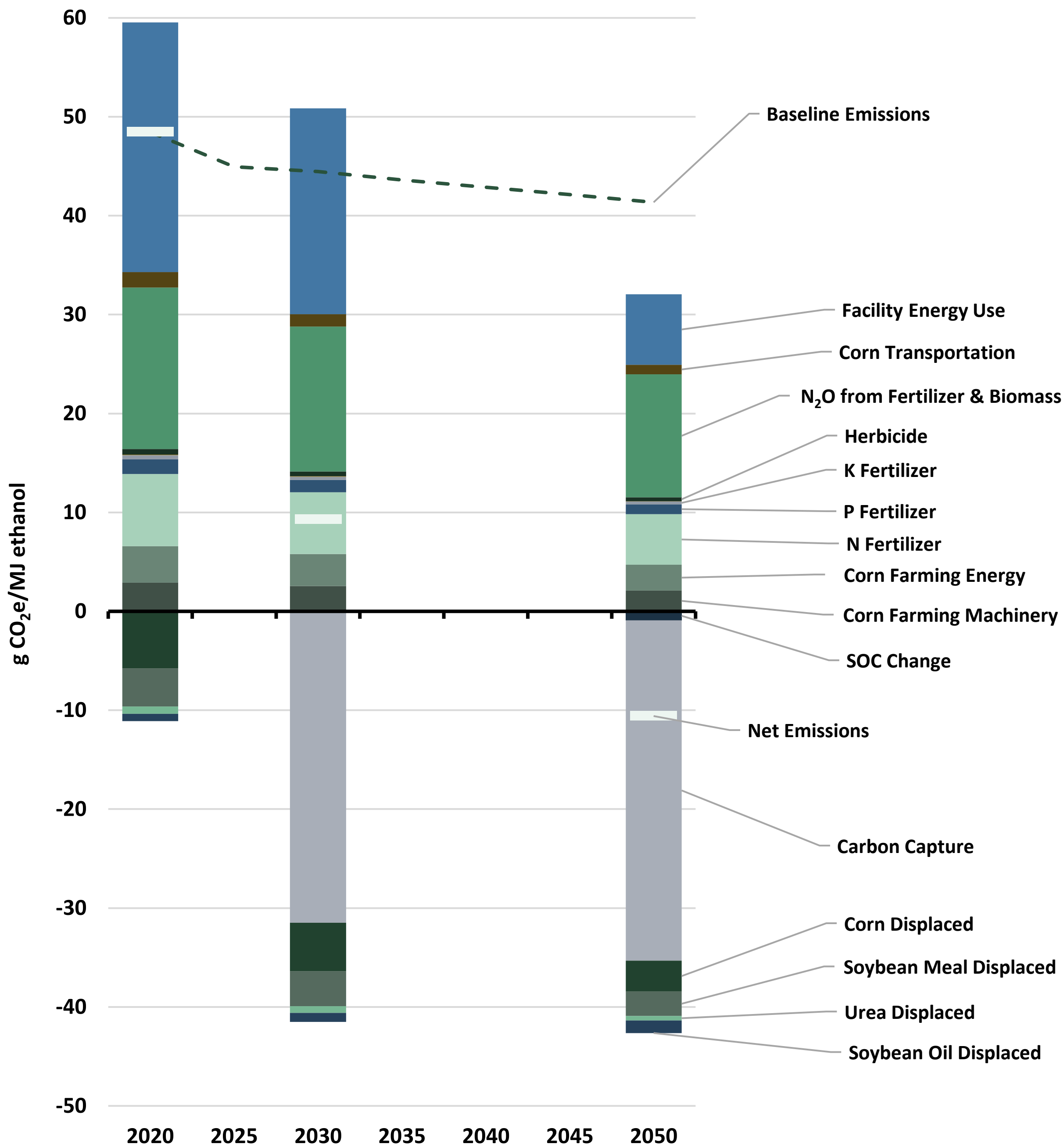


*Figure 6: Core pathway results for a single dry mill ethanol producer achieving RFA target emissions reductions in 2030 and 2050.*

target without renewable electricity purchases, it appears likely that those investments will provide a positive return.

To achieve the remaining emissions reductions necessary to reach net zero emissions by 2050, the core pathway uses a combination of efficiency improvements (producing ethanol from corn kernel fiber and reducing DGS drying) and bio-methane for process energy. While these actions alone would be sufficient, the core pathway also includes modest emissions reductions from corn producers, including 75% adoption of renewable electricity and 75% increase in reduced tillage practices. Combined, these actions by a facility's suppliers contribute under 1 g $CO_2$e/MJ of emissions reductions, improving core pathway performance from -9.8 to -10.6 g $CO_2$e/MJ. They are included in the pathway because they are cost-effective and highly feasible emissions reduction actions, and therefore likely to occur with relatively little additional effort on the part of ethanol producers.

## 3.2. Alternative Pathways to Zero Carbon Ethanol

### 3.2.1. Cost-priority Pathways

Ethanol facility operators have an incentive to prioritize lower-cost action to reduce emissions. The two cost-priority pathways prioritize operational cost (cost per MJ ethanol) and emissions reduction cost (cost per t $CO_2$ mitigated). Both pathways make use of a wide range of emissions-reduction actions. Because the largest-magnitude actions are not prioritized, these pathways must utilize a larger number of actions to reach the target emissions reductions.

The 'cost-per-MJ' alternative pathway to net zero carbon ethanol uses several actions to reduce emissions at the biorefinery and on the farm that may increase revenues for ethanol producers or corn farmers. Corn kernel fiber utilization, renewable electricity use, improved yeast, and reduction in DGS drying energy reduce facility emissions 9.4 g $CO_2$e/MJ or 37% by 2030. Renewable electricity and biodiesel use by corn suppliers, as well complete adoption strip-till or no-till farming, 25% adoption of cover crops, and complete adoption of 4R fertilizer management combine to reduce farming and supply chain emissions by 12.6 g $CO_2$e/MJ and increase soil carbon by an additional 6.5 g $CO_2$e/MJ. Total ethanol emissions by 2030 are 21.5 g $CO_2$e/MJ, or 77% lower than the RFS baseline for gasoline (figure 7).

After these actions, few opportunities are left to reduce emissions from fossil fuels and fertilizers. Substitution of fossil natural gas with bio-methane from manure at the biorefinery could eliminate another 13 g $CO_2$e/MJ, but this would leave the operator with 8.5 g $CO_2$e/MJ in difficult-to-reduce emissions from chemical and machinery manufacturing and fertilizer $N_2O$ emissions. These remaining emissions, despite the near-complete adoption of conservation practices by farmers, extensive renewable energy purchases, and coproduct credits, highlight the importance of CCS in reaching net zero emissions from corn ethanol.

To reach net zero by 2050, the 'cost-per-MJ' pathway used two additional actions: further expansion of cover crops from 25% to 50% adoption rate and CCS of $CO_2$ from fermentation. Though CCS would be sufficient to reach net zero emissions, cover crop expansion has a much lower cost per MJ ($0.00016 versus $0.0016) and is selected first. These two actions, combined with further reductions in supply chain emissions from expansion of renewable energy generation in the background electricity mix, lead to net emissions of -21.8 g $CO_2$e/MJ in 2050.

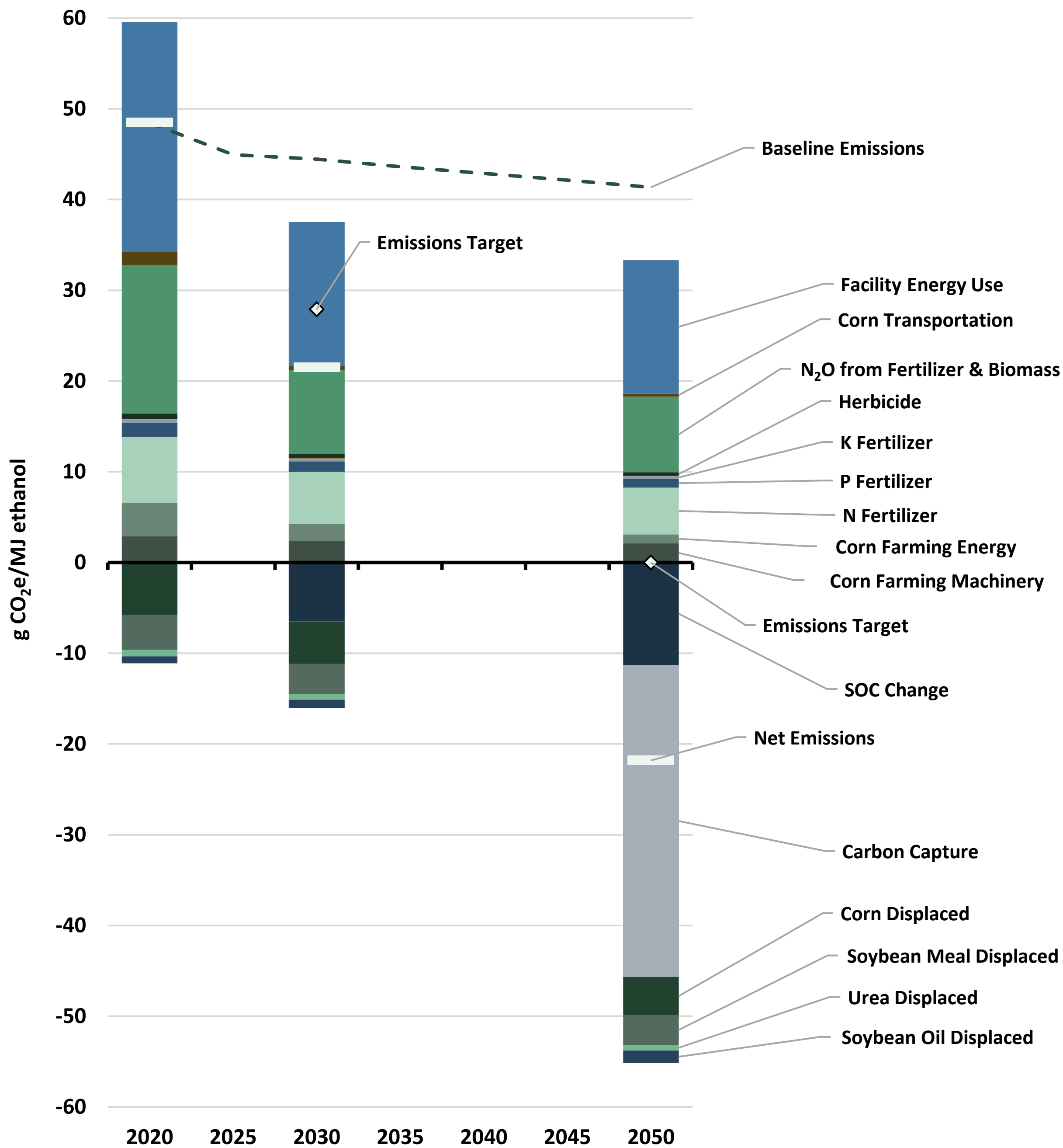


*Figure 7: Ethanol GHG emissions from the 'cost-per-MJ' alternate pathway.*

Assessing the cost of emissions reduction actions per ton of GHG reduction rather than per MJ led to a pathway with many of the same potentially cost-negative actions but a very different prioritization of cost-positive actions (see table 10). Like the 'cost-per-MJ' pathway, 'cost-per-$CO_2$' utilized corn kernel fiber fermentation, improved yeast, and renewable electricity purchases at the biorefinery in combination with 25% adoption of cover crops on supplying farms to reach the 2030 emissions reduction target. Instead of reducing DGS drying energy and sourcing exclusively from no-till farms, however, prioritizing cost per GHG led to prioritizing adoption of reduced tillage and CCS of $CO_2$

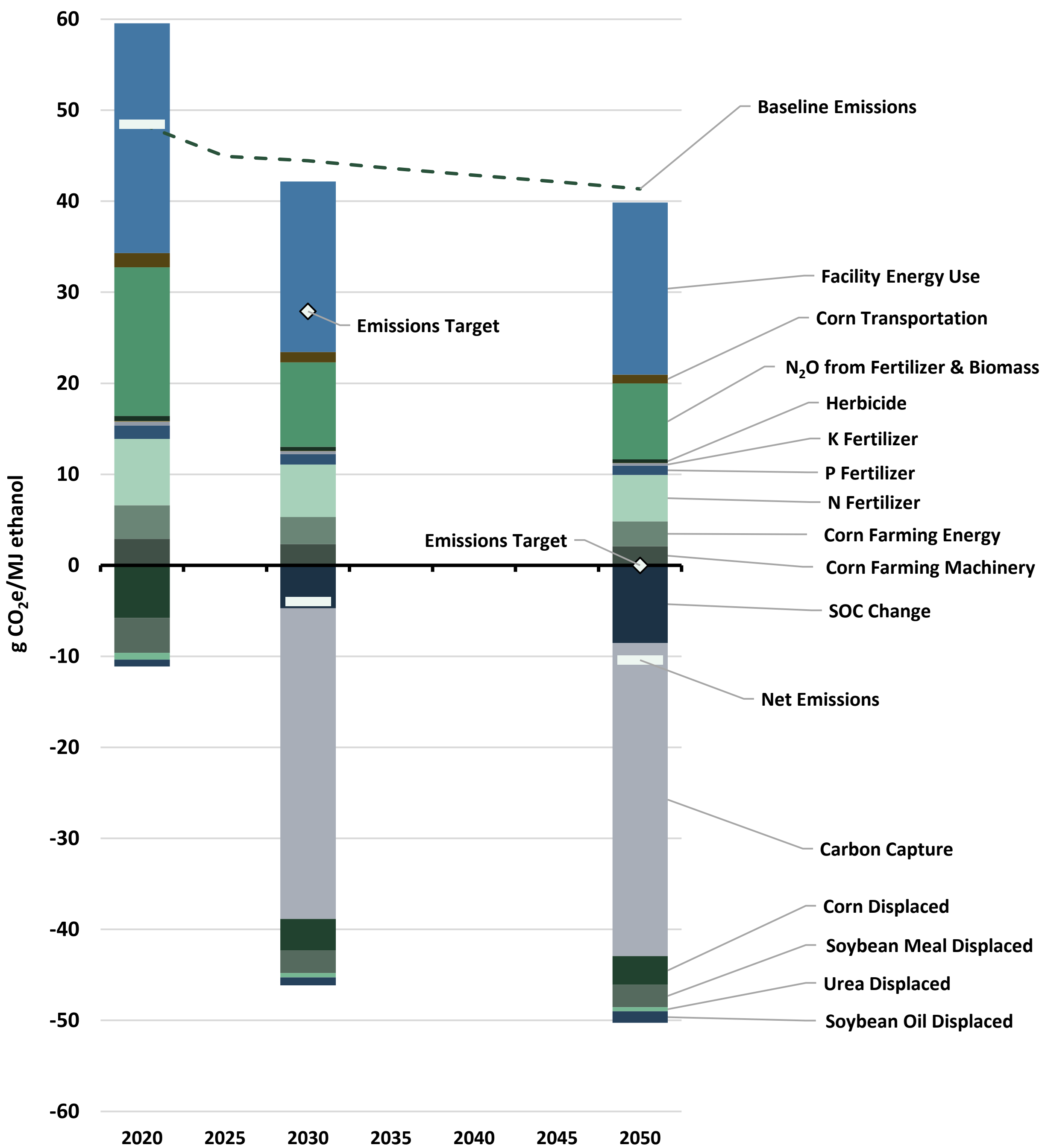


*Figure 8: Ethanol GHG emissions from the 'cost-per-$CO_2$' alternate pathway.*

from fermentation (figure 8). The magnitude of CCS' impact on ethanol emissions (-34 g $CO_2$e/MJ for a dry mill with corn kernel fiber fermentation) means that without CCS, the facility would not meet the target of 70% reduction versus gasoline by 2030, but with CCS the facility achieves net negative emissions (-4.0 g $CO_2$e/MJ).

Beyond reductions in supply chain emissions from expansion of renewable energy generation in the background electricity mix, the only additional action in this alternative pathway was further adoption of cover crops to 50% of supplying farmers. This improved soil carbon accumulation by 4 g $CO_2$e/MJ, resulting in final 2050 emissions of -10.4 g $CO_2$e/MJ.

### 3.2.2. Magnitude-priority Pathway

The magnitude-priority pathway utilized the five emissions reduction actions with the largest individual emissions benefits which also rank highly for technical feasibility and which are compatible (i.e. two different power sources cannot be selected for the same process). The largest single action, CCS of $CO_2$ from fermentation, was all that was necessary to reach a 70% reduction versus gasoline by 2030 (see figure 9). Implementing the four following actions by 2050, CHP from corn stover, CCS of $CO_2$ from stover CHP, 50% adoption of cover crops (at a rate of 2%/yr starting in 2025), and 75% substitution of green ammonia for conventional ammonia (at a rate of 2.5%/yr starting from 25% in 2025). The result was an ethanol carbon intensity of -48 g $CO_2$e/MJ by 2050.

This pathway reduced life cycle fossil fuel and fertilizer loss emissions by 28 g $CO_2$e/MJ by using renewable energy for ammonia fertilizer manufacturing and biomass for heat and power at the biorefinery. Changes in land management lead to up to 8.4 g $CO_2$e/MJ in soil carbon accumulation. The most effective mitigation efforts captured a combined 58.7 g $CO_2$e/MJ from corn grain and stover biomass for subsequent deep well injection.

### 3.2.3. Climate Action Future Pathway

The baseline scenario behind each of the previous emissions reduction pathways assumed relatively minor policy action on climate change. To assess the potential emissions from corn ethanol under a scenario of active climate policy and energy transition, such as a carbon price or national renewable energy target, the study provides an alternative 'climate action future' baseline (figure 10). Assuming only business-as-usual improvements in ethanol facility efficiency and yield, this scenario achieved

*Table 13: Ethanol GHG emissions by facility type, industry average, and % reduction vs gasoline in the Climate Action Future baseline, 2020-2050. Reductions vs gasoline estimated against the 93 g$CO_2$e/MJ RFS baseline. COE = corn oil extraction. CKF = corn kernel fiber ethanol production.*

| | **Wet Mill** | | **Dry Mill** | | **Dry Mill + COE** | | **Dry Mill + CKF** | | **Industry Average** | **Reduction vs Gasoline** |
|---|---|---|---|---|---|---|---|---|---|---|
| | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % | (g$CO_2$e/MJ) | % |
| *2020* | 64.7 | 9% | 49.0 | 4.6% | 48.5 | 86.5% | 47.3 | 0% | 49.9 | 46% |
| *2025* | 61.8 | 9% | 46.7 | 4.6% | 44.1 | 71.5% | 43.0 | 15% | 45.7 | 51% |
| *2030* | 54.9 | 9% | 40.2 | 4.6% | 38.0 | 66.5% | 37.2 | 20% | 39.5 | 58% |
| *2035* | 48.3 | 9% | 33.8 | 4.1% | 31.9 | 62.0% | 31.3 | 25% | 33.4 | 64% |
| *2040* | 41.9 | 9% | 28.4 | 3.6% | 26.6 | 57.5% | 26.3 | 30% | 28.0 | 70% |
| *2045* | 36.5 | 9% | 23.8 | 3.1% | 22.0 | 53.0% | 22.0 | 35% | 23.4 | 75% |
| *2050* | 32.2 | 9% | 20.3 | 2.6% | 18.5 | 48.5% | 18.6 | 40% | 19.8 | 79% |

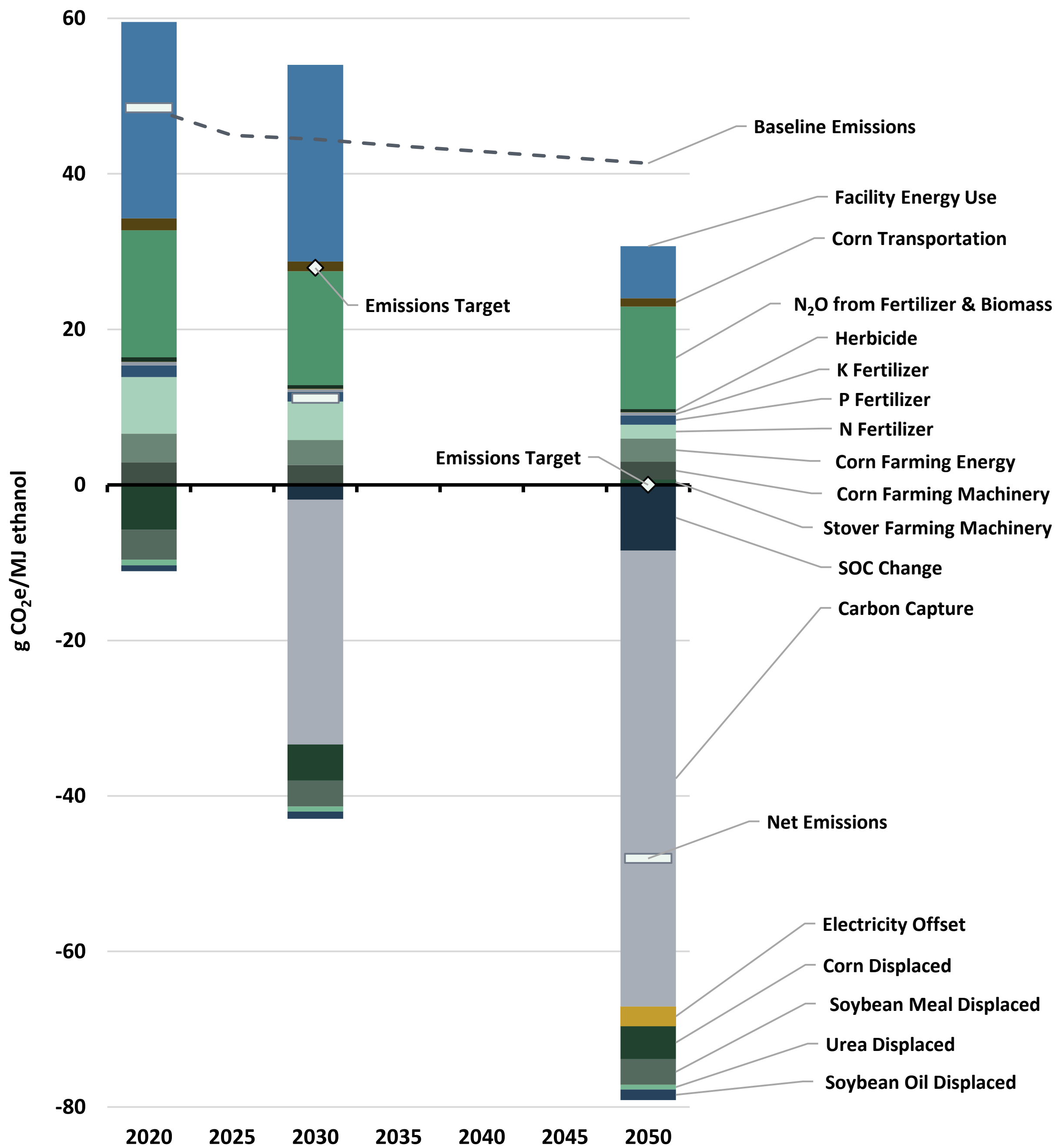


*Figure 9: Ethanol GHG emissions from the 'highest-magnitude' alternate pathway.*

ethanol emissions of 39.5 g $CO_2$e/MJ by 2030 (11% lower than the 2030 baseline) and 19.8 g $CO_2$e/MJ by 2050 (52% lower than the 2050 baseline) (see table 13). Notably, even GHG emissions of ethanol from wet mill facilities drop to 32 g $CO_2$e/MJ, 50% lower than the 2020 baseline and reaching a 65% emissions reduction versus gasoline.

These industry-wide improvements were driven by reductions in energy-related emissions from the biorefinery (-12 g $CO_2$e/MJ), lower $N_2O$ emissions rates from improved fertilizer management practices

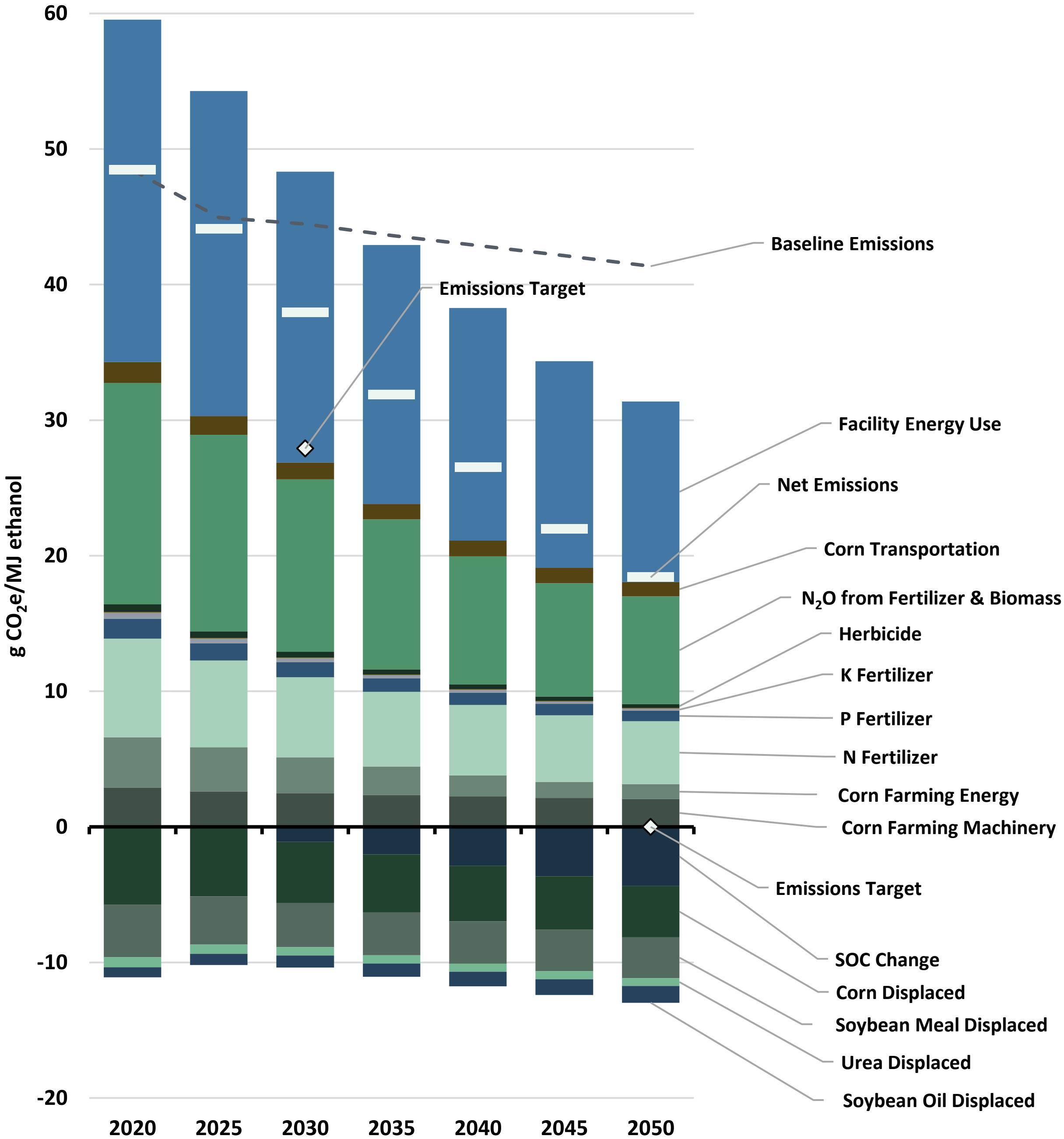


*Figure 10: Ethanol GHG emissions under the 'Climate Action Future' baseline scenario.*

(-8 g $CO_2$e/MJ), and soil carbon accumulation due to widespread adoption of conservation practices (-4 g $CO_2$e/MJ). Lower economy-wide energy emissions meant that co-product credits for DGS decreased over time as well, but these losses were minor compared to the large benefits of reduced supply chain emissions.

Expanding on the climate action baseline, the climate action pathway demonstrates how ethanol producers can build on a decarbonized economy to reach net zero carbon ethanol by 2050. In 2030, the climate action pathway achieves 26.9 g $CO_2e$/MJ, a 71% emissions reduction versus the RFS gasoline benchmark (table 14). This was accomplished with 50% of ethanol facilities using all-renewable electricity, 50% of facilities converted to ferment corn kernel fiber, 25% of facilities equipped for CCS of $CO_2$ from fermentation, and 'better-than-BAU' efficiency improvements that were expected to vary between facilities. These actions may be less costly and more accessible to biorefinery operators under the climate action scenario than in the baseline scenario, assuming that the same policy incentives driving the transition to renewable electricity generation and biodiesel are also available to ethanol producers.

Given the substantial emissions reductions from the climate action future baseline, the ethanol industry can meet RFA member targets with slower adoption rates for some additional emissions reduction actions. The pathway results shown in figure 11, for example, are achieved with a CCS adoption rate of only 1%/yr after 2030, with just 45% of facilities participating in carbon capture and sequestration by 2050. In the core pathway, 90% of facilities operate CCS of $CO_2$ from fermentation. Though the climate action pathway meets the 2050 net zero emissions target by the smallest margin of the pathways examined in this study (-0.1 g $CO_2e$/MJ), it does so with minimal adoption of new technologies across the ethanol industry. This highlights the flexibility provided to ethanol producers in a 'climate action future' scenario with economy-wide progress toward decarbonization of the energy, manufacturing, and chemical sectors. With additional investment and more rapid adoption of emissions-reducing technologies like CCS, the corn ethanol industry could achieve average emissions well below net zero.

*Table 14: Ethanol GHG emissions by facility type, industry average, and % reduction vs gasoline in the Climate Action Future pathway, 2020-2050. Reductions vs gasoline estimated against the 93 $gCO_2e$/MJ RFS baseline. COE = corn oil extraction. CKF = corn kernel fiber ethanol production.*

| | **Wet Mill** | | **Dry Mill)** | | **Dry Mill + COE)** | | **Dry Mill + CKF** | | **Industry Average** | **Reduction vs Gasoline** |
|---|---|---|---|---|---|---|---|---|---|---|
| | ($gCO_2e$/MJ) | % | ($gCO_2e$/MJ) | % | ($gCO_2e$/MJ) | % | ($gCO_2e$/MJ) | % | ($gCO_2e$/MJ) | % |
| *2020* | 64.7 | 9% | 49.0 | 4.6% | 48.5 | 86.5% | 47.3 | 0% | 49.9 | 46% |
| *2025* | 61.8 | 9% | 45.8 | 4.6% | 40.6 | 61.5% | 39.3 | 25% | 42.4 | 54% |
| *2030* | 46.7 | 9% | 30.7 | 4.6% | 25.1 | 36.5% | 23.5 | 50% | 26.9 | 71% |
| *2035* | 38.2 | 9% | 22.4 | 4.1% | 16.5 | 12% | 15.0 | 75% | 18.4 | 80% |
| *2040* | 30.0 | 9% | 15.4 | 3.6% | 9.3 | 2.5% | 7.9 | 85% | 11.1 | 88% |
| *2045* | 22.7 | 9% | 9.4 | 3.1% | 3.2 | 3.0% | 2.1 | 85% | 5.0 | 95% |
| *2050* | 16.5 | 9% | 4.3 | 2.6% | -1.7 | 3.5% | -2.7 | 85% | -0.1 | 100% |

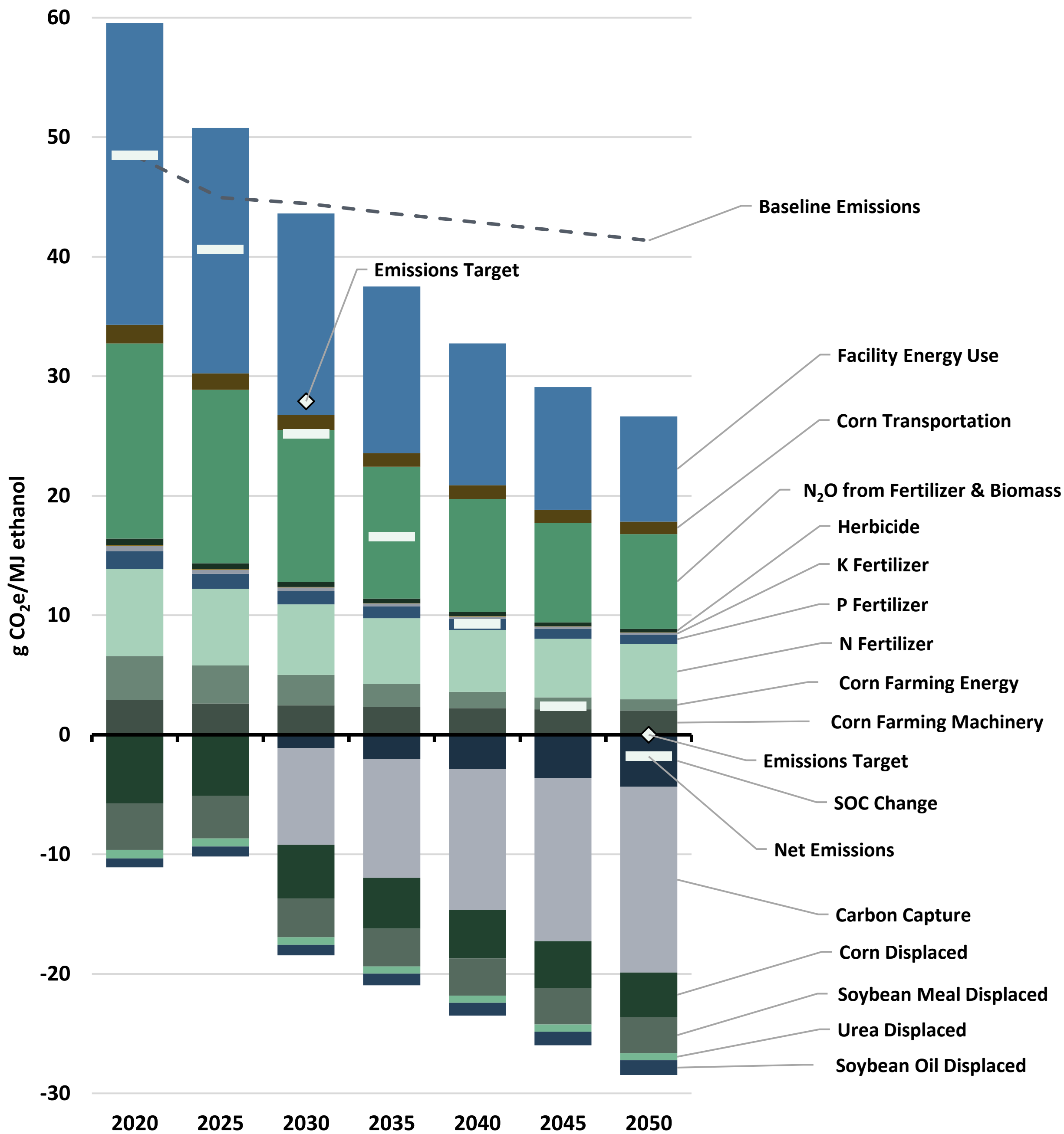


*Figure 11: Industry-average ethanol GHG emissions from the 'Climate Action Future' net zero pathway.*

## 3.3. Ethanol Yield Improvements

Ethanol yield has a strong effect on the net GHG emissions from corn ethanol. Producing more ethanol per bushel of corn dilutes the upstream emissions from fertilizer production, corn farming, and biorefinery operations. Yield improvements directly benefit ethanol producers through increased revenue, making them an attractive target for innovation and research. The 'improved yeast' action highlights this effect, showing a 1.6 g $CO_2$e/MJ reduction (3% of baseline 2020 emissions), primarily from a 2% improvement in ethanol yield. An improvement from 97.6% to 98.6% of the maximum theoretical yield (2.92 to 2.95 gal/bu) also contributes to the emissions reductions of the 'better-than-BAU' action. However, while it will certainly be beneficial to use the starch fraction of corn more efficiently, improving ethanol yields by breeding higher-starch corn grain may create a trade-off between ethanol emissions gains and reduced coproduct credits.

A special case study explored the potential of a hypothetical high-starch corn variety to reduce the CI of corn ethanol beyond the plateau at 2.92 gal/bu in the baseline scenario. By reducing the protein, fiber, and 'other' components of corn grain by 20% and oil by 10%, starch content was improved from 72.9% to 78.0% of grain dry weight (table 15). The effects of this change on GHG emissions was modeled as a linear shift in corn composition from the current average in 2030 to the high-starch variety in 2050. Ethanol yield was improved to 99% of the maximum theoretical yield by 2050 to a maximum to 3.17 gal/bu (table 16). DGS and corn oil coproduct yields were decreased according to the change in grain proximate composition.

Results of show that broader efforts to improve corn ethanol yields, such as through the development of high-starch corn varieties, can reduce the CI of fuel ethanol. In this case study, increasing corn starch content and simultaneously improving ethanol yields at the biorefinery provide a 2.1 g $CO_2$e/MJ emissions reduction. This includes a 5% decrease in farming emissions and an 8% decrease in biorefinery energy emissions from both the yield efficiency improvement and lower natural gas use for DGS drying due to the lower coproduct volumes.

The sensitivity of case study results to changes in coproduct credits highlights the importance of biorefinery process assumptions in emissions calculations. Excluding the reduction in DGS drying energy, the benefits of a higher ethanol yield are fully offset by the loss in coproduct credits (41.5 g $CO_2$e/MJ in the high-starch case study compared to 41.4 g $CO_2$e/MJ in the baseline scenario in 2050). Though a dry mill producing 20% less DGS could be expected to use less natural gas for grain drying than an industry-average facility, actual energy use at any facility depends on the local market for DDGS and WDGS. Ethanol producers and analysts should not lose sight of the importance of such fundamental process drivers when assessing emissions reduction priorities.

*Table 15: Proximate composition of corn grain (dry weight basis) for the current 10-year US average and a hypothetical high starch variety.*

| | US Avg (2011-20) | High Starch | Difference |
|---|---|---|---|
| *Starch* | 72.90% | 78.0% | 7% |
| *Protein* | 8.60% | 6.88% | -20% |
| *Oil* | 3.90% | 3.51% | -10% |
| *Other* | 14.60% | 11.68% | -20% |

*Table 16: Ethanol, DGS, and oil yields and corn ethanol GHG emissions in the baseline and high starch scenarios, 2020-2050. The high starch scenario is identical to the baseline scenario in 2020 – 2030.*

| | Ethanol Yields (gal/bu) | | Coproduct Yields (Baseline) (dry lb/gal) | | | Coproduct Yields (High Starch) (dry lb/gal) | | | GHG Emissions (g $CO_2e$/MJ) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Baseline** | **High Starch** | **DDGS** | **WDGS** | **Oil** | **DDGS** | **WDGS** | **Oil** | **Baseline** | **High Starch** |
| **2020** | 2.85 | 2.85 | 3.25 | 1.36 | 0.27 | - | - | - | 48.5 | - |
| **2025** | 2.90 | 2.90 | 3.1 | 1.29 | 0.31 | - | - | - | 44.9 | - |
| **2030** | 2.92 | 2.92 | 2.94 | 1.23 | 0.35 | - | - | - | 44.5 | - |
| **2035** | 2.92 | 2.98 | 2.94 | 1.23 | 0.39 | 2.79 | 1.17 | 0.380 | 43.6 | 43.2 |
| **2040** | 2.92 | 3.04 | 2.94 | 1.23 | 0.44 | 2.65 | 1.11 | 0.409 | 42.9 | 42.0 |
| **2045** | 2.92 | 3.11 | 2.94 | 1.23 | 0.48 | 2.50 | 1.05 | 0.439 | 42.1 | 40.8 |
| **2050** | 2.92 | 3.17 | 2.94 | 1.23 | 0.52 | 2.352 | 0.984 | 0.468 | 41.4 | 39.7 |

## 3.4. Emissions Accounting, Land Use Change, and Soil Carbon

The life cycle GHG emissions accounting method in this study differs from those included in emissions standards administered by EPA and CARB. The accounting standards for the EPA RFS, for example, excludes farm equipment-related emissions (on the basis that these capital investments would be utilized regardless of whether the farm produced corn for ethanol or some other product) but includes losses of soil and biomass carbon due to direct and indirect land use change. The net effect of these differences varies depending on the rate of estimated GHG emissions from farm equipment (2.3 – 2.9 g $CO_2e$/MJ in this baseline scenario) and land use change (7.4 g $CO_2e$/MJ according to the most recent work by Argonne National Laboratory (Lee et al., 2021), 30.1 g $CO_2e$/MJ in the EPA RFS2 standards set in 2010, (EPA, 2010; Lewandrowski et al., 2019), and an average of 19.8 g $CO_2e$/MJ under the 2015 CARB LCFS (CARB, 2015).

The implications for meeting RFA member targets of 70% emissions reduction vs gasoline in 2030 and net zero in 2050 are substantial. With the current methodology, average dry mill ethanol emissions in the core industry pathway are 21.8 g $CO_2e$/MJ in 2030, a 76% reduction over gasoline. Using emissions calculations aligned with the current EPA RFS cuts the emissions reduction to 47%, or 49.4 g $CO_2e$/MJ. Under the emissions calculations aligned with the CARB LCFS, core industry pathway emissions are 39.1 g $CO_2e$/MJ, a decrease of 62% compared to the anticipated 2030 gasoline baseline of 103 g $CO_2e$/MJ (CARB, 2020).

There is broad consensus in the scientific community that the very high assessments of LUC emissions used by EPA and CARB are inaccurate (Lewandrowski et al., 2019). Advancements in modeling global trade, armed with more historical data available on the influence of the US ethanol industry on global agriculture, lead specialists in agricultural economics to the much lower values reported by Argonne National Laboratory and implemented in the recent GREET model update (Wang et al., 2021). Using these updated values in place of the outdated RFS2 LUC emissions factors, most of the ethanol emissions reduction pathways assessed in this report meet RFA member goals in 2030 and 2050 for both the direct-emissions accounting rules (excluding LUC emissions) and under RFS2 accounting rules. For most pathways, the same set of actions can be used to meet the 2030 and 2050 targets under both accounting standards. Even the largest difference in target calculation between the two standards, 5.2 g $CO_2$e/MJ in 2050, can be overcome with a higher adoption rate for major emissions-reduction actions by ethanol producers (for example, a 16% higher carbon capture and storage adoption rate) or corn farmers (for example, a 24% increase in cover crop adoption). While these are substantial differences, they show that if updated LUC emissions factors are applied under the RFS2, producers can apply the same broader trajectory of actions to reach aggressive, long-term emissions targets.

Perhaps more important than the differences in today's accounting standards for renewable fuels are the time-limited nature of LUC emissions factors themselves. LUC emissions factors represent the loss of biomass and soil carbon when land cover with a higher biological carbon content (such as prairie or woodland) is replaced with a land cover type with lower carbon storage (such as cropland). When such land use changes occur, most of the carbon from the initial land cover is lost in the first 1-5 years as the plant material is harvested, ploughed, or burned. Slower carbon losses occur over a longer period of time as soil carbon levels adjust to the new land use pattern (Qin et al., 2016). Additional losses from foregone sequestration, or the lack of additional carbon storage by the original grasses or trees, can also contribute to LUC emissions factors. Current best practices in agricultural emissions accounting are to amortize the sum total of LUC emissions over 30 years, while the United Nations Framework Convention on Climate Change and Intergovernmental Panel on Climate Change (IPCC) use a 20-year equilibration period for cropland (IPCC, 2006). This means that, for example, corn grown on former perennial pastureland is assigned the same LUC emissions factor every year for 30 years, instead of being assigned the "real" annual emissions factors, which would change every year.

Current LUC emissions factors for corn ethanol are based on shifts in global land use associated with the ethanol industry's growth between 2000 and 2011. All major US ethanol emissions policies are based on this 30-year amortization of emissions from that initial shift in US and international agricultural production to accommodate the ethanol industry (CARB, 2015; Dunn et al., 2017; Plevin et al., 2015). Assuming that current GHG accounting practices are maintained by the relevant agencies (particularly EPA and CARB), the LUC emissions factors for corn ethanol should expire by 2041, 30 years after the development of the ethanol market. The 30.1 g $CO_2$e/MJ LUC emissions factor under the RFS2 and the average 19.8 g $CO_2$e/MJ LUC emissions factor under the CARB LFCS should not apply to corn ethanol in 2050, making it easier for RFA members to meet a target of net-zero emissions under a wider range of accounting benchmarks.

Though the actual modeling of LUC emissions factors is quite complex, it is expected that the slower growth of the ethanol industry from 2012 will lead to smaller shocks to the global food and agriculture system and therefore smaller LUC emissions factors for added ethanol capacity. Even if the same LUC emissions factors were applied to ethanol capacity added after 2011 on a per-bushel or per-acre corn basis, the net contribution of these LUC emissions factor penalties would be much smaller than the current industry-wide LUC emissions factors because they would be diluted by the larger total production volume. Under current RFS and LCFS accounting methods, ethanol producers should expect a decrease in the LUC emissions penalty per gallon of ethanol between 2040 and 2050.

Soil carbon credit accounting follows the same basic method as LUC emissions factors, with implications for corn ethanol producers' efforts to meet their carbon targets. Emissions credits for SOC gains from changing land management practices on the farm are estimated using some of the same models and fundamental assumptions as LUC emissions, including the 30-year amortization rule. If the farmers supplying a corn ethanol facility increase their adoption of cover crops or strip tillage, the credits for soil carbon gain are determined by modeling the total expected change from maintaining those practices over several decades and dividing the benefits over the corn bushels produced over the next 30 years.

The 30-year amortization of SOC credits from conservation practices means that the ethanol emissions reductions from actions that create SOC credits will essentially expire after 30 years, similar to the expiration of LUC emissions factors. This study does not investigate the longer-term implications of this expiration of credits, as conservation practices adopted today will still be expected to have emissions credits through 2050. But clearly, pathways that are more reliant on soil carbon accumulation to meet RFA member emissions targets (such as the 'cost-per-$CO_2$' and Climate Action Future pathways) will be at risk of rising emissions after 2050-2060 if SOC credits expire. Producers setting very long-term plans for emissions reduction should consider the longevity and effectiveness of land-use and land management strategies to manage emissions.

## 4. Conclusions

This study identifies five distinct pathways to net zero CI corn ethanol by 2050 based on a set of 28 emissions reduction actions. The core pathway achieves average net zero emissions across the entire corn ethanol industry by sourcing renewable energy (both renewable electricity and bio-methane), investing in 'better-than-BAU' energy efficiency improvements and technological innovations, working with farmers to encourage expanded adoption of reduced tillage, and installing CCS systems to capture $CO_2$ from fermentation.

To meet RFA member goals of a 70% lower CI than gasoline by 2030, the core pathway modeled moderate adoption rates of each of these actions across the industry: roughly one-third of producers source all-renewable electricity from wind or solar, 20% source renewable methane, 25% more farmers use reduced tillage, and 35% of producers utilize CCS. Continuing adoption of these emissions-reduction actions across the industry leads to net zero emissions before 2045. The average CI of corn ethanol drops to -4.9 g $CO_2$e/MJ in 2050 as bio-methane adoption rises to nearly 80% and CCS of fermentation $CO_2$ to 90%. Individual producers can achieve emissions below -10 g $CO_2$e/MJ.

Driven by a priority ranking of actions that emphasizes technological readiness, the core pathway demonstrates that meeting RFA member goals for 2030 and 2050 is possible with near-term technology. The pathway also avoids potentially high-cost actions, such as investing in new combined heat and power infrastructure, green ammonia fertilizers, and high-cost soil amendments, although bio-methane costs are likely to be high initially as that industry develops. Another advantage of the core pathway is a focus on actions taken at the biorefinery. While many corn producers may be able and willing to shift their fertilizer purchases and land management practices to reduce emissions, those actions may not be suitable in all regions for a combination of biophysical, financial, and social reasons. Many ethanol producers, and potentially the industry as a whole, could reach net zero by 2050 without relying on their suppliers to risk investing in new practices or equipment.

By comparison, the cost-priority pathways to net zero avoid potentially expensive emissions reductions like bio-methane in favor of a variety of lower-cost actions by farmers and higher-risk technical developments like improved yeast strains. An ethanol producer in a region suitable for higher adoption rates of strip-till/no-till and cover cropping, and with corn suppliers willing to enact strict '4R' fertilizer management practices, could meet the 2030 emissions target without installing a carbon capture system. Adding CCS capacity in the following decades and reducing facility energy use by identifying a larger market for WDGS would lower ethanol CI below -20 g $CO_2$e/MJ by 2050.

The 'cost-per-$CO_2$' pathway succeeds in reducing ethanol CI to -4 g $CO_2$e/MJ by 2030 and -10 g $CO_2$e/MJ by 2050 without taking any actions expected to cost more than $50/t $CO_2$e. Many actions, such as reduced tillage, corn kernel fiber fermentation, and use of improved yeast strains are expected to reduce costs. Others, including changes to farm management like 4R and cover cropping, have the potential to become profitable at a carbon price as low as \$30/t $CO_2$. These alternative pathways highlight the benefits for ethanol producers of working with their supply chain to drive relatively low-cost emissions reductions on the farm, and to invest in potentially highly profitable technologies like yeast strain development.

Producers interested in making only a few highly effective investments in emissions reduction can obtain a very low ethanol CI by combining carbon capture of multiple $CO_2$ streams with biomass-fueled CHP and by encouraging supplying farmers to adopt cover crops and green ammonia. The 'magnitude-priority' pathway applies the five most impactful compatible emissions reduction actions. Such a facility could achieve an ethanol CI of 11 g $CO_2$e/MJ in 2030, an 88% reduction versus gasoline, through CCS of fermentation $CO_2$, 25% green ammonia adoption and 10% cover crop adoption. By adding a CHP system sufficient to provide all process energy for the facility and expanding the CCS system to capture $CO_2$ from the biomass power source, ethanol emissions could drop as low as -48 g $CO_2$e/MJ by 2050. Though the costs of these actions would likely be substantial – roughly \$0.48/gal without accounting for changes to corn costs – the emissions reduction could be worthwhile, depending on the climate policy and carbon market landscape by 2050.

These pathways succeed even with only modest progress by the rest of the US energy sector. The 'climate action future' scenario shows that changes to the energy and agriculture sectors in line with current US goals of reaching net zero emissions by 2050 have dramatic benefits for ethanol producers. Baseline emissions for corn ethanol are below 20 g $CO_2$e/MJ for most producers by 2050 in the 'climate action future' – less than half the emissions in the default baseline scenario. The industry can take advantage of this nationwide progress to achieve a net zero ethanol CI with fewer and less-costly emissions reduction actions than in the core pathway to net zero (including CKF fermentation, 'better-than-BAU' efficiency and process improvements) and with less pressure to expand carbon sequestration capabilities to facilities that might be less well-located for underground carbon storage.

In a 'climate action future' where the US achieves economy-wide net zero emissions, producers may have more incentives and fewer barriers to negative-emissions corn ethanol. With technological advancements in fermentation efficiency, access to fuel from an established renewable bio-methane industry, and a moderate carbon price of \$50 per ton $CO_2$ that allowed a biorefinery to break even on CCS costs, a producer could generate ethanol with a CI as low as -15 to -40 g $CO_2$e/MJ. That is equivalent to a 1-ton $CO_2$ credit for every 300-750 gallons of ethanol, adding \$0.07 to \$0.18/gallon in value under the same \$50/t $CO_2$ carbon price.

## 4.1. Agriculture and Climate Futures

Reducing agricultural emissions will be key to meeting UNFCCC Paris Climate Accord targets. IPCC modeling of global emissions reduction scenarios suggests that limiting global warming to 1.5°C will require reductions of 2 to 5 billion metric tons of $CO_2$e from the agriculture sector compared to business as usual by 2050 (Frank et al., 2018; Leahy et al., 2020). Modeling studies have achieved such reductions by applying carbon prices over \$100/t $CO_2e$ to the agricultural sector in developed countries – a policy that has not been seriously proposed anywhere and would likely have undesirable economic effects unless well-managed.

While such policies currently seem unrealistic and unlikely, the need for rapid and ambitious action to reduce methane and $N_2O$ emissions from fertilizers, manure, and other agricultural sources could serve as an opportunity for ethanol producers to take a leading role in expanding best practices and establishing a market for low-carbon farm products. The pathways in this study demonstrate that sourcing lower-carbon feedstock can facilitate achieving an extremely low CI for corn ethanol. If a carbon price is applied to agricultural goods, ethanol producers could benefit from the incentives to farmers to provide lower-emissions corn. If carbon prices include alternative fuels but exclude farm products, producers could be further incentivized to pursue low-cost supply chain emissions reductions, such as 4R fertilizer efficiency improvements, reduced tillage, or cover crop adoption, that require minimal up-front investment but could expand profitability from credits for lower-CI ethanol.

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