EFI
FOUNDATION

A Strategic Roadmap for Decarbonizing the U.S. Ethanol Industry

SEPTEMBER 2024

Project Team

Dr. Ernest J. Moniz
CEO and President, EFI Foundation

Joseph S. Hezir
Executive Vice President, Treasurer, EFI Foundation

Dr. Madeline Gottlieb Schomburg
Director of Research, EFI Foundation

Dr. Tatiana Bruce da Silva
Project Manager and Contributing Senior Analyst, EFI Foundation

Dr. Minji Jeong
Research Specialist, EFI Foundation

Annika Bowman
Research Fellow, EFI Foundation

Kathryn Ford
Research Fellow, EFI Foundation

Divine Maduakolam
Research Fellow, EFI Foundation

Additional Contributors

Jeffrey D. Brown
Managing Director, Energy Futures Finance Forum (EF^3), EFI Foundation

Dane McFarlane
Principal, Horizon Climate Group

Elizabeth Abramson
Lead Analyst, Horizon Climate Group

Communications Team

David Ellis
Senior Vice President of Policy Strategy & Outreach, EFI Foundation

Adrienne Young
Senior Communications Lead, EFI Foundation

Georgia Lyon
Communications Associate, EFI Foundation

Adam Patterson
Communications Associate, EFI Foundation

Copy Editing

Danielle Narcisse
M. Harris & Co.

Jane Hirt
M. Harris & Co.

Study Advisory Board

The EFI Foundation wishes to thank the following individuals for contributing subject matter expertise to this study. Board participation does not imply endorsement of the analysis, approach, findings, or conclusions.

Daniel Bresette
President, Environmental and Energy Study Institute (EESI)

Byron Dorgan
Former United States Senator and Representative from North Dakota; Senior Policy Advisor at ArentFox Schiff LLP; Senior Fellow at the Bipartisan Policy Center; Adjunct Professor at Georgetown University

Heidi Heitkamp
Former United States Senator from North Dakota; Director of the Institute of Politics at the University of Chicago

Alex Laska
Deputy Director for Transportation and Innovation, Climate and Energy Program at Third Way

Sasha Mackler
Executive Director of the Energy Program, Bipartisan Policy Center

Dan Sanchez
Assistant Professor of Cooperative Extension in the Department of Environmental Science, Policy, and Management at the University of California-Berkeley

Phil Sharp
Former United States Representative from Indiana; Senior Advisor at Resources for the Future; Advisory Board Member to Center on Global Energy Policy (CGEP), Columbia University; Member of the External Advisory Board of the MIT Energy Initiative

Jess Vilsack
General Counsel, Summit Carbon Solutions

Michael Wang
Distinguished Fellow, Senior Scientist, and Director of the Systems Assessment Center – Environmental Assessment Leader within the Energy Systems and Infrastructure Analysis division, Argonne National Laboratory

Catherine Woteki
Former Undersecretary for the USDA Research, Education, and Economics (REE) mission area; Member of the President’s Council of Advisors on Science and Technology (PCAST); Visiting Distinguished Institute Professor in the Biocomplexity Institute at the University of Virginia; Professor of Food Science and Human Nutrition at Iowa State University

The EFI Foundation also extends its thanks to the individuals who, through interviews, provided subject matter expertise for this study.

Report Sponsors

The EFI Foundation would like to thank Growth Energy for sponsoring this work. The EFI Foundation is solely responsible for the final content of this report

Suggested Citation: EFI Foundation. “A Strategic Roadmap for Decarbonizing the U.S. Ethanol Industry.” September 2024.

www.efifoundation.org

The EFI Foundation advances technically grounded solutions to climate change through evidence-based analysis, thought leadership, and coalition-building. Under the leadership of Ernest J. Moniz, the 13th U.S. Secretary of Energy, the EFI Foundation conducts rigorous research to accelerate the transition to a low-carbon economy through innovation in technology, policy, and business models. EFI Foundation maintains editorial independence from its public and private sponsors.

Cover photo: EFI Foundation

Table of Contents

Table of Figures

Executive Summary

Emergence of Ethanol as a Key Enabler of the Transition to Low-Carbon Fuels

The U.S. clean energy transition requires a transition to both carbon-free electricity and clean fuels. Ethanol has been the leader in the move to low-carbon fuels, as long-standing attempts to develop other advanced low-carbon liquid fuels (cellulosic biofuels, algae-derived fuels, e-fuels, etc.) have not succeeded in achieving scalable production at an acceptable cost.

Since 2005, the overall carbon intensity (CI)[a] of ethanol has decreased by 23%.[1] Ethanol's CI today is 53.6 grams of carbon dioxide equivalent per megajoule of ethanol produced (gCO_2e/MJ), 42% lower than unblended gasoline. This has enabled blends of ethanol and gasoline to reduce on-road vehicle greenhouse gas (GHG) emissions by over 544 million tons of CO_2.[b, 2]

This reality leads the EFI Foundation (EFIF) to present in this report a strategic roadmap to further decarbonize the U.S. ethanol industry through a portfolio of actions that can help it reach a goal of net-zero carbon intensity by midcentury, and several additional options that can achieve net-negative carbon intensity. The strategic roadmap will enable ethanol to play a central role in decarbonizing the transportation sector, which accounted for 29% of total U.S. GHG emissions in 2021.[3]

Continued decarbonization of ethanol, combined with higher blend levels, can complement the shift to electrification of light-duty vehicles—both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs)—in achieving further reductions in 2030 and beyond.[4] Conversion of ethanol into aviation fuel will allow blends of sustainable aviation fuel (SAF) at a significant scale. Further decarbonization of the U.S. ethanol industry also will strengthen its contribution to the U.S. economy, particularly to the rural economy.

In 2023, the United States produced 15.6 billion gallons of ethanol, making it the world's leading producer and exporter of ethanol, responsible for producing over half of the global supply.[5, 6] The ethanol industry accounted for 28% of farm GDP, contributing $57 billion to total U.S. GDP in 2022. The ethanol industry supports more than 420,000 jobs.[7, 8]

---

[a] Carbon intensity (CI) refers to the amount of carbon dioxide emitted per unit of energy or activity.

[b] In the United States, nearly all gasoline sold today is blended with ethanol at a 10% rate (E10). E10's CI is 3% lower than unblended gasoline's.

Corn production for ethanol[c] is a high value-added proposition—ethanol producers use about 30% to 40% of the U.S. corn crop, spending $38 billion, but require only about 1.5% of total U.S. farmland (an estimated 13.9 million acres).[9, 10, 11, 12, 13] Since 2001, the U.S. food crops industry overall has maintained relatively consistent land use for planting while yields have continued to increase, indicating that corn is not in direct competition for acreage with other food crops.[d, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23] This report does not assume any increase in corn planting for ethanol production.

Assessment of Measures to Further Decarbonize the Life Cycle Carbon Intensity of Ethanol

The strategic roadmap for decarbonizing the U.S. ethanol industry was developed based on current estimates in the U.S. Department of Energy (DOE)-sponsored GREET model, developed at Argonne National Laboratory.[e] The model provides estimates of carbon uptake and emissions across the entire ethanol life cycle, including corn farming, biorefining, and end use.

Currently, the R&D GREET model[f] (hereafter referred to as "GREET") estimates that, on average, U.S. corn ethanol emits around 53.6 gCO_2e/MJ throughout its life cycle. Figure ES1 illustrates the composition of the emissions sources and sinks that comprise ethanol's net carbon footprint.

---

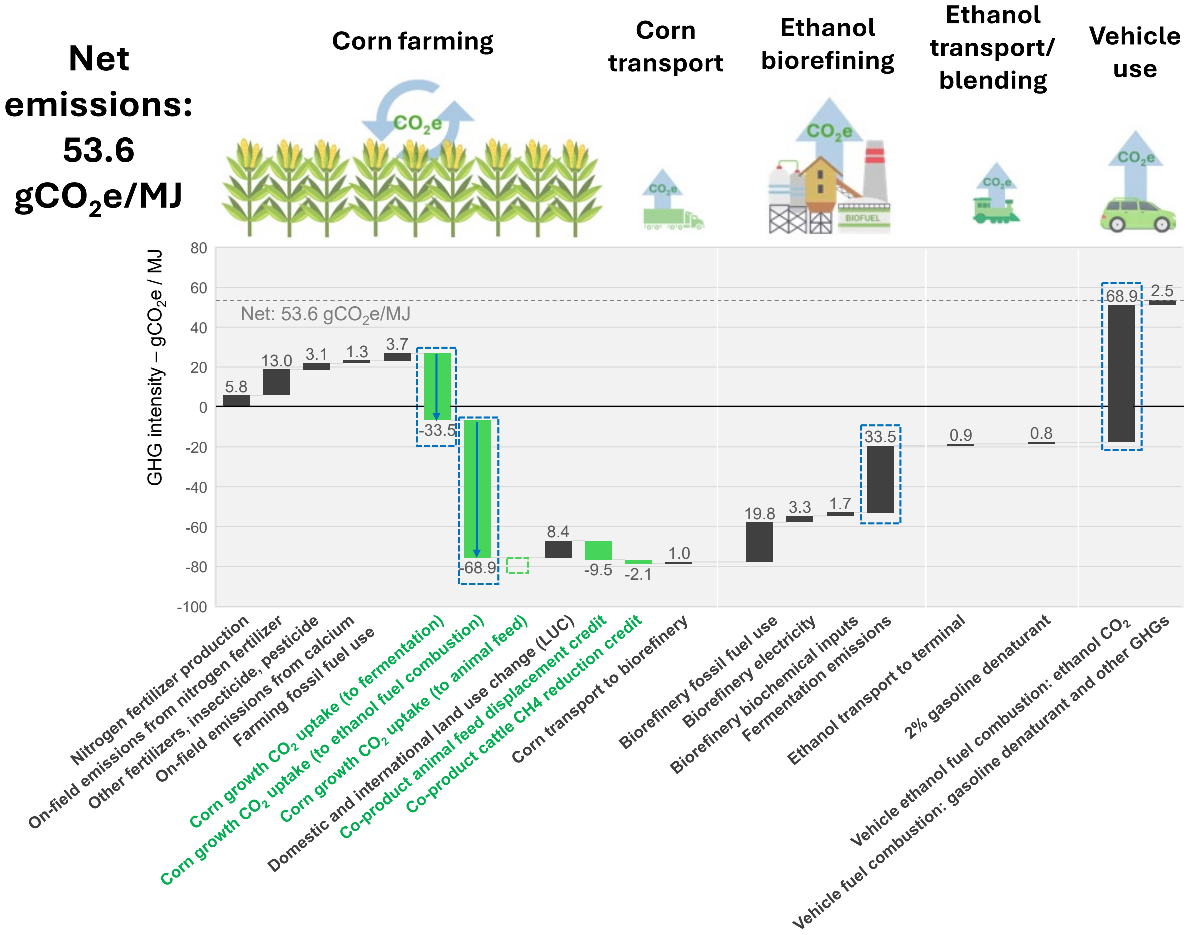
[c] Corn-based ethanol currently accounts for an estimated 94% of total U.S. ethanol production.

[d] The land use for planting U.S. food crops has decreased by 2.1% from 2001 to 2024, while the yield has increased by 25.1%, showing the industry has been able to increase crop yield substantially while keeping land use relatively consistent.

[e] The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model is a tool developed by Argonne National Laboratory with support from the U.S. Department of Energy to evaluate the energy and environmental impacts in the energy systems of various technology and fuel combinations.

[f] R&D GREET is used to guide research, development, and decision-making for researchers, industry, or fuel consumers. A specific GREET model could be developed for a policy program. For example, tax credits 40B and 45V and California's Low-Carbon Fuel Standard have their own versions of GREET.

Figure ES 1. Components of the dry mill ethanol life cycle (emissions in gCO_2e/MJ)



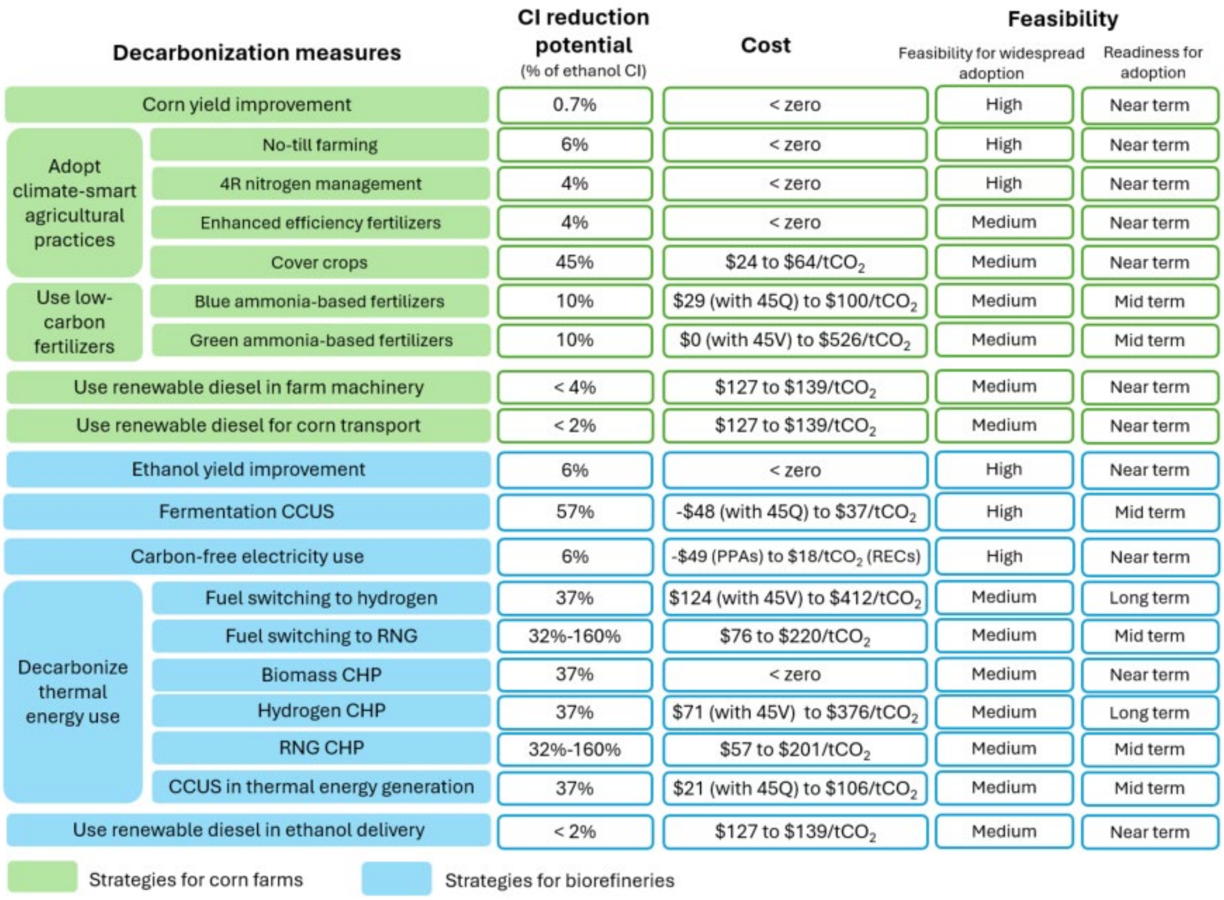
Ethanol emissions in a dry mill facility (the production method most common in the U.S.) occur during corn farming, fuel production, and consumption. Emissions sources are depicted in black, and emissions sinks in green. Data from: GREET (2024); Horizon Climate Group for fermentation emissions.

The GREET estimates are used as the baseline for developing the strategic decarbonization roadmap. The estimates are based on the dry mill biorefining process for ethanol production, the most commonly used technology in the United States. The baseline shows significant variation among sources and sinks of CO_2 emissions throughout the ethanol life cycle.

The three largest sources of emissions are end-use combustion, the fermentation process, and the use of fossil fuels to provide process heat. CO_2 uptake occurs in the corn-growing process and is also accounted for, or “scored,” in GREET as a “credit” in the life cycle analysis. The credit covers emissions from the fermentation and end-use combustion processes. Also noteworthy in the GREET estimates is that the indirect emissions associated with electricity used in biorefining are included in the model, as well as the carbon footprint of the production of fertilizer used to support corn growing.

EFIF's assessment of the ethanol life cycle identified a broad range of measures that can significantly reduce the CI of ethanol. The assessment incorporated four factors: adoption readiness, the feasibility for widespread adoption, the magnitude of CI reduction potential, and cost-effectiveness, as measured in terms of cost per ton (t) of CO_2 removed from the life cycle baseline. The measures examined included modifications in agricultural practices for corn growing, improvements in biorefining, use of low-carbon fuels and electricity, and carbon capture from the biorefining process. Figure ES2 provides a summary of the assessment.

Figure ES 2. Assessment of ethanol decarbonization measures



Decarbonization measures		CI reduction potential (% of ethanol CI)	Cost	Feasibility	
				Feasibility for widespread adoption	Readiness for adoption
Corn yield improvement		0.7%	< zero	High	Near term
Adopt climate-smart agricultural practices	No-till farming	6%	< zero	High	Near term
	4R nitrogen management	4%	< zero	High	Near term
	Enhanced efficiency fertilizers	4%	< zero	Medium	Near term
	Cover crops	45%	\$24 to \$64/tCO_2	Medium	Near term
Use low-carbon fertilizers	Blue ammonia-based fertilizers	10%	\$29 (with 45Q) to \$100/tCO_2	Medium	Mid term
	Green ammonia-based fertilizers	10%	\$0 (with 45V) to \$526/tCO_2	Medium	Mid term
Use renewable diesel in farm machinery		< 4%	\$127 to \$139/tCO_2	Medium	Near term
Use renewable diesel for corn transport		< 2%	\$127 to \$139/tCO_2	Medium	Near term
Ethanol yield improvement		6%	< zero	High	Near term
Fermentation CCUS		57%	-\$48 (with 45Q) to \$37/tCO_2	High	Mid term
Carbon-free electricity use		6%	-\$49 (PPAs) to \$18/tCO_2 (RECs)	High	Near term
Decarbonize thermal energy use	Fuel switching to hydrogen	37%	\$124 (with 45V) to \$412/tCO_2	Medium	Long term
	Fuel switching to RNG	32%-160%	\$76 to \$220/tCO_2	Medium	Mid term
	Biomass CHP	37%	< zero	Medium	Near term
	Hydrogen CHP	37%	\$71 (with 45V) to \$376/tCO_2	Medium	Long term
	RNG CHP	32%-160%	\$57 to \$201/tCO_2	Medium	Mid term
	CCUS in thermal energy generation	37%	\$21 (with 45Q) to \$106/tCO_2	Medium	Mid term
Use renewable diesel in ethanol delivery		< 2%	\$127 to \$139/tCO_2	Medium	Near term

🟩 Strategies for corn farms 🟦 Strategies for biorefineries

The CI reduction potential is the maximum potential for full adoption of each measure, estimated using the GREET model. The cost is a levelized cost of carbon abatement (LCCA), relative to the cost of the business-as-usual alternative. It is calculated by dividing cost by CO_2 abated. Negative LCCA results from reducing energy or fertilizer inputs, selling energy back to the grid, or obtaining tax credits. The market feasibility was evaluated by reviewing publicly available data and literature on technological and economic feasibility and the barriers to adoption.

Notes: 4R – right source, time, rate, and place; blue ammonia – produced with capturing and sequestrating CO_2 from hydrogen production; green ammonia – produced with renewable energy for hydrogen production (note that hydrogen is a primary feedstock for making either blue or green ammonia); CCUS – carbon capture, utilization, and storage; RNG – renewable natural gas; CHP – combined heat and power; PPAs – power purchase agreements; RECs – renewable energy certificates; 45Q – tax credit for carbon oxide sequestration; 45V – clean hydrogen production tax credit. Source: EFI Foundation analysis.

As shown in the figure, the measures providing the largest reductions, in terms of the magnitude of CI reduction potential, include:

- Carbon capture, utilization, and storage (CCUS) in the fermentation process[g]
- Replacing the use of natural gas for process heat with low-carbon process fuels such as renewable natural gas (RNG)
- Planting cover crops in corn farms in intervals between regular corn cropping

These three measures alone could lead to an estimated reduction of up to 140 gCO_2e/MJ, resulting in a net-negative CI score.

The mix of options changes when other factors are considered, such as cost-effectiveness and feasibility for adoption. Widespread adoption of RNG is limited by high costs, limited current supply, and competition with other uses. Even if all available U.S. RNG is dedicated to the ethanol industry, it could replace only 76% of the natural gas used in the industry.[24]

Options that are ready for widespread adoption at a relatively low cost per ton of CO_2 removed (less than $18 per ton reduced) can reduce overall CI by 14 gCO_2e/MJ (a 26% reduction from the current baseline) and include:

- Purchasing carbon-free electricity in the biorefinery
- Continuously improving ethanol yield
- Procuring corn from farms continuously improving corn yield
- Employing no-till farming
- Using enhanced efficiency fertilizers (EEFs)
- Adopting 4R (right source, time, rate, and place) nitrogen management practices

Introducing a combined heat and power (CHP) system running on biomass, such as corn stover and other residual agricultural wastes, also can be a cost-efficient option for the long term because of the low cost of biomass and increased energy efficiency.

CCUS is a low-hanging fruit for ethanol decarbonization. Capturing CO_2 emissions from the biorefining process is technologically feasible at a relatively modest cost of capture of about $37/$tCO_2$. This cost could be covered by the carbon sequestration tax credit (Section 45Q), which pays $85/$tCO_2$; however, transportation and sequestration of CO_2 are challenging. As most ethanol plants are in areas unsuitable for geologic sequestration of CO_2, the captured CO_2 in ethanol plants would have to be transported via pipelines to suitable sites.

---

[g] CO_2 utilization is considered with CO_2 sequestration as the technologies converting captured CO_2 into products are under development.

Uncertainties surrounding permitting of the CO_2 pipeline infrastructure and geologic storage site (Class VI)[h] have been the most significant barriers to scaling up CO_2 transportation and sequestration infrastructure. The permitting issues are complex because the pipeline infrastructure would cross multiple states (e.g., five states in the Summit pipeline project, three states in the Tallgrass Energy Gas-to-CO_2 project) and require permit approvals by state and local governments.

Strategic Decarbonization Pathways for the U.S. Ethanol Industry

Based on the assessment of options, EFIF developed two strategic pathways that the ethanol industry could take to achieve net-zero or even negative emissions by midcentury:

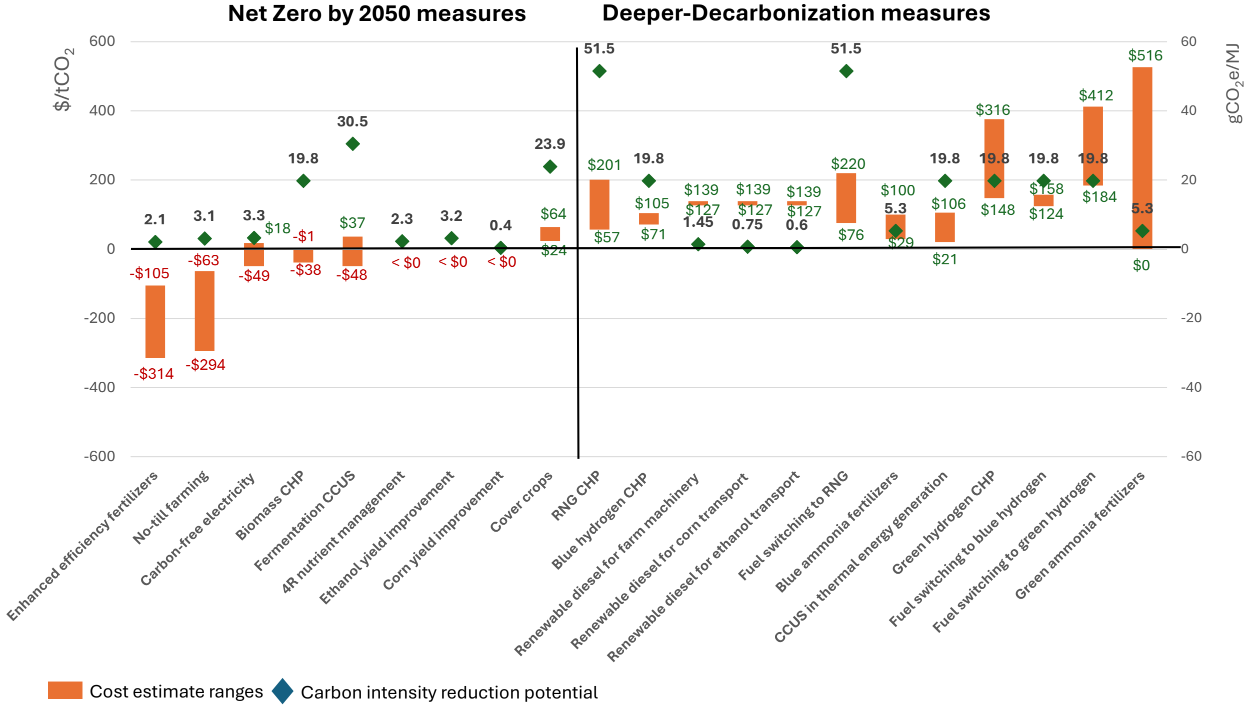
- ***Net Zero by 2050 Pathway*:** This pathway includes core decarbonization measures to enable the ethanol industry to reach net-zero emissions by midcentury, with substantial progress toward that goal by 2035. The core decarbonization measures are ready to adopt and have a relatively low cost per ton of CO_2 removed. Many measures have a net cost of less than zero because of the cost savings that accompany them, and the most expensive measure costs at most \$64/tCO_2. Note that costs are relative to the current practice.
- ***Deeper-Decarbonization Options*:** Adopting additional measures enables the ethanol industry to reach almost net-zero emissions by 2035, and negative emissions in 2050. The additional measures are not yet ready-to-adopt and their costs are relatively higher or uncertain, with a wide range of estimates. Since most measures, such as clean ammonia, are in the early phases of market development, their degree of penetration into the ethanol supply chain is uncertain for the near term and midterm. The costs of these additional measures range from zero to \$516/tCO_2.

Figure ES3 shows that the core measures combined offer a portfolio to reach net-zero emissions by 2050 at a relatively small cost per ton and in some cases a negative cost per ton relative to the cost of current practices. The additional measures could provide even deeper decarbonization, but the range of costs is much greater and more uncertain.

---

[h] A Class VI well is a well for CO_2 geologic sequestration.

Figure ES 3. Cost and carbon intensity reduction potential by decarbonization measure

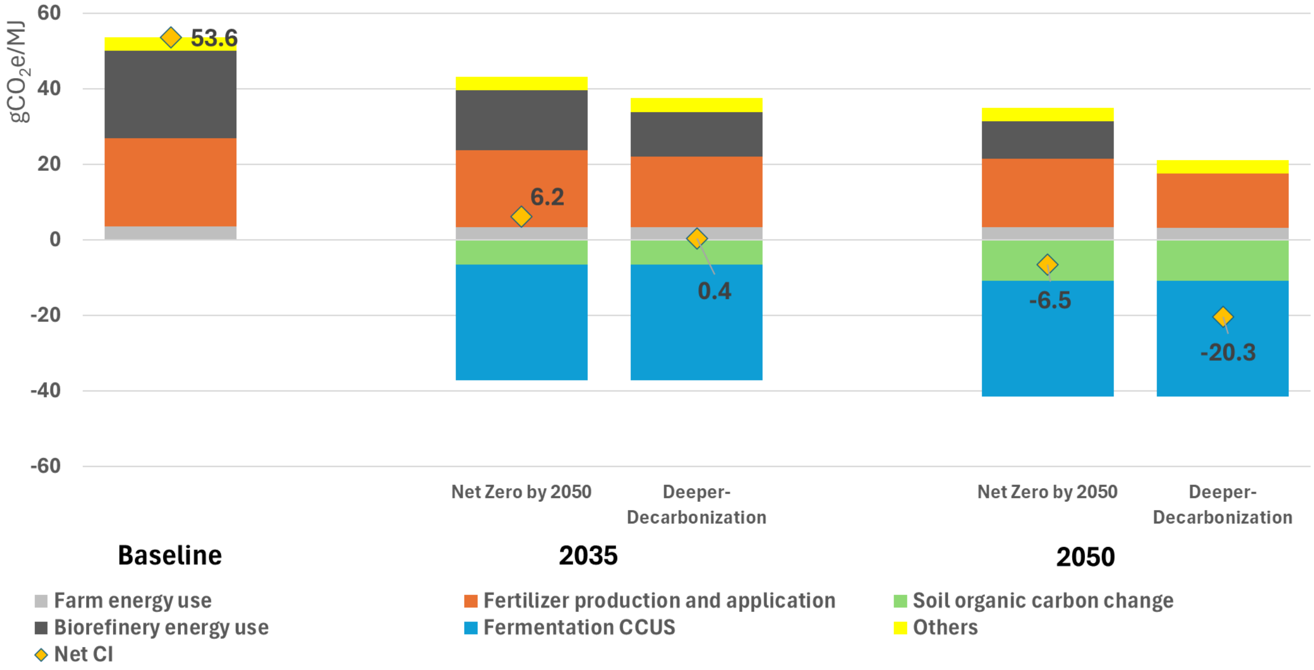


A negative cost means that the new measure costs less than the currently adopted measure because of reduced energy or fertilizer inputs (e.g., no-tillage farming, 4R nitrogen management), a lower cost for securing energy (e.g., PPAs), policy incentives (e.g., fermentation CCUS), or additional electricity production (e.g., biomass CHP). Source: EFI Foundation analysis.

The midterm pathway (by 2035) and the long-term pathway (by 2050) were modeled with varying assumptions about the prevalence of each decarbonization measure. Further details on assumptions can be found in Chapter 4 of the report.

Under the Net Zero by 2050 Pathway, a biorefinery can reduce almost 90% of its ethanol CI by 2035 and reach net-zero emissions by 2050. With the Deeper-Decarbonization Options, a biorefinery can reach almost net zero by 2035 and negative emissions in 2050 (Figure ES4).

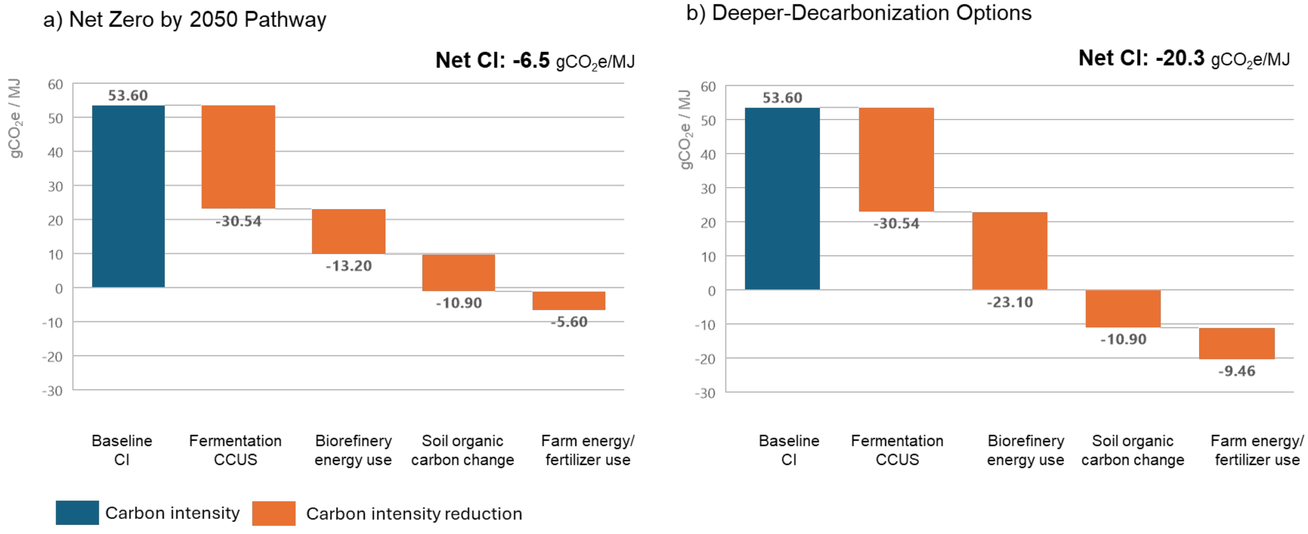
Figure ES 4. Ethanol carbon intensity in the baseline, Net Zero by 2050 Pathway, and Deeper-Decarbonization Options, 2035 and 2050



Source: EFI Foundation analysis.

Under the Net Zero by 2050 Pathway, the largest reduction comes from CCUS in the fermentation process, which reduces CI by 60%, a 30.5 gCO2e/MJ reduction from the baseline CI of 53.6 gCO_2e/MJ. Decarbonizing energy use in a biorefinery is the second-largest source of reductions. With the Deeper-Decarbonization Options, the largest reduction also comes from CCUS in the fermentation process. But, compared to the Net Zero by 2050 Pathway, decarbonizing energy use in the biorefinery reduces a larger amount of the CI as natural gas use for thermal energy generation is completely replaced by a mix of low-carbon fuels. See Figure ES5 for more detail.

Figure ES 5. Sources of CI reduction, Net Zero by 2050 and Deeper-Decarbonization, 2050



Source: EFI Foundation analysis.

Enabling Decarbonization of the Transportation Sector

The decarbonization pathways for the U.S. ethanol industry allow ethanol to play a much larger role in decarbonization across the entire transportation sector.

Lower-CI ethanol can complement electric vehicles in decarbonizing the light-duty vehicle fleet. As mentioned, transportation is the largest source of GHG emissions in the United States. The Biden-Harris administration has called for half of all new vehicles sold by 2030 to be electric vehicles (EVs), with a longer-term goal that most light-duty vehicles (LDVs) will be electric by 2050.[4, 25] Achieving these goals alone is insufficient to reach a net-zero transportation sector.[26] Decarbonizing ethanol can substantially complement strategies for electrification of LDVs in reducing vehicle transportation emissions.[27]

Further, plug-in hybrid electric vehicles (PHEVs), which still use some gasoline, currently make up about 27% of EVs in the United States.[28, 29] Their presence in the vehicle fleet is expected to grow as automakers invest more in PHEVs, driven by consumer demand.[30] As a result, low-CI ethanol can play a role in further reducing emissions in new and in-use PHEVs alongside battery electric vehicles as transportation electrifies.

Decarbonized ethanol has the potential to be an abundant feedstock to expand the supply of sustainable aviation fuel (SAF). SAF is a drop-in fuel with jet fuel-like properties that requires no aircraft or supply chain infrastructure modifications. In the United States, SAF can take advantage of production tax credits. The clean fuel production tax credit (Section 45Z) of the Inflation Reduction Act (IRA) of 2022 goes into effect in January 2025 and requires life cycle SAF emissions to be no more than 50 kilograms (kg) of CO_2 per million British thermal units (MMBtu), or 47.4 gCO_2e/MJ.[i] The current CI score of ethanol alcohol-to-jet (ATJ) SAF is approximately 70.36,[j] meaning ethanol's carbon intensity must be reduced to qualify for tax credits.

As SAF currently costs around $6.69 per gallon, compared to $2.85 for fossil-based jet fuel, achieving the 45Z credit is essential for making ATJ SAF cost-competitive.[31] With the full 45Z credit plus existing state-level tax incentives for SAF, the cost of SAF could be in the range of $2.94 to $3.69 per gallon.

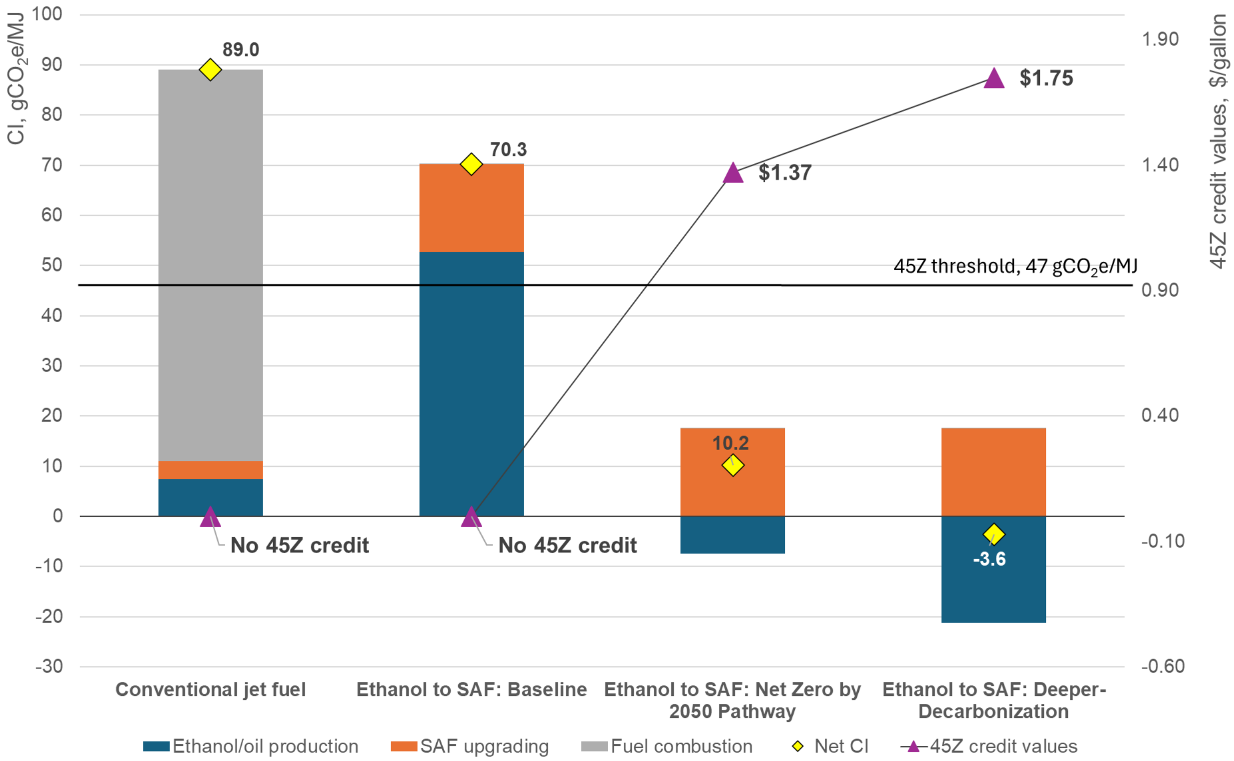
Figure ES6 demonstrates that both decarbonization pathways enable ATJ ethanol SAF (E-SAF) to achieve a CI under the 45Z threshold. The Deeper-Decarbonization pathway enables ATJ E-SAF to qualify for the maximum 45Z credit of $1.75 per gallon.

---

[i] Including upstream feedstock emissions and emissions from SAF production.

[j] Estimated using the GREET model, assuming a dry mill with corn extraction facility, which represents more than 86% of ethanol production in the United States. The GREET default is 85.5% dry mill with corn extraction facility, 10% dry mill without the extraction facility, and 4.5% of wet mill.

Figure ES 6. Carbon intensity of conventional jet fuel and ATJ E-SAF, including under different decarbonization pathways



The emissions from fuel combustion are zero for ATJ E-SAF because they are offset by corn growth CO2 uptake. Source: EFI Foundation analysis.

Current Incentives Provide a Foundation for Ethanol Decarbonization

Currently available incentives are a helpful starting point to leverage decarbonization options but are not enough on their own. Beginning in January 2025, SAF production and higher gasoline blending will be able to obtain the 45Z clean fuels tax credit. To qualify for 45Z, clean fuels must be “suitable for use as a fuel in a highway vehicle or aircraft” and emit no more than 50 kg of CO_2 per MMBtu. When combined with other eligibility criteria such as meeting wage and apprenticeship standards, producers can receive a production tax credit of up to $1 per gallon for nonaviation fuels and $1.75 per gallon for SAF.[32]

State-level low-carbon fuel standards (LCFS) have also provided an effective mechanism for gradually decarbonizing transportation fuels. Currently, an LCFS program is in place in California, Oregon, and Washington. Twelve other states have introduced or discussed LCFS-like legislation, and three of these states (New York, Michigan, and Illinois) are among the top ethanol consumers. The LCFS programs in California[33], Oregon[34], and Washington[35] have not only incentivized reductions in the

CI value of ethanol[36] but also have led to reductions in the CI of other alternative fuels, including RNG. Additionally, they have provided flexible and technology-neutral compliance options, have spurred private investment in lower-CI technologies, and have incentivized cleaner fuel production beyond state borders.[37]

Policy support for climate-smart agricultural practices also has been increasing.[k] The IRA provided $19.5 billion of additional funds over a five-year period to a portfolio of U.S. Department of Agriculture (USDA) conservation programs targeted to support adoption of climate-smart practices. The $19.5 billion was allocated among six separate programs: the Environmental Quality Incentive Program ($8.45 billion), Regional Conservation Partnership Program ($4.95 billion), Conservation Stewardship Program ($3.25 billion), Agricultural Conservation Easement Program ($1.4 billion), Conservation Technical Assistance ($1 billion), and for measuring, evaluating, and quantifying GHG emissions reductions ($300 million).[38]

The USDA has committed $2.1 billion of these funds in 2022 and 2023, is estimated to commit $3.1 billion by the end of 2024, and plans to commit $5.6 billion in 2025, though farmer interest to date has far exceeded the available funds. When the USDA made $850 million of these funds available in 2023, applicants requested almost $3 billion in total.[39]

Blending requirements have become a pivotal aspect of the broader strategy to decarbonize transportation fuels. Such requirements mandate a specific percentage of renewable fuels be blended with gasoline, helping to lower the overall CI of the fuel mix. In the United States, the Renewable Fuel Standard (RFS) requires 15 billion gallons of conventional renewable fuels to be blended into the nation's fuel supply each year.[l] For 2024, ethanol is expected to fulfill approximately 93% of the RFS volume requirement.[40] E10 is the most common blend used to achieve these volume obligations, with states such as Minnesota, Missouri, and Oregon requiring E10 blending by law. State E10 mandates combined with the RFS have resulted in E10 becoming the de facto standard for gasoline across the country.[41]

---

[k] Climate-smart agriculture is a way to build resilience in farming operations, benefiting both farmers and ranchers and the environment. The goals of CSA are to increase or maintain productivity and yield, enhance resilience to environmental changes, and reduce GHG emissions. CSA practices include many techniques already used by farmers, such as cover cropping, no- and reduced-tillage farming, and nutrient management.

[l] Conventional renewable fuel refers to fuel made from renewable biomass that either achieves at least a 20% reduction in greenhouse gas emissions compared to the fossil fuel it replaces or is exempt from this requirement if produced in facilities built before December 19, 2007. Renewable biomass includes wood, agricultural crops, and wastes from municipal, industrial, and agricultural sources. Source: U.S. Environmental Protection Agency, Renewable Fuel Standard (RFS) Program: Standards for 2023, 2024, and 2025, Federal Register, July 12, 2023, https://www.govinfo.gov/content/pkg/FR-2023-07-12/pdf/2023-13462.pdf.

Additional Policies Are Necessary to Accelerate the Decarbonization of Ethanol Supply Chains

Additional policy measures will accelerate the adoption of a strategic decarbonization roadmap for the ethanol industry to reach net-zero CI and move beyond to net-negative CI. Employing ready-to-adopt and modest-cost decarbonization measures will enable the ethanol industry to reach net-zero emissions, but even these measures face barriers to implementation, such as lack of infrastructure, the need for upfront investment, and uncertain implementation outcomes. To lower these barriers, a range of industry actions and policy changes are required.

The ethanol life cycle is complex, and the implementation of a strategic decarbonization roadmap requires coordinated action among five major players: corn growers, ethanol bio refiners, energy suppliers (electricity and fuels), fertilizer producers, and an emerging carbon management industry. A key factor in the design of additional policy measures is the need to address the roles of all major players, including ways to encourage cooperative and mutually reinforcing actions. The recommendations that follow are intended to comprehensively address decarbonization actions across all the players in the ethanol life cycle.

USDA support for expanding farmers' adoption of climate-smart agricultural (CSA) practices

CSA adoption rates are low because of economic challenges and uncertain outcomes because of variation in environmental factors like soil type and climate.[42,43,44] In some instances, CSA practices require significant upfront investments, such as purchasing specialized equipment that does not necessarily result in immediate productivity increases. Further, the lack of a robust measuring, monitoring, reporting, and verification (MMRV) framework for CSA practices is another critical barrier preventing farmers from ensuring the outcome of their investment. Additional policy support is needed to provide farmers with CSA data and funding.

- ***Recommendation 1.*** *Congress should preserve the existing IRA funds for conservation programs so the USDA can proceed with the full multiyear funding allocations to expand the adoption of CSA practices.*
- ***Recommendation 2.*** *The USDA should provide farmers with a comprehensive information package, including grants, loan programs, technical support, tools, and contracts, which can be used to invest in CSA practices.*
- ***Recommendation 3.*** *The USDA should accelerate collecting field-based data on CSA practices, develop an MMRV framework for CSA practices, and disseminate the data and framework to stakeholders, including federal agencies designing incentive programs, GREET modelers, farmers, and the ethanol industry.*

- ***Recommendation 4.*** *The IRS, working with DOE, should expand the portfolio of CSA practices that can be considered in qualification for the 45Z credit to include all GREET options. Also, the IRS should allow flexibility in letting farmers select individual measures in a practice-by-practice fashion, rather than require bundling of measures—as has been done with the current SAF tax credit (40B).*
- ***Recommendation 5.*** *In collaboration with the USDA, the IRS should consider ways to help ethanol producers share the value of these credits with corn growers who contributed to reducing the carbon intensity of ethanol by adopting CSA practices.*

Production tax credits

The 45Z production tax credit, which becomes effective in 2025, can provide a powerful incentive to produce lower-CI ethanol for use as a gasoline blending agent and to significantly expand SAF supplies. It also could further reduce the CI of ethanol blends in gasoline. Under current law, the 45Z credit will apply only until Dec. 31, 2027. This period of time is insufficient to incentivize the capital investment needed to reduce the CI throughout the ethanol life cycle.

- ***Recommendation 6.*** *Congress should modify the 45Z clean fuels production tax credit in a manner similar to other IRA incentives, i.e., extend it for 10 years to facilities that commence production of qualified transportation fuels before Jan. 1, 2033.*
- ***Recommendation 7.*** *In collaboration with the USDA, DOE should continue improving the GREET model to reflect a broader range of emissions-reduction practices, such as options for combined heat and power. These practices should be incorporated into the IRS 45Z guidance.*

Decarbonizing energy use in biorefineries

Natural gas accounts for 91% of energy consumption at biorefineries, contributing significantly to ethanol’s carbon intensity. Alternatives such as renewable natural gas and clean hydrogen blended with natural gas can be used as drop-in fuels to reduce ethanol’s CI score. Both agricultural and landfill biogas resources are abundant in the Midwest, but conversion to RNG production has been limited. The impediments include large upfront capital investment requirements, lack of transportation infrastructure, and fragmented market demand. Other options that could significantly lower ethanol’s CI from electricity use are procuring carbon-free electricity from utilities that are decarbonizing their generation portfolio; seeking direct power purchase agreements (PPAs) with clean electricity generators; or purchasing renewable energy certificates, such as energy attribute certificates (EACs), with independent power producers.

- ***Recommendation 8.*** *Ethanol producers should seek opportunities to increase carbon-free sources of electricity for use at biorefineries—including electricity* *from biomass and other renewables, hydrogen, nuclear, hydropower, and others—in cases where the grid is not being decarbonized quickly enough.*

- ***Recommendation 9.*** *Ethanol producers should consider measures to decarbonize process heat, including biofuels and RNG—for example, facilitating demand aggregation that could incentivize expanded RNG production while mitigating financial risks. Market demand formation measures could range from establishing RNG certificate programs to forming buyers' cooperatives.*

Decarbonizing fertilizer

Decarbonizing the production of fertilizers could significantly reduce ethanol's CI, as the emissions from fertilizer production account for about 11% of ethanol's carbon intensity. Low-carbon fertilizer production from either blue hydrogen or green hydrogen currently is more costly than conventional fertilizer supplies. Farmers are not motivated to pay a significant premium for low-carbon fertilizers, given their small profit margins and uncertain incentives for using them. Implementation of the new 45V tax credit for clean hydrogen, as well as DOE's hydrogen hubs program and the Hydrogen Demand Initiative,[m] could potentially close this gap.

- ***Recommendation 10.*** *DOE's hydrogen hubs program and the Hydrogen Demand Initiative should consider making clean ammonia one of their early targets for financial support.*
- ***Recommendation 11.*** *The USDA should reopen and repurpose its domestic fertilizer production program, focusing on retrofitting existing facilities to produce low-carbon fertilizers using funds from the Commodity Credit Corporation (CCC). Congress should not restrict the USDA's authority to use CCC funds for this purpose in pending farm bill legislation.*

Demand-side mandates for clean fuels

Demand-side mandates can have a synergistic effect when added to production incentives. State-level LCFS, for example, have proven effective in reducing the carbon intensity of ethanol. California's LCFS program has led to a 25% reduction in ethanol's carbon intensity since its implementation in 2011.[45] However, creating a national clean fuel standard (CFS) requires further investigation into policy design options, as the specifics of the standard substantially shape its efficacy. A key issue in the design of a national CFS is the interplay between a CFS and the existing federal RFS program. The current RFS implicitly considers the blend rates of ethanol in gasoline when setting the

---

[m] The Hydrogen Demand Initiative is a consortium selected by DOE and led by the EFI Foundation to help accelerate the commercial liftoff of the clean hydrogen economy.

target. A CFS could encourage higher blend rates, reflecting the fact that today, the vast majority of on-road vehicles are capable of using blends up to 15%, and drive the demand for SAF.[46] It could also incentivize the ethanol industry to further decarbonize the supply chain to meet the requirements for CFS.

- ***Recommendation 12.*** *The administration should launch an interagency study of the feasibility of a national CFS, including a process for broad public engagement.*
- ***Recommendation 13.*** *Apart from the CFS, the U.S. Environmental Protection Agency should consider the feasibility of higher blending levels in the formulation of RFS standards, and states should consider expanding current mandates, including establishing requirements for E15 and higher blends in gasoline.*

1. Emergence of Ethanol as a Key Enabler of the Transition to Low-Carbon Fuels

The U.S. clean energy transition requires a transition to both carbon-free electricity and clean fuels. As the United States accelerates its transition to clean energy, low-carbon fuels are critical, with ethanol emerging as a front-runner over the past two decades because of its ability to significantly reduce transportation emissions while leveraging existing infrastructure and feedstock availability.[47] Long-standing attempts to develop other advanced lower-carbon liquid fuels (cellulosic biofuels, algae-derived fuels, e-fuels, etc.) have not achieved scalable production at an acceptable cost.

This report presents a comprehensive strategic plan for decarbonizing the U.S. ethanol industry by 2050.[n] Reducing the industry's carbon footprint could significantly contribute to climate and clean energy policy objectives.

Blending ethanol with gasoline already has reduced on-road vehicle emissions by more than 544 million tons of carbon dioxide equivalent (CO_2e) since 2005 and can potentially be a major contributor to further reductions in transportation emissions by 2030 and beyond.[1] As the leading global producer and exporter of corn-based ethanol, the United States is uniquely positioned to leverage this sector to achieve significant reductions in carbon emissions, thereby aligning with national climate and clean energy objectives.[48]

The EFI Foundation has developed this roadmap to identify and assess viable strategies for minimizing the carbon footprint of ethanol production while strengthening its longer-term economic competitiveness. The roadmap envisions ethanol not merely as a fuel but as a catalyst for sustainable progress.

The analysis in this report focuses on carbon-reduction options for the existing ethanol industry rather than on expanding the footprint of corn farming or the ethanol industry. The purpose of this report is to identify technologically and economically feasible options for the ethanol industry to achieve decarbonization in a cost-effective manner,

---

[n] This roadmap focuses on corn-based ethanol, hereafter referred to as ethanol, which accounts for 94% of U.S ethanol production. The remaining 6% of U.S. ethanol production comes from cellulosic biomass (such as crop residues, grasses, and woody biomass), sugar crops (like sugarcane and sugar beets), industrial waste and byproducts (including waste gases and food waste), and other grains and crops (such as sorghum, barley, and wheat). Source: U.S. Department of Energy Alternative Fuels Data Center “Ethanol Fuel Basics,” accessed February 9, 2024, https://afdc.energy.gov/fuels/ethanol_fuel_basics.html.

and to recommend additional policy actions to accelerate the implementation of these options.

This report does not analyze the impact of ethanol decarbonization on food or fuel prices in the market. Any such impacts would need to account for the net cost impact after the application of policy and financial incentives.

Economic Impact of U.S. Ethanol Industry: A Key Contributor to Rural and National Growth

The U.S. ethanol industry contributes billions of dollars annually to the rural economy.[49] In 2022, the ethanol industry— including corn farming—contributed $57 billion to U.S. GDP (about 0.25% of total U.S. GDP or 28% of national farming GDP) and created $34.8 billion in household income. [50, 51] Approximately 78,000 U.S. jobs are directly associated with the ethanol industry, and an additional 342,800 indirect or induced jobs across sectors like construction and retail are connected to ethanol production.[52]

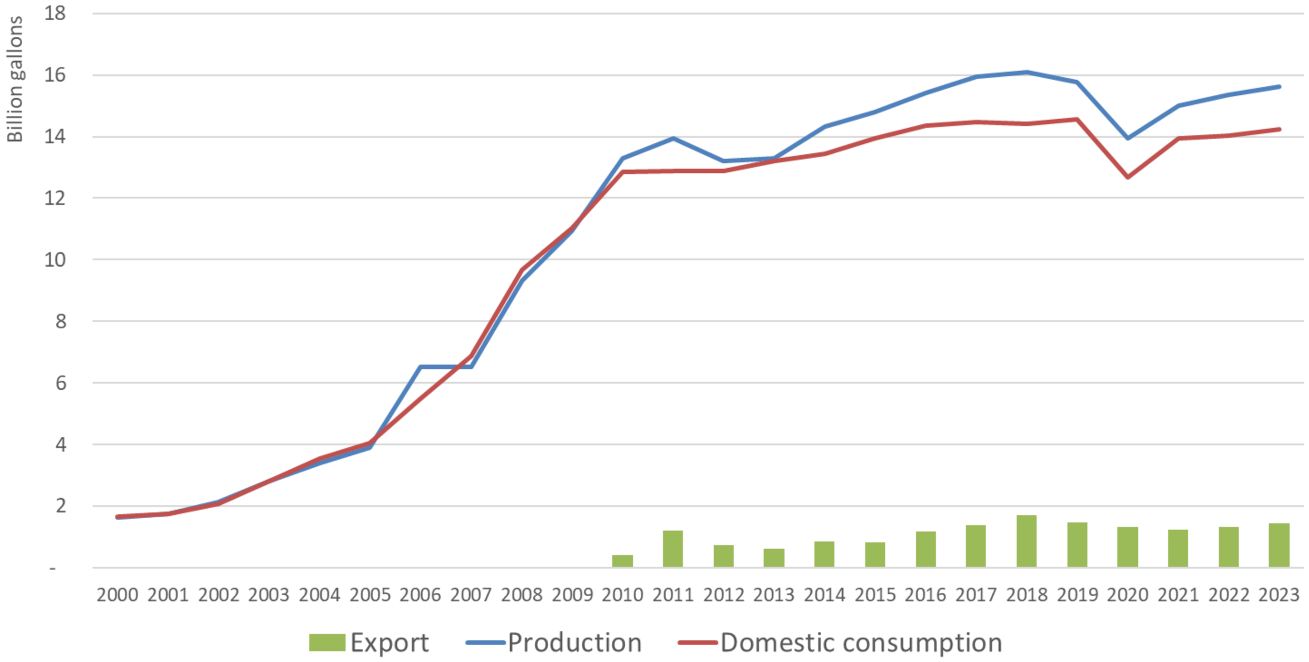
In the United States, nearly all gasoline sold today contains about 10% ethanol by volume (E10). All vehicles sold in the U.S. can use E10, and vehicle models from 2001 on can use higher ethanol blends like E15.[53] E85 (51% to 83% ethanol) is available only for flex-fuel vehicles. Ethanol is the most commonly produced and consumed biofuel in the United States. In 2022, it accounted for 82% and 75% of domestic biofuel production and consumption, respectively, comprising 5% of total liquid fuel production in the country.[54, 55] Ethanol production in the United States has risen substantially over the past two decades: From 2000 to 2023, U.S. ethanol production rose from 1.6 billion gallons to 15.6 billion gallons.[56] Of the ethanol destined for fuel, 98% of the total U.S. ethanol production is destined for gasoline blending,[57] while the remaining 2% becomes E85.[o]

National ethanol consumption similarly rose from 1.6 billion gallons to 14.2 billion gallons from 2000 to 2023 (Figure 1).[58] Figure 1 shows a steady rise in ethanol consumption, production, and exports over the past 20 years, with noticeable declines during the COVID-19 pandemic. Currently, the United States exports around 9% of all domestically produced ethanol—1.43 billion gallons, worth $3.82 billion[59]—primarily to Canada, India, and Brazil.[60]

---

[o] Ethanol's nonfuel applications—roughly 2% of total production—include pharmaceutical products, disinfectants, and solvents.

Figure 1. Fuel ethanol domestic production, consumption, and exports

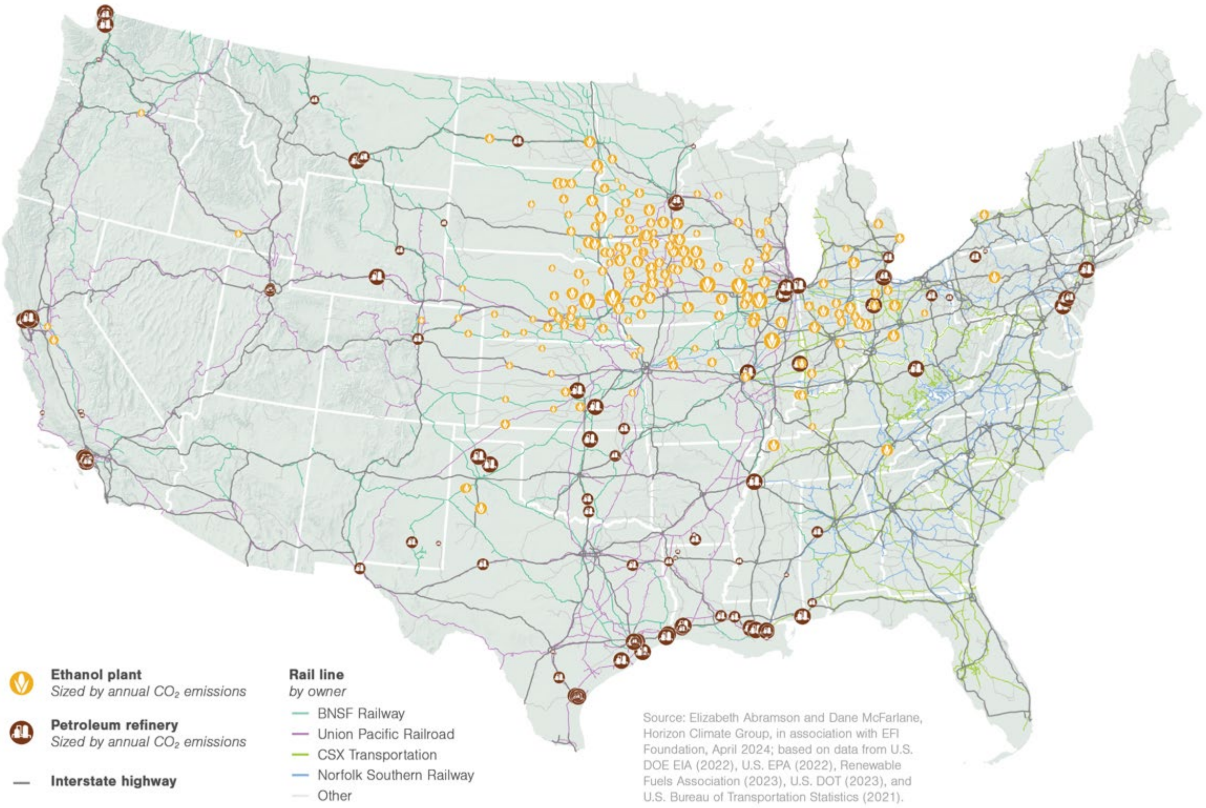


The United States became a net exporter of fuel ethanol in 2010. Data from: U.S. Energy Information Administration (2024): fuel ethanol overview and U.S. exports of fuel ethanol.

The U.S. ethanol industry concentrates in rural areas across the Midwest, where most corn farming occurs (Figure 2). Approximately 30% to 40% of the total U.S. corn crop is used to produce ethanol, which uses 13.9 million acres of land, or 1.5% of total U.S. farmland. [49, 61, 62, 63, 64]

A total of 187 biorefineries located across the Midwest Corn Belt process and distill ethanol made primarily from corn starch, which is transported by barge and rail to blending terminals.[61] There, ethanol is blended with gasoline and additives, placed on trucks, and delivered to retail stations.

Figure 2: U.S. ethanol production, transport, and blending infrastructure



Source: Elizabeth Abramson and Dane McFarlane, Horizon Climate Group, in association with EFI Foundation, April 2024; based on data from U.S. DOE EIA (2022), U.S. EPA (2022), Renewable Fuels Association (2023), U.S. DOT (2023), and U.S. Bureau of Transportation Statistics (2021).

This map highlights the distribution of ethanol plants across the U.S., with a concentration primarily in the Midwest Corn Belt region, reflecting the area's prominence in corn production. Data from: Horizon Climate Group.

Ethanol Production Coexists with Food Production

Box 1 illustrates that the increase in corn production over the past two decades has resulted from enhanced yield productivity rather than expanded land use. A similar trend is observed in other food crops. Since 2001, the U.S. food crops industry overall has maintained relatively consistent land use for planting, while yields have continued to increase, indicating that corn is not in direct competition for acreage with other food crops.[14,15,16,17,18,19,20,21,23]

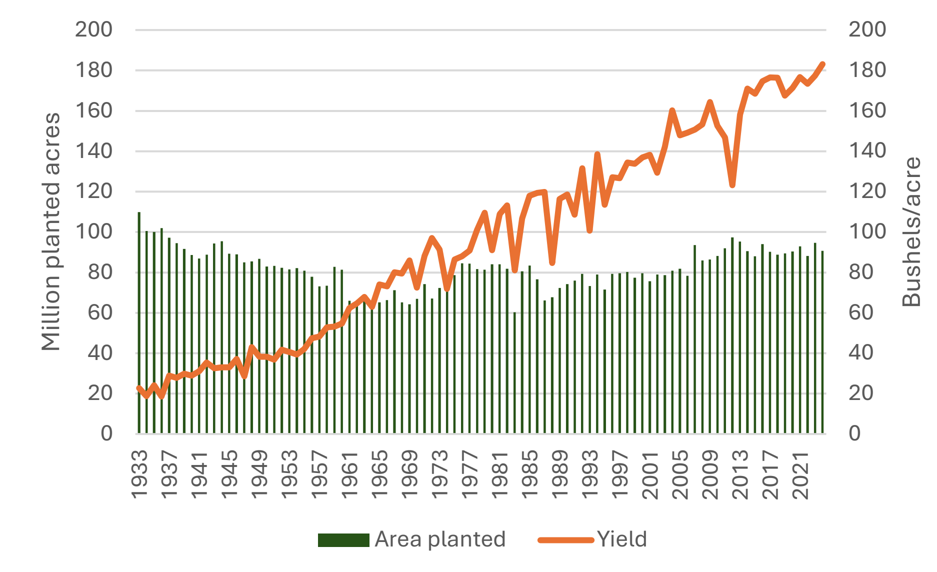
The land used for planting U.S. food crops has decreased by 2.1% from 2001 to 2024, while the yield has increased by 25.1%, showing the industry has been able to increase crop yield substantially while keeping land use relatively consistent. This indicates that increased corn ethanol production has not affected other food crops' production and land use. In addition, the byproducts of ethanol production can complement the food supply; for example, distillers grains with solubles (DGS) provide high-protein feed for livestock, minimizing the amount of additional agricultural land used to grow food for animals.

Box 1

Food crop production and yield

The U.S. corn industry has maintained a stable footprint, with land use for corn planting remaining consistent over the years. Despite this, corn yields have continued to increase (Figure 3). This demonstrates that corn production is becoming more efficient and productive with less land. This trend is not unique to corn. Other staple grains, such as barley and rice, have also seen substantial yield improvements, producing more with a relatively stable amount of land dedicated to their cultivation.

Figure 3. Corn productivity increase – U.S. corn acreage and average yield

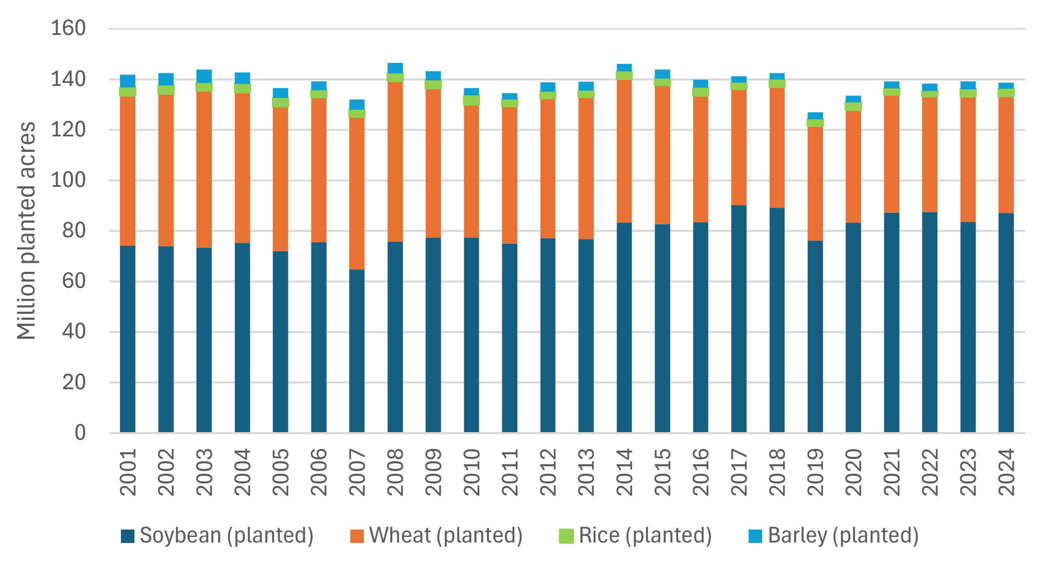


Corn yields have steadily increased over the years, despite consistent planted acres, indicating significant productivity gains in corn production. Data from: U.S. Department of Agriculture National Agricultural Service “Quick Stats”: corn acreage and corn planted.

Wheat and soybean production also is climbing. According to National Agricultural Statistics Service data from the U.S. Department of Agriculture, wheat acreage decreased by 12% from 2023 to 2024—from 49 million to 43 million acres—yet yields increased by approximately 8% (Figures 4 and 5). In contrast, soybean growers plan to expand their planted acreage to 86.5 million acres in 2024, representing a 3% increase from the previous year.[65]

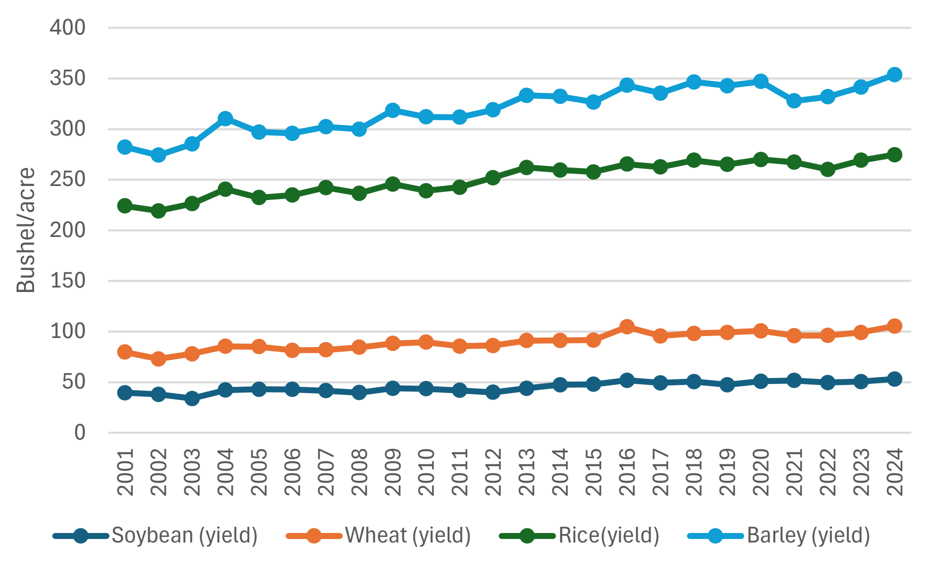
These developments indicate that corn is not in direct competition with other food crops. Land use for these crops remains relatively stable, as well as yields, which have shown a slight uptick in recent years. This suggests that the production of corn for biofuel can coexist with food crops, allowing for increased overall productivity across multiple staple grains without further encroaching on land dedicated to food production.

Figure 4: Planted acreage of staple grains



Planted acreage of staple grains like soybean, wheat, rice, and barley has remained stable over the past two decades, highlighting consistent cultivation patterns. Data from: U.S. Department of Agriculture National Agricultural Service "Quick Stats": soybean, wheat, rice, and barley.

Figure 5: Yield of staple grains



Yields of staple grains have remained steady, with a slight increase in recent years, demonstrating that increased corn productivity is not affecting food crop production. Data from: U.S. Department of Agriculture National Agricultural Service "Quick Stats": soybean, wheat, rice, and barley.

Ethanol Production and Global Market: U.S. Leads the Way in Biofuel Supply

Globally, the U.S. ethanol market is the largest in the world, responsible for producing over half the total ethanol supply.[66] Together, the United States and Brazil produce around 81% of the global supply, followed by the European Union, China, and Canada.[66] In the U.S. and globally, demand for ethanol is driven primarily by government mandates for blending ethanol with fossil-based gasoline. Brazil has the highest ethanol blending mandate among these countries, requiring gasoline to contain 27% ethanol.[67] Blending mandates in China, the EU, and Canada are 10%, less than 10%, and 5%, respectively.[68, 69, 70] The global ethanol market size was valued at $94.2 billion in 2022 and is projected to reach $153.5 billion by 2032, driven by increasing demand for renewable energy, government policies supporting biofuels, and advances in production technologies.[p]

---

[p] With a compound annual growth rate of 5.1%.

2. Ethanol's Current Carbon Footprint Is Less Than Gasoline's but Not Yet Zero

U.S. ethanol's emissions intensity has continuously decreased in the last couple of decades, primarily because of increasing corn grain and ethanol yields and decreasing energy use in ethanol production. From 2005 to 2019, corn ethanol's carbon intensity (CI) has decreased by 23%.[q, 1] Currently, the corn-to-ethanol industry produces an estimated 64.9 million metric tons per year of carbon dioxide (CO2) emissions over ethanol's life cycle, accounting for about 1% of total U.S. net CO2 emissions in 2022.

The baseline used in the assessment of decarbonization options was a reference ethanol production facility consisting of a dry mill with corn extraction facility, which represents more than 86% of ethanol production in the United States. [r, 71] The baseline CI value for this reference facility was estimated using the R&D GREET model[s] (Greenhouse gases, Regulated Emissions, and Energy use in Transportation), a tool developed by Argonne National Laboratory to evaluate the energy and environmental impacts in the energy system of various technology and fuel combinations.[71] The resulting baseline estimate of carbon intensity was 53.6 grams of CO_2 equivalent per megajoule of ethanol produced (gCO_2e/MJ) throughout the life cycle of the reference case, which includes corn farming, ethanol production, and end-use. The estimated CI aligns with the reported CI scores of existing ethanol facilities, which range from 48 to 68 gCO_2e/MJ, indicating it accurately reflects a typical ethanol production facility.[72] Figure 6 breaks down ethanol's life cycle emissions estimates from corn farming to combustion. The major components comprising the baseline carbon intensity estimate are described in further detail in the following sections.

Corn Farming Emissions

- Nitrogen fertilizer production and use (5.8 gCO_2e/MJ): Manufacturing nitrogen fertilizer is an energy-intensive process that typically relies on natural gas (more details in Chapter 3).

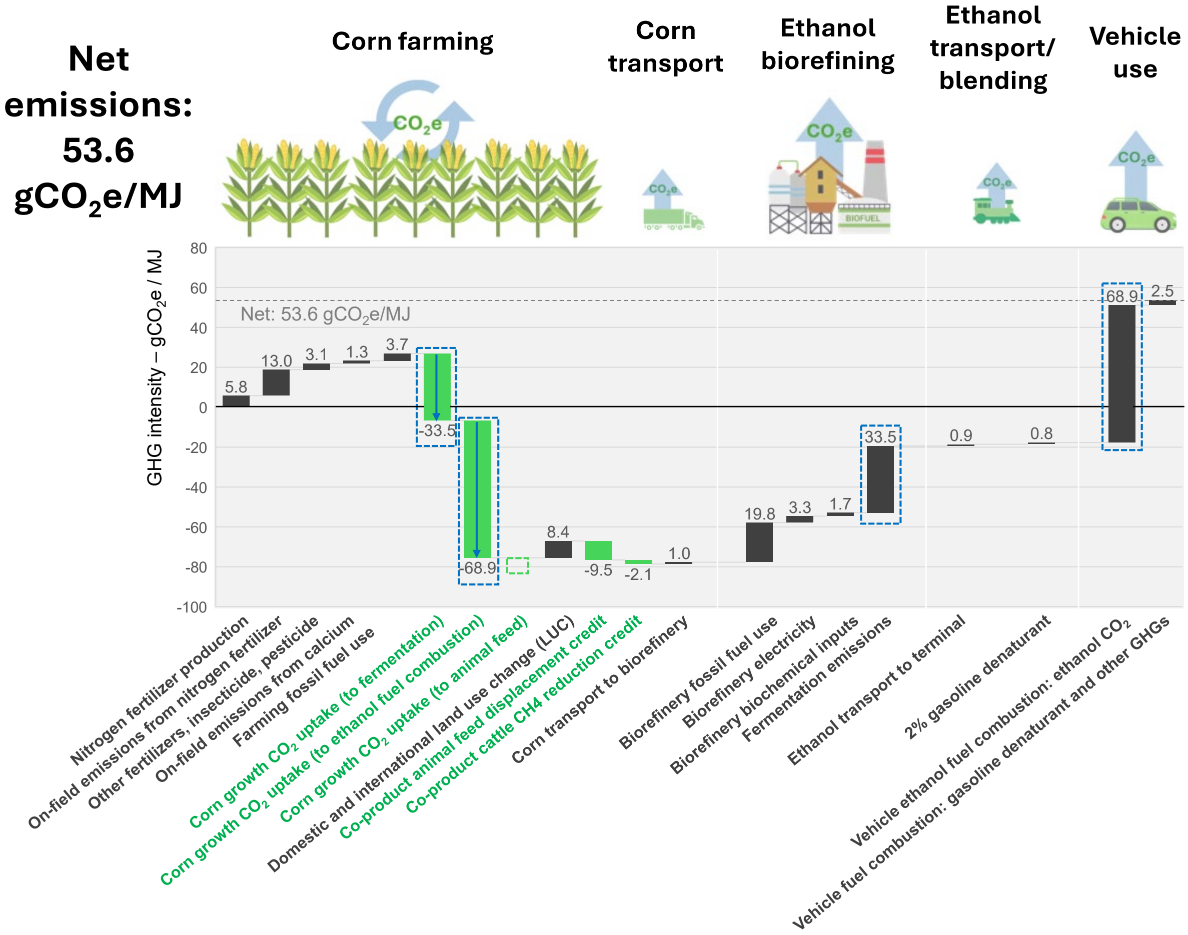
---

[q] Carbon intensity (CI) refers to the amount of carbon dioxide emitted per unit of energy or activity.

[r] The dry mill ethanol production process grinds dry corn grains instead of soaking them (wet mill). This report focuses on dry mill ethanol production because it is the most common and technically feasible production process, though it is more carbon intensive.

[s] R&D GREET is used to guide research, development, and decision-making for researchers, industry, or fuel consumers. A specific GREET model could be developed for a policy program. For example, tax credits 40B and 45V and California's Low-Carbon Fuel Standard have their own versions of GREET.

Figure 6. Components of the dry mill ethanol life cycle (emissions in gCO_2e/MJ)



Ethanol emissions in a dry mill facility (the production method most common in the U.S.) occur during corn farming, fuel production, and consumption. Emissions sources are depicted in black, and emissions sinks in green. Data from: GREET (2024); Horizon Climate Group for fermentation emissions.

- On-field emissions from nitrogen fertilizer (13 gCO_2e/MJ): Emissions from nitrous oxide released because of fertilizer application.
- Other fertilizers, insecticides, pesticides, and on-field emissions from calcium (4.4 gCO_2e/MJ): Includes emissions from the use of urea, herbicides, insecticides, and $CaCO_3$ (calcium carbonate), P_2O_5 (phosphorus pentoxide), and K_2O (potassium oxide), which are chemical compounds used in agriculture as soil amendments and fertilizers to supply essential nutrients like calcium, phosphorus, and potassium, improving soil fertility and plant growth.
- Farming fossil fuel use (3.7 gCO_2e/MJ): Includes the fuel and electricity consumed by machinery and equipment for planting, cultivating, irrigating,

harvesting, and transporting agricultural products, such as diesel used in vehicles.

- Domestic and international land use change[t] (8.4 gCO_2e/MJ): Emissions from converting land for agricultural use to produce bioenergy crops, both within the United States and globally, impacting carbon storage and biodiversity.

Corn Growth CO_2 Uptake

- To fermentation (-33.5 gCO_2e/MJ): Ethanol production fermentation emissions are considered biogenic, that is, offset during corn growth.[73] For the purpose of calculating carbon credits, we estimate that fermentation emissions are around 33.5 gCO_2e/MJ, based on 2.85 kilograms (kg) CO_2 per gallon of ethanol according to stoichiometric calculations consistent with previously published experimental data.[74]
- To ethanol fuel combustion (-68.9 gCO_2e/MJ): Ethanol combustion in internal combustion engines is also considered biogenic and offset during corn growth.
- To animal feed: The dotted green box in Figure 6 represents the total CO_2 absorbed by corn during its growth that surpasses the animal feed displacement credits outlined next.
- **Co-product animal feed displacement credit** (-9.5 gCO_2e/MJ) refers to the reduction in the need for traditional feed crops, such as corn and soybeans, when distillers grains (DGS), a byproduct of ethanol production, are used as animal feed, leading to lower overall agricultural emissions as less land and resources are required to produce these traditional feed crops, thus generating a credit.
    - **Co-product cattle CH4 reduction credit** (-2.1 gCO_2e/MJ) occurs because feeding DGS to cattle can improve their digestive efficiency, resulting in reduced methane (CH_4) emissions from enteric fermentation, which is a significant source of GHG emissions in livestock production.

---

[t] Land use change emissions methodology considers international land use change (ILUC) emissions for corn used to produce ethanol in the United States because increased corn demand can drive agricultural expansion globally, leading to deforestation, habitat loss, and carbon emissions in other countries as they convert forests or grasslands into agricultural land to meet the rising demand for bioenergy crops.

Corn Transport Emissions

- Corn transportation to the biorefinery (1 gCO_2e/MJ): Vehicle emissions from transporting corn from farms to the biorefinery.

Ethanol Biorefining Emissions

- Fossil fuel use (19.8 gCO_2e/MJ): Natural gas is the largest contributor to biorefinery emissions (91.1%), accounting for the energy used to generate process heat and steam during the ethanol production process, produce electricity through combined heat and power systems, and dry DGS.
- Electricity (3.3 gCO_2e/MJ): Emissions associated with the electricity consumed by the biorefinery.
- Biochemical inputs (1.7 gCO_2e/MJ): Emissions from the various biochemical inputs required for the biorefining process—includes enzymes, yeast, nutrients, chemicals for pH adjustment, and additives, all of which are essential for converting biomass into ethanol and other products efficiently.

Ethanol Transport and Blending Emissions

- Ethanol transport and distribution (0.9 gCO_2e /MJ): Emissions from transporting and distributing ethanol, which mostly happens by rail and road.
- 2% gasoline denaturant (0.8 gCO_2e /MJ): Emissions from the gasoline used to denature ethanol, making it unsuitable for drinking.

Vehicle Use Emissions

- Vehicle fuel combustion—gasoline denaturant and other GHGs (2.5 gCO_2e/MJ): emissions released from combusting the denaturant added to ethanol when it is burned as fuel in engines.

Ethanol’s emissions already are significantly lower than fossil fuel alternatives (e.g., gasoline and jet fuel emit around 94 gCO_2e/MJ and 89 gCO_2e/MJ, respectively). But reducing ethanol’s carbon intensity even more will increase its contribution in a future net-zero economy in which fossil fuel production and use are expected to decrease. The next chapters will discuss the methods to decarbonize ethanol and the roadmap to achieve them.

3. Assessment of Measures to Further Decarbonize the Life Cycle Carbon Intensity of Ethanol

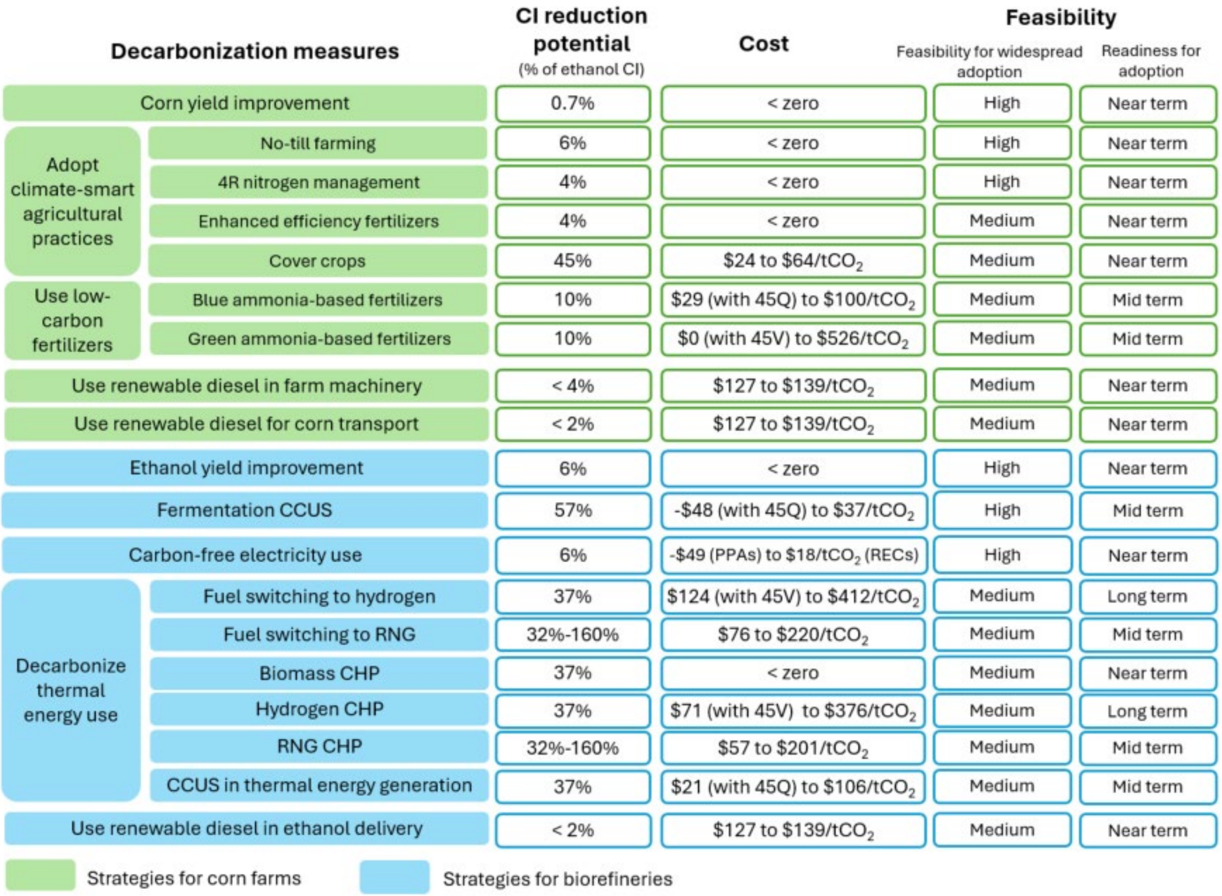
The assessment of the ethanol life cycle identified a broad range of measures that can significantly reduce ethanol's CI. The assessment incorporated four factors:

- Adoption readiness
- Feasibility for widespread adoption
- The magnitude of CI reduction potential
- Cost-effectiveness, as measured in terms of cost per ton of CO_2 removed from the life cycle baseline.

The measures examined included modifications in agricultural practices for growing corn, improvements in biorefining, use of low-carbon fuels and electricity, and carbon capture from the biorefining process. Figure 7 provides a summary of the assessment.

The magnitude of CI reductions was measured using the R&D GREET model. Each strategy's potential CI reduction is the maximum potential of a full adoption of each strategy (e.g., replacing the entire electricity used in a biorefinery with carbon-free electricity). The cost of each measure is a levelized cost of carbon abatement (LCCA), a methodology that measures how much CO_2 can be reduced by a specific technology or policy, which is the net cost of each measure divided by the CO_2 abated by adopting each strategy. Negative LCCA results from reducing energy or fertilizer inputs, selling energy back to the grid, or obtaining tax credits. The net cost was estimated based on current production costs, market prices, and existing policy incentives, not based on targets, commitment, or optimistic long-term projections (for details, see Appendix C). The market feasibility was evaluated by reviewing publicly available data and literature on technological and economic feasibility and the barriers to adoption.

Figure 7. Assessment of ethanol decarbonization measures



Decarbonization measures		CI reduction potential (% of ethanol CI)	Cost	Feasibility	
				Feasibility for widespread adoption	Readiness for adoption
Corn yield improvement		0.7%	< zero	High	Near term
Adopt climate-smart agricultural practices	No-till farming	6%	< zero	High	Near term
	4R nitrogen management	4%	< zero	High	Near term
	Enhanced efficiency fertilizers	4%	< zero	Medium	Near term
	Cover crops	45%	\$24 to \$64/tCO_2	Medium	Near term
Use low-carbon fertilizers	Blue ammonia-based fertilizers	10%	\$29 (with 45Q) to \$100/tCO_2	Medium	Mid term
	Green ammonia-based fertilizers	10%	\$0 (with 45V) to \$526/tCO_2	Medium	Mid term
Use renewable diesel in farm machinery		< 4%	\$127 to \$139/tCO_2	Medium	Near term
Use renewable diesel for corn transport		< 2%	\$127 to \$139/tCO_2	Medium	Near term
Ethanol yield improvement		6%	< zero	High	Near term
Fermentation CCUS		57%	-\$48 (with 45Q) to \$37/tCO_2	High	Mid term
Carbon-free electricity use		6%	-\$49 (PPAs) to \$18/tCO_2 (RECs)	High	Near term
Decarbonize thermal energy use	Fuel switching to hydrogen	37%	\$124 (with 45V) to \$412/tCO_2	Medium	Long term
	Fuel switching to RNG	32%-160%	\$76 to \$220/tCO_2	Medium	Mid term
	Biomass CHP	37%	< zero	Medium	Near term
	Hydrogen CHP	37%	\$71 (with 45V) to \$376/tCO_2	Medium	Long term
	RNG CHP	32%-160%	\$57 to \$201/tCO_2	Medium	Mid term
	CCUS in thermal energy generation	37%	\$21 (with 45Q) to \$106/tCO_2	Medium	Mid term
Use renewable diesel in ethanol delivery		< 2%	\$127 to \$139/tCO_2	Medium	Near term

🟩 Strategies for corn farms 🟦 Strategies for biorefineries

The CI reduction potential represents the proportion of expected carbon intensity reduction relative to the baseline carbon intensity of ethanol, 53.6gCO_2e/MJ. It is the maximum potential for full adoption of each measure, estimated using the GREET model. The cost is a levelized cost of carbon abatement (LCCA), relative to the cost of the business-as-usual alternative. It is calculated by dividing cost by CO_2 abated. Negative LCCA results from reducing energy or fertilizer inputs, selling energy back to the grid, or obtaining tax credits. The market feasibility was evaluated by reviewing publicly available data and literature on technological and economic feasibility and the barriers to adoption. In the context of readiness for adoption, 'near-term' refers to the measures that can be adopted immediately or within a few years, 'mid-term' refers to those likely to be adopted by 2035, and 'long-term' refers to those expected to be adopted after 2035.

4R – right source, time, rate, and place; blue ammonia – produced with capturing and sequestrating CO_2 from hydrogen production; green ammonia – produced with renewable energy for hydrogen production (note that hydrogen is a primary feedstock for making either blue or green ammonia); CCUS – carbon capture, utilization, and storage; RNG – renewable natural gas; CHP – combined heat and power; PPAs – power purchase agreements; RECs – renewable energy certificates; 45Q – tax credit for carbon oxide sequestration; 45V – clean hydrogen production tax credit. Source: EFI Foundation analysis.

In the figure, the various decarbonization measures are organized by the various stages in the ethanol production life cycle, with items in green consisting of measures that could be implemented on the farm and items in blue consisting of measures that could be implemented at the biorefinery.

As shown in the figure, the measures providing the largest reductions, in terms of the magnitude of CI reduction potential, include:

- Carbon capture, utilization, and storage (CCUS) in the fermentation process[u]
- Replacing the use of natural gas for process heat with low-carbon fuels such as renewable natural gas (RNG)
- Planting cover crops in corn farms in intervals between regular corn crops.

These three measures alone could result in an estimated reduction of up to 140 gCO_2e/MJ, resulting in a net-negative CI score.

The mix of options changes when other factors are considered, such as cost-effectiveness and feasibility for adoption. Widespread adoption of RNG is restricted by high costs, limited supply and competition with other uses. Even if all available U.S. RNG is dedicated to the ethanol industry, it could replace only 76% of the industry's natural gas use.[75]

Options that are ready for widespread adoption at a relatively low cost per ton of CO_2 removed (less than $18 per ton reduced) can reduce overall CI by 14 gCO_2e/MJ (26% reduction from the current baseline) and include:

- Purchasing carbon-free electricity in the biorefinery
- Continuously improving ethanol yield
- Procuring corn from farms continuously improving corn yield
- Employing no-till farming
- Using enhanced efficiency fertilizers (EEFs)
- Adopting 4R (right source, right time, right rate, and right place) nitrogen management practices

Introducing a combined heat and power (CHP) system running on biomass, such as residual agricultural wastes like corn stover also can be a cost-efficient option for the long term because of the low cost of biomass and increased energy efficiency.

Assessing Measures to Decarbonize Biorefineries

Ethanol Yield Improvement

A 10% ethanol yield improvement could reduce CI by 3.2 gCO_2/MJ, or 6%. Over the years, ethanol yield has shown significant improvement, driven by advancements in

---

[u] CO_2 utilization is considered with CO_2 sequestration as the technologies converting captured CO_2 into products are under development.

conversion efficiency at ethanol facilities. Ethanol yield increased to 2.95 gallons per bushel of corn in 2023 from 2.83 gallons per bushel in 2015, representing a 4% increase in eight years.[76] Modern ethanol facilities achieve higher yields through enhanced energy efficiency and improved fermentation processes, resulting in greater output and reduced input costs. As facilities continue optimizing their processes, the economic incentives remain strong for further improvements in energy use and fermentation efficiency, ultimately supporting higher ethanol yields. A study suggested that the maximum theoretical ethanol yield could reach 3.17 gallons per bushel by increasing the starch content of corns.[77]

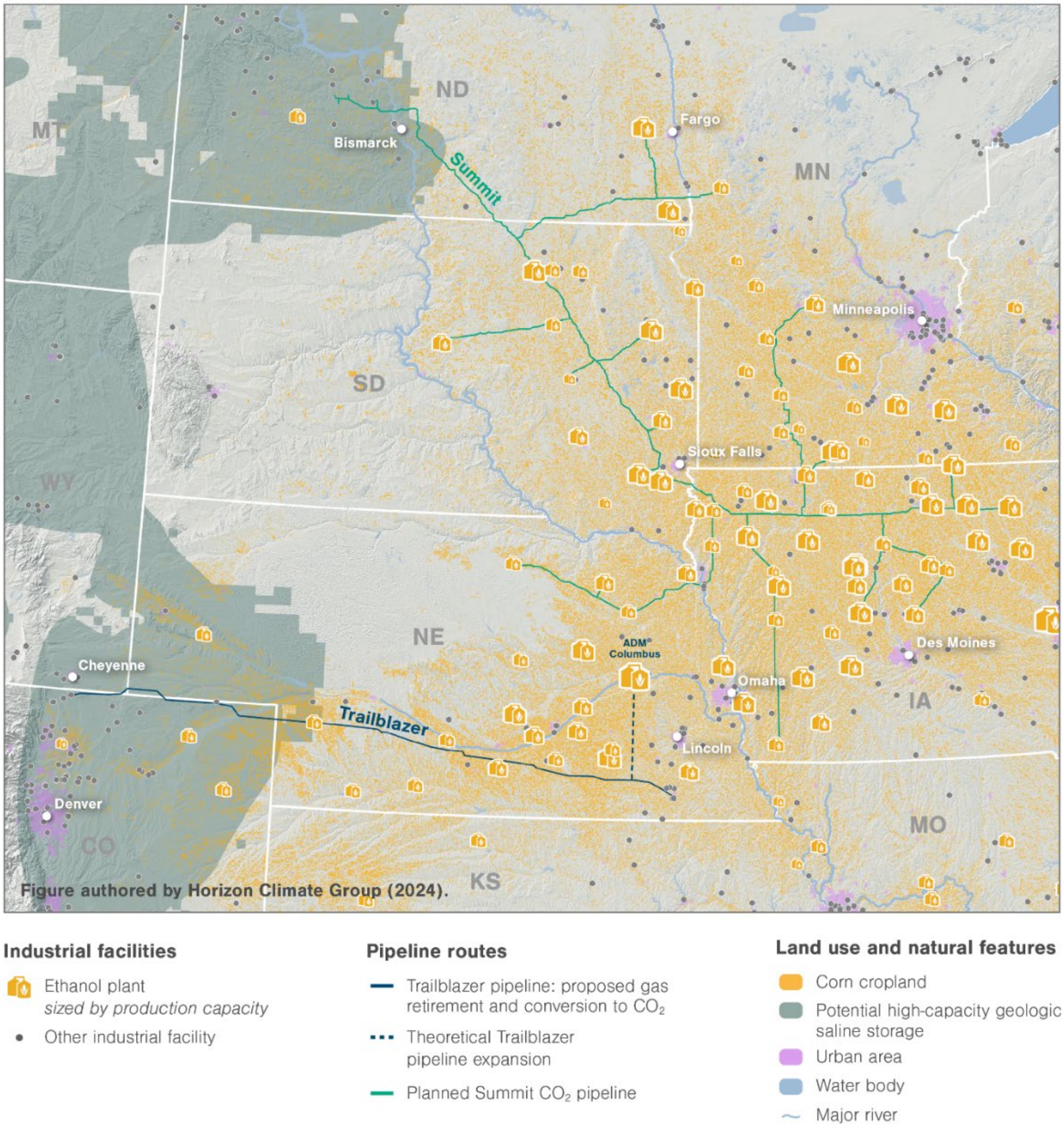
The GREET model currently uses a facility yield of 2.81 gallons of ethanol per bushel of corn. However, as mentioned above, recent data suggests that this figure could be updated to reflect a more accurate yield of 2.95 gallons per bushel.[76] Looking ahead to 2035 and 2050, it is reasonable to project further increases in ethanol yield as technology and processes advance. However, ethanol yield improvement will reach a ceiling, considering the potential for diminished returns as efficiencies approach their theoretical limits.

Fermentation CCUS

Carbon capture, utilization, and storage for ethanol's fermentation emissions could decrease ethanol's CI by 30.5 gCO_2e/MJ, or 57%. CCUS in ethanol plants has great potential to scale because capture costs are relatively low because of the high purity of CO_2 generated from ethanol fermentation. The cost of CCUS for ethanol fermentation emissions is estimated to be \$37 per ton of CO_2 (tCO_2), which is lower than the amount offered by the 45Q carbon sequestration tax credits of \$85/tCO_2. In recent years, ethanol producers have been actively developing CCUS projects. As of 2023, four CCUS projects of 1.78 million metric tons per annum of CO_2 (Mtpa CO_2) in total capacity are in operation, 39 projects of 11 Mtpa CO_2 in total capacity are in advanced development, and 22 projects of 6 Mtpa CO_2 in total capacity are in early development in ethanol plants.[78] In sum, CCUS projects in development represent 18.78 Mtpa CO_2 carbon storage capacity compared to the corn-to-ethanol industry's emissions of around 64.9 Mtpa CO_2.

Although capturing CO_2 emissions is relatively straightforward in ethanol plants, transportation and sequestration of CO_2 are challenging. As shown in Figure 8, most ethanol plants are located in areas unsuitable for geologic sequestration of CO_2, so the captured CO_2 must be transported out of state to appropriate geological sites, which requires building interstate pipelines.

Figure 8. Ethanol plants and saline CO_2 storage



Most ethanol plants in the Midwest require pipelines to transport captured CO_2 to storage sites. The map shows the proposed Trailblazer pipeline from Tallgrass Energy and the planned Summit Carbon Solutions pipeline within the region. Source: Horizon Climate Group.

The uncertainties surrounding pipeline permitting have been the most significant barrier to scaling up CO_2 transportation and sequestration infrastructure. Interstate CO_2 pipeline developers encounter varying regulations, as state governments are responsible for permitting CO_2 pipeline siting. Each state has different regulations for CO_2 pipelines, and some states lack clear regulations altogether.[79] Obtaining permits for geologic sequestration is particularly challenging as the timeline to obtain Underground Injection Class (UIC) VI permits from the U.S. Environmental Protection Agency to inject CO_2 in geologic reservoirs has been lengthy and uncertain.[79] Although the EPA aims to complete permit reviews within two years, approval typically takes three to six years. The EPA cited staff shortages as a principal reason for permitting delay.

The recent cancellation of a CO_2 pipeline project—Navigator CO_2 Ventures' Heartland Greenway —highlights the regulatory challenges. In October 2023, Navigator announced the cancellation of its CO_2 pipeline project, which was supposed to capture up to 15 million metric tons of CO_2 per year from more than 30 Midwest ethanol plants and transport it to Illinois via pipeline. The month before, the South Dakota Public Utilities Commission denied Navigator construction permits. Navigator cited the reason for cancelation as "the unpredictable nature of the regulatory and government processes."[80]

Despite regulatory challenges, several CO_2 pipeline projects are still going. In partnership with 57 ethanol plants in multiple states, Summit Carbon Solutions has been developing a multi-state CO_2 pipeline project, including Iowa, Minnesota, North Dakota, South Dakota, and Nebraska. CO_2 storage will take place in North Dakota.[81] This multibillion-dollar project was enabled by the investments of many companies, including John Deere, Continental Resources, and ethanol producers, and by the commitment of ethanol producers to use the pipeline infrastructure. Having commercial contracts with ethanol producers helps CO_2 transport and sequestration infrastructure projects secure sufficient financing.

Tallgrass Energy is also advancing a project to convert its Trailblazer natural gas pipelines to CO_2 pipelines, transporting CO_2 captured in Nebraska and Colorado to a sequestration site in Wyoming. The project was granted a permit from the Federal Energy Regulatory Commission (FERC) in October 2023 and signed a community benefits agreement with Bold Alliance, a local group working on eminent domain issues, clean energy, and water.[82]

Carbon-Free Electricity

Using carbon-free electricity in a biorefinery enables a CI reduction of up to 3.3 gCO_2e/MJ, or 9%. Currently, the U.S. electricity generation emits 0.39 tCO_2 per megawatt-hour (MWh).[83] Biorefineries can reduce the emissions from their electricity use by obtaining electricity from carbon-free alternatives, such as wind, solar, or nuclear energy. One option is for biorefineries to work with their current utilities to encourage them to accelerate their efforts to transition to carbon-free electricity. Other options include seeking direct power-purchase agreements (PPAs) with suppliers, purchasing renewable energy certificates (RECs), and installing on-site electric generation facilities.

Current market data indicate that seeking direct PPAs with independent power producers, where available, may be the lowest-cost option for a biorefinery to obtain carbon-free electricity. In 2022, for example, the average prices for electricity via PPAs were \$26/MWh for wind power, and \$35/MWh for solar power in the Central region, which is much lower than the wholesale electricity price in the MISO region of \$75/MWh in 2022 and \$45/MWh in 2023.[v, 84, 85, 86]

Purchasing RECs is a higher-cost option than PPAs to secure carbon-free electricity. Although the average REC price has been low much of the last decade—around \$1/MWh—in 2021, it reached almost \$7/MWh.[87] Only Installing on-site electric generation facilities is estimated to be the most expensive option to secure carbon-free electricity since it requires upfront investment. Combined heat and power systems, as described further in the section below, are more cost effective.

For purposes of this analysis, the LCCA of using carbon-free electricity is estimated to range from -\$48/tCO$_2$ to \$18/tCO$_2$. The option of entering into PPAs brings cost savings since the electricity price via PPAs is estimated to be lower than the wholesale electricity price. The option of purchasing RECs ranges from \$3/tCO$_2$ to \$18/tCO$_2$ depending on the price of RECs.

Current efforts by industry to move toward an administration goal of 100% carbon-free electricity by 2035 has the potential to help biorefineries increase their use of carbon-free electricity as it drives decarbonizing the U.S. electric grid. With a fully decarbonized electric grid, biorefineries would not need to pursue PPAs, RECs, or on-site generation facilities to decarbonize.

Decarbonize Thermal Energy Use in Biorefineries

Thermal energy use in biorefineries is the source of 19.8 gCO$_2$e/MJ of emissions or 37% of ethanol's total emissions. Decarbonizing thermal energy use is challenging as the existing options—combined heat and power (CHP) with biomass, RNG, hydrogen, and CCUS in heat generation—cost more than natural gas, require upfront investment, or are in the early phases of market development.

- *Combined heat and power (CHP) with biomass*: CHP with biomass is estimated to be the lowest-cost option to decarbonize thermal energy in biorefineries. The LCCA of biomass CHP ranges from -\$38/tCO$_2$ to -\$1/tCO$_2$ depending on the cost of biomass. The negative cost comes from saving energy costs as CHP generates electricity as well. With the CHP capacity meeting the entire heat demand in a biorefinery, the generated electricity may exceed the biorefinery's electricity demand in the biorefinery; thus, the excess electricity needs to be sold

---

[v] The Central region encompasses MISO, SPP, and ERCOT, where most biorefineries in the U.S. are located. MISO (Midcontinent Independent System Operator) is the largest regional transmission organization (RTO) stretching across Arkansas, Illinois, Indiana, Iowa, Kentucky, Louisiana, Michigan, Minnesota, Mississippi, Missouri, Montana, North Dakota, South Dakota, Texas, Wisconsin, and the Canadian province of Manitoba. SPP (Southwest Power Pool) manages the electricity grid across Arkansas, Iowa, Kansas, Louisiana, Minnesota, Missouri, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming. ERCOT (Electric Reliability Council of Texas) operates Texas' electrical grid.

to the grid, generating additional revenue. To do so, may require overcoming additional regulatory and permitting hurdles to gain grid access.

Currently, about 20% of the existing 187 U.S. ethanol plants already have CHP systems.[88] Although most of the systems use natural gas, biomass can be mixed with natural gas in many CHP boiler systems at biorefineries. Corn stover appears to be an attractive option to provide biomass fuel[89] for CHP systems because it is relatively low-cost and readily accessible. However, the choice of using corn stover as a fuel for CHP needs would require a substitute for corn stover currently being used for soil conservation and other uses.

- *Blue and green hydrogen*: The LCCA of replacing natural gas with blue hydrogen is estimated to be \$158/tCO$_2$, and it can be lowered to \$124/tCO$_2$ with 45Q carbon sequestration tax credits. Green hydrogen is more expensive, ranging from \$184/tCO$_2$ with the 45V tax credit for clean hydrogen production to \$412/tCO$_2$ without 45V. If the DOE goal to reduce the cost of clean hydrogen to \$1 per kilogram of hydrogen can be achieved, the cost could be lowered to \$46/tCO$_2$. With existing technology, it is estimated that hydrogen can be blended with natural gas only up to 20% without significant upgrades to the thermal energy system.[90] Moreover, existing natural gas infrastructure is not readily compatible with hydrogen, requiring modifications to pipelines and storage facilities.[91] Therefore, using hydrogen for heat generation can be considered a mid- or long-term solution.
- *Renewable natural gas*: Switching from natural gas to RNG can reduce ethanol's CI by 17 to 86 gCO$_2$e/MJ. The LCCA of this option ranges from \$76/tCO$_2$ to \$220/tCO$_2$ depending on the sources of RNG. In the Midwest, where most biorefineries are located, both agricultural and landfill biogas resources are abundant but currently largely untapped for RNG production.[92] Livestock biogas-producing facilities in the Midwest are already equipped with anaerobic digestors although they are not optimized for RNG production. While there is potential to significantly increase RNG production, it is estimated that its full potential will provide only limited displacement of natural gas in biorefining. The full potential of biogas resources in the United States is estimated to be 351 billion cubic feet (Bcf) per year, which is equivalent to 1.1% of the U.S. natural gas consumption in 2023 of 32 trillion cubic feet. If all available U.S. RNG is used for the ethanol industry, it could replace 76% of the natural gas use in the industry.[93] There is, however, rising demand for RNG to decarbonize a range of hard-to-abate end uses, such as heating and industrial uses.
- *CCUS in thermal energy generation*: Discussions on capturing CO$_2$ from the thermal energy generation in biorefineries have been emerging since CCUS in the fermentation process became a promising option. As CO$_2$ transport and sequestration infrastructure is built for fermentation CCUS, adding a carbon capture facility in biorefineries would eliminate the need for additional transport and sequestration investment. However, the economic viability of this option is uncertain as robust techno-economic studies are lacking. The LCCA is estimated

to be around \$94/tCO$_2$ to \$118/tCO$_2$, similar to the cost of CCUS in combined cycle gas turbine plants. Thus, it would command a premium above the current 45Q credit of \$85/tCO$_2$.

Assessing Measures to Decarbonize Corn Farming

Climate-Smart Agricultural Practices

Adopting climate-smart agricultural (CSA) practices in corn farming has the potential to reduce ethanol's CI score by 31.4 gCO$_2$e/MJ, or 56%. Climate-smart agriculture is a way to build resilience in farming operations, benefiting both farmers and ranchers and the environment. The goals of CSA are to:

- Increase or maintain productivity and yield
- Enhance resilience to environmental changes
- Reduce GHG emissions[94]

CSA practices include many techniques already used by farmers, such as cover cropping, reduced tillage, and nutrient management. The USDA's Natural Resources Conservation Service (NRCS) released a list of 55 climate-smart agriculture and forestry (CSAF) practices eligible for Inflation Reduction Act (IRA) funding for conservation programs in fiscal year 2024. These practices are divided into nine mitigation categories:

- Soil health: reducing emissions and enhancing soil carbon sequestration.
- Nitrogen management: improving nitrogen management to reduce nitrous oxide, a potent greenhouse gas.
- Livestock partnership: reducing potent methane emissions from manure.
- Grazing and pasture: reducing emissions and building soil carbon stocks in grazing systems.
- Agroforestry, forestry and wildlife habitat: building carbon stocks in perennial biomass and soils.
- Restoration of disturbed lands: improving the quality of previously mined or degraded lands to increase soil and perennial biomass carbon stocks.
- Energy, combustion and electricity efficiency: reducing emissions from agricultural operations and infrastructure through energy and fuel efficiency and system and operational improvements.
- Wetlands: restoring wetlands to enhance carbon storage in soils and vegetation.

- Rice: reducing methane emissions from rice fields through irrigation water management.[95]

The IRS guidance for the 40B sustainable aviation fuel (SAF) production tax credit, released in April 2024, identified three farming practices as a requisite bundle of CSA practices for alcohol-to-jet (ATJ) ethanol production to be eligible for a credit of 10 gCO_2e/MJ of emissions reduction that can be used to help qualify for the credit. The requisite bundle of practices include no-till farming, planting cover crops, and applying enhanced efficiency fertilizers (EEFs). The GREET model includes a fourth farming practice–manure application—that is not eligible for purposes of qualifying for the credit. Precision agriculture—a suite of technologies enabling precise application of water, fertilizer, and feed—also helps minimize GHG emissions, but they also are not eligible for the credit.

The 40B tax credit will be replaced with the 45Z tax credit for clean fuel production at the end of this year, and as such there has been a growing interest in how the full suite of CSA practices will be incorporated into the eligibility determination for the new credit in the upcoming 45Z guidance. Stakeholders have raised concerns about prescriptive and all-or-nothing approaches on CSA practices and have suggested a more flexible approach. The IRS announced that it will do further work on modeling, data, assumptions, and verification to credit CSA practices in the 45Z.[96]

The rate of adoption rates of CSA practices has been low. No-till farming was used on 38% of U.S. cropland as of 2022, increasing only slightly from 35% in 2012.[42] The adoption rate of cover cropping in the Midwest reached only 7.2% in 2021, even after a rapid increase from 1.8% in 2011.[43] Precision agriculture practices were adopted by 27% of U.S. farms or ranches in 2023.[44]

Adopting CSA practices is not always economically viable. Farmers need to make upfront investments, such as purchasing special equipment, which do not necessarily result in increased productivity. No-till farming, 4R (right source, right rate, right time, and right place) nitrogen management and applying EEFs are expected to be paid off by saving fuels, fertilizers, or labor. However, the LCCA of planting cover crops is estimated to be $44/$tCO_2$ on average, ranging from $24 to $64/$tCO_2$.[97, 98]

Two kinds of support have helped farmers fill the cost gap to adopt CSA practices: direct support from the federal and state governments (e.g., grants, cost-sharing programs) and voluntary purchases of carbon offsets. The USDA's financial assistance for conservation practices has helped implement CSA practices. Still, many farmers have not been able to benefit from the assistance because the USDA conservation programs have been popular and oversubscribed.[99] Selling carbon offsets to voluntary markets helps fill the cost gap, but offset prices are not high enough to cover the cost in many cases. For example, carbon credit prices in voluntary markets, estimated to be $10 to $28/acre based on California carbon prices in 2022, do not exceed the cost estimate of cover crops, which was around $35 to $45/acre per year in the Midwest in 2017.[100]

Another barrier to adopting CSA practices is the lack of a robust measuring, monitoring, reporting, and verification (MMRV) framework. Existing GHG emissions estimates and modeling of agricultural practices are not keeping pace with current on-farm conditions and advances in best practices.[101] The challenge of providing accurate, up-to-date estimates of GHG emissions reductions from adopting CSA practices discourages investment.

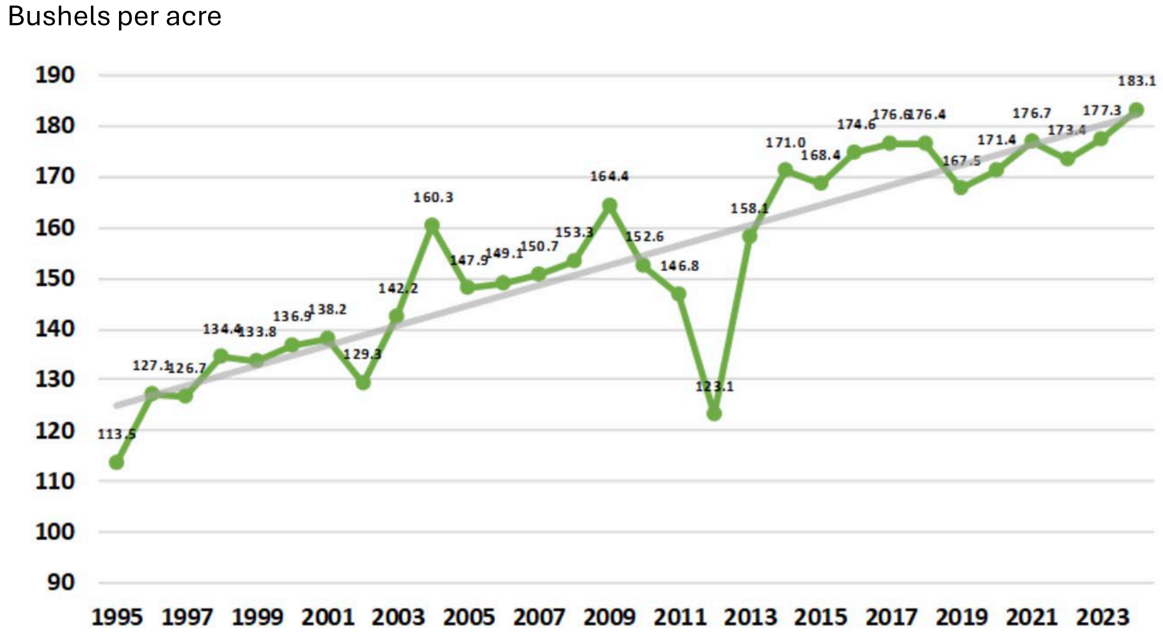
More importantly, because of the lack of such an MMRV framework, the current guidance for the 40B SAF credit may underestimate the actual impact of CSA practices on carbon intensity. The IRS 40B guidance included the “limitations of currently available verification mechanisms, empirical data, and modeling” as the principal rationale for bundling CSA practices under a single default value. The CI reduction value of the bundle of three CSA practices is 10 gCO_2e/MJ in the 40B tax credit guidance. Analysis of the individual measure suggests that the actual CI reduction of these practices could total 29 gCO_2e/MJ.

Corn Yield Improvement

Improving corn yield by 10% reduces the ethanol CI by 0.4 gCO_2e/MJ. Although the CI reduction value is relatively low, it can be achieved at little or no incremental cost relative to what will otherwise occur in the market.

Corn yield in the United States has seen remarkable improvements over the years, driven by advancements in agricultural practices, technology, and crop genetics.[102] According to the USDA, corn yield has consistently increased in the last few decades, from 113.5 bushels per acre in 1995 to 183.1 bushels per acre in 2023, reflecting the efficiency and productivity gains in U.S. agriculture (Figure 9).[103] Enhanced farming techniques, better pest and disease management, and adoption of genetically modified crops have all contributed to this upward trend. As a result, the ability to produce more corn per acre has not only bolstered the agricultural sector but also supported the ethanol industry's growth by providing a more abundant and reliable feedstock.

Figure 9. Corn yield in the United States, 1994-2023



The increase in corn yield from 113.5 bushels per acre in 1995 to 183.1 in 2023 demonstrates improved corn production efficiency.
Source: USDA, “Corn Yield: United States,” August 12, 2024,
https://www.nass.usda.gov/Charts_and_Maps/Field_Crops/cornyld.php

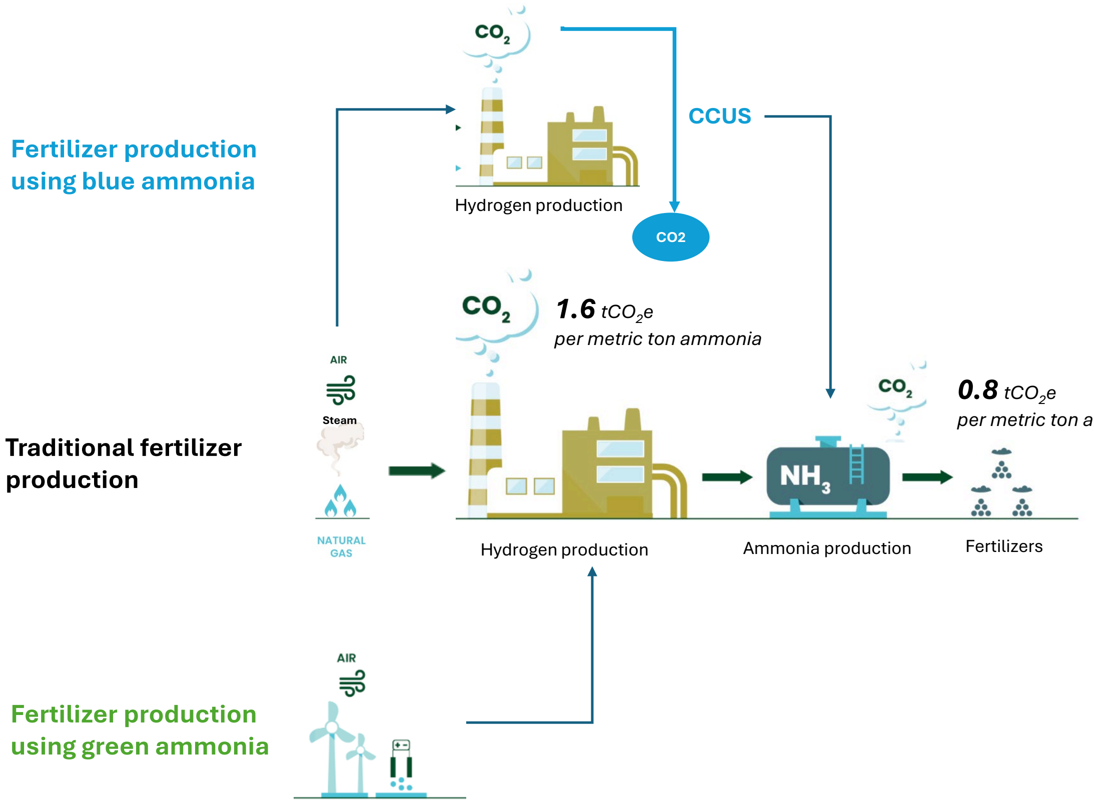
Increasing corn yield helps reduce the CI of ethanol production by improving land and resource efficiency. Higher yields mean more corn can be produced on the same land, reducing the need for agricultural expansion and minimizing emissions from land-use change. Additionally, fewer inputs such as fertilizers and water are required per unit of corn, lowering the overall carbon footprint of farming.

Low-Carbon Fertilizers

Decarbonizing fertilizer production using green or blue ammonia could reduce ethanol’s CI by 5.3 gCO_2e/MJ, or 10%. Current production of nitrogen fertilizers is carbon-intensive and relies heavily on fossil fuels.[104] Most CO_2 emissions in fertilizer production come from ammonia production, the key component of nitrogen fertilizers. Thus, decarbonizing fertilizer production requires decarbonizing ammonia production.

Fertilizer production involves several steps (Figure 10). It begins with the production of hydrogen, which is typically derived from natural gas through steam methane reforming (SMR). The hydrogen is combined with nitrogen gas from the air under high pressure and temperature to synthesize ammonia. In the conventional production process, the GHG emissions from hydrogen production is 1.6 tCO_2e per metric ton of ammonia, and the emissions from ammonia production is 0.8 tCO_2e per metric ton of ammonia.[105]

Figure 10. Fertilizer Production Process



Traditional fertilizer production starts with hydrogen production from natural gas through steam methane reforming. The hydrogen is combined with nitrogen to produce ammonia, serving as a key component of various fertilizers. Adapted from Fertilizers Europe, “Decarbonizing Fertilizers and Food,” https://www.fertilizerseurope.com/decarbonising-fertilizers-by-2050/ using data from Xinyu Liu et al., "Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products," Green Chemistry 22, no. 17 (2020): 5751-5761. https://pubs.rsc.org/en/content/articlelanding/2020/gc/d0gc02301a

Replacing natural gas with renewable energy for hydrogen production (i.e., green ammonia) or capturing and sequestrating CO_2 from hydrogen production (i.e., blue ammonia) are among the most advanced strategies to decarbonize ammonia production. Although the costs of green and blue ammonia are currently higher than gray ammonia produced from natural gas without carbon capture and storage (CCS), with the existing incentives, low-carbon ammonia could become cost competitive with gray ammonia in some U.S. regions.[106] Existing incentives include the carbon sequestration tax credit (45Q), hydrogen production tax credit (45V), clean electricity production tax credit (45Y), and clean electricity investment tax credit (45E). Moreover, projections of declining equipment and renewable energy costs could make green ammonia cheaper than gray ammonia in the United States by 2040.[107] The LCCA of blue ammonia is estimated to be \$100/tCO_2, but with the 45Q tax credit, the LCCA could be reduced to \$29/tCO_2. The LCCA of green ammonia would be \$526/tCO_2, but with all policy incentives, it could reach almost zero.

Supply is the challenge. Announced low-carbon ammonia projects set to be built by 2035 could decarbonize most of the current ammonia demand, which is 187 million tons per year; however, these announced projects have yet to reach final investment decision (FID) because of a lack of secured offtake contracts and financing.[107] Of the 185 low-carbon ammonia projects, only 45 have offtake agreements, and only 15 are under construction or have secured financing. The lack of clarity over the value of the 45V tax credit for clean hydrogen feedstock for ammonia has created significant uncertainty, and farmers are unwilling to pay a significant premium for green fertilizers.[107]

Replace Diesel with Renewable Diesel in Farm Machinery

On-farm energy use accounts for 3.7 gCO_2e/MJ of ethanol's CI. Corn farms could decarbonize energy use by replacing fossil fuels with lower-carbon fuels and using lower-carbon electricity. Replacing fossil fuels with lower-carbon options could significantly reduce emissions since diesel and gasoline account for 13% and 5% of the energy inputs in corn production, respectively.[108] However, as electricity accounts for less than 1% of energy inputs in corn production, using lower-carbon electricity will not contribute greatly to emissions reduction.[108]

Currently, diesel is the dominant fuel in trucks, tractors, and other agricultural equipment used in farm operations. In 2021, diesel accounted for more than 60% of fuel expenditure in U.S. farms, followed by gasoline (20%), and liquefied petroleum gas (8%).[109]

Electrification of farm vehicles and equipment and using low-carbon biofuels have been explored to minimize diesel use in farm operations. Electrification of farm machinery and equipment could reduce their emissions by 65% to 90% of the farm machinery and equipment emissions.[110] However, the high capital cost to switch to electrified equipment, the electric infrastructure limitation in rural areas, and the reluctance of farmers to bear technology risk for vehicle lifespan and charging times are barriers to electrifying farm machinery.[109] As of early 2022, the sales of electric tractors were only 0.02% of the total U.S. tractor sales.[111]

Renewable diesel can be used as a direct replacement for conventional diesel in existing combustion engines without engine modification; however, renewable diesel is a costly option for decarbonization. The price of renewable diesel as of April 2024 was $5.36/gallon, while the price of conventional diesel in the Midwest was $3.95/gallon.[112, 113] This difference in price makes the LCCA of renewable diesel $138/$tCO_2$, which is higher than the costs of many other ethanol decarbonization strategies analyzed above. Moreover, the limited potential supply of renewable diesel will restrict its widespread use in farm machinery. According to the U.S. Energy Information Administration (EIA), the projected total renewable diesel market share could increase to 6% of current diesel fuel demand by 2035 and 8% by 2050 in the United States.[114] Given the expected competition for renewable diesel with other users, replacing conventional diesel with renewable diesel on farms will be very challenging.

Renewable diesel also can be used for transportation of both corn and ethanol. Doing so reduces the ethanol CI by up to 2 gCO_2e/MJ, a less than 4% reduction of the total ethanol CI.

Other Options for Further Innovation

Several options were excluded from the assessment because they would be difficult to apply widely in the ethanol industry without further innovation. While immediate integration of these options is constrained by technological, economic, or logistical challenges, further innovation could enable these solutions to help the industry's deep-decarbonization efforts.

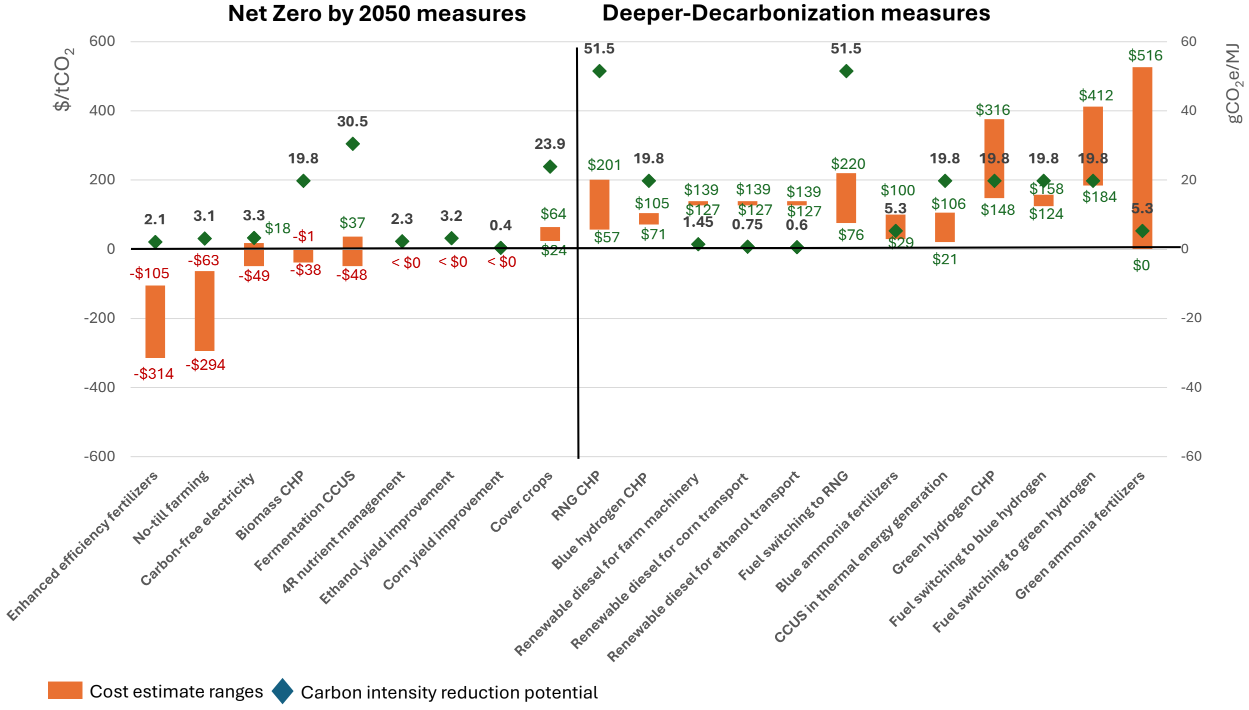
- *Increasing wet DGS production*: Shifting from dried DGS to wet DGS could significantly reduce ethanol CI by saving the energy used to dry the grains at each facility. However, currently wet DGS production is limited in serving the entire DGS demand because of transportation and storage challenges. For this option to play a more prominent role in reducing CI, innovations in storage and transport technologies or local demand creation are needed.
- *1.5-generation ethanol biorefining technology*: 1.5-generation ethanol technology allows existing ethanol facilities to add corn kernel fiber to ethanol production, improving ethanol yield and reducing CI. At the same time, however, adding fiber requires additional energy inputs and reduce DGS production, leading to lower DGS displacement credits and heating energy demand to dry DGS. With these factors offsetting each other, the use of 3.5% of corn stover is estimated to reduce 0.6 gCO_2/MJ, or 1.1% of total ethanol CI. This technology has not been scaled up because of multiple barriers, including high production costs, policy uncertainty, and the competition with petroleum fuels.[115]
- *Integrated corn and corn stover ethanol production*: Integrating corn ethanol and corn stover ethanol processes can reduce CI by 27.4 gCO_2/MJ. In this process, corn stover can be used as both feedstock material and a fuel source to supply process heat. This option has significant potential for CI reduction, but utilizing corn stover as additional feedstock material would require significant retrofitting of existing plants.

4. Strategic Decarbonization Pathways for the U.S. Ethanol Industry

Based on the assessment of options, EFIF developed two strategic pathways that the ethanol industry could take to achieve net-zero or even negative emissions by midcentury:

- ***Net-Zero by 2050 Pathway*****:** This pathway includes core decarbonization measures to enable the ethanol industry to reach net-zero emissions by midcentury, with substantial progress toward that goal by 2035. The core decarbonization measures are ready-to-adopt and relatively low-cost per ton of CO_2 removed. Many measures have a net cost of less than zero because of accompanied cost savings, and the highest-cost measure is capped at \$64/tCO_2.
- ***Deeper-Decarbonization Options*****:** Adopting additional measures enables the ethanol industry to reach almost net-zero emissions by 2035, and negative emissions in 2050. The additional measures are not yet ready-to-adopt and their costs are relatively higher or uncertain, with a wide range of estimates. Since most measures, such as clean ammonia, are in the early phases of market development, their degree of penetration into the ethanol supply chain is uncertain in the near term and midterm. The costs of these additional measures range from zero to \$516/tCO_2 (Figure 11).

Figure 11. Cost and carbon intensity reduction potential by decarbonization measure



A negative cost means that the new measure costs less than the currently adopted measure because of reduced energy or fertilizer inputs (e.g., no-tillage farming, 4R nitrogen management), a lower cost for securing energy (e.g., PPAs), policy incentives (e.g., fermentation CCUS), or additional electricity production (e.g., biomass CHP). Biofuels with positive CIs can still represent carbon reductions, since they replace fossil fuels. Source: EFI Foundation analysis.

Assumptions for Pathways

The midterm pathway (by 2035) and the long-term pathway (by 2050) were modeled with varying assumptions about the prevalence of each decarbonization measure (Table 1). The projection includes the adoption of no-till farming and 4R nitrogen management by 50% of corn farms by 2035 and 100% by 2050, based on their current adoption rate of approximately 30%. The model assumes that the transition to 100% carbon-free electricity can be achieved by 2035, consistent with the Biden-Harris administration's goal. The expected improvement in ethanol yield by 10% by 2050 is based on an expert interview suggesting a ceiling for yield enhancement. Corn yield is projected to match the current best practice by 2050. The adoption of enhanced efficiency fertilizers (EEFs) and cover crops is estimated at 30% by 2035 and 50% by 2050, considering that these practices may not be suitable for all farms because of environmental factors such as soil type and climate.

Table 1
Assumptions of decarbonization pathways

Net Zero by 2050 measures		Current Status	Assumption by 2035	Assumption by 2050
	No-till farming	38% adoption rate (U.S., 2022)[42]	50%	100%
	4R nitrogen management	27% adoption rate (precision agriculture, U.S., 2023)[44]	50%	100%
	Carbon-free electricity in biorefinery	40% (U.S., 2023)[116]	100%	100%
	Ethanol yield improvement	0.5% increase per year on average in the last eight years[117]	5% improvement	10% improvement
	Corn yield improvement	1.2% increase per year on average in the last three decades[118]	12% improvement	18% improvement
	Enhanced efficiency fertilizers (EEFs)	12% of U.S. corn cropland used nitrogen inhibitor[119]	30%	50%
	Fermentation CCUS	Four facilities are in operation in 2023[120]	Adopted	Adopted
	Cover crops	7.2% adoption rate in the Midwest in 2021[43]	30%	50%
	CHP boiler/steam turbine with a mix of fuels	20% of biorefineries have CHP systems[88]	Replace 20% of natural gas with biomass	Replace 50% of natural gas with biomass
Deeper-decarbonization measures	Blue ammonia	Early phase of market development	25%	0%
	Green ammonia		25%	100%
	Renewable diesel in farm machinery	Minimal	5%	10%
	CHP boiler/steam turbine with a mix of fuels	20% of biorefineries have CHP systems[88]	Replace 40% of natural gas with a mix of biomass, RNG, and blue hydrogen	Replace 100% of natural gas with a mix of biomass, RNG and green hydrogen
	Renewable diesel vehicles for ethanol transport	Minimal	5%	10%
	Renewable diesel vehicles for corn transport	Minimal	5%	10%

The model assumes that CCUS in the fermentation process will be adopted by 2035, based on the economic viability provided by existing tax incentives and the proposed construction of CO_2 transport and sequestration infrastructure by that year. For combined heat and power (CHP) systems, the model projects that 20% of natural gas will be replaced with biomass by 2035, increasing to 50% by 2050. This projection considers the potential availability of biomass, estimating that using 50% of biomass in CHP across the entire ethanol industry would consume 8% of the available biomass in the United States.[121]

Blue and green ammonia are assumed to replace the gray ammonia feedstock of fertilizers by 50% in 2035 and 100% in 2050. Fertilizers use about 70% of total ammonia produced, and are expected to continue to dominate the market in 2050 (resulting in minimal competition with other uses).[122] The clean ammonia market is expected to be established by 2035 since announced blue and green hydrogen projects for ammonia production can replace about 90% of gray ammonia by 2035.[107] Among the announced clean hydrogen projects in the United States, blue hydrogen is the dominant production method; thus, blue ammonia was modeled for 2035, but was assumed to be replaced by green ammonia in 2050 if the cost of green ammonia is lower than that of blue ammonia in the United States by 2040, as shown in some projections.[107]

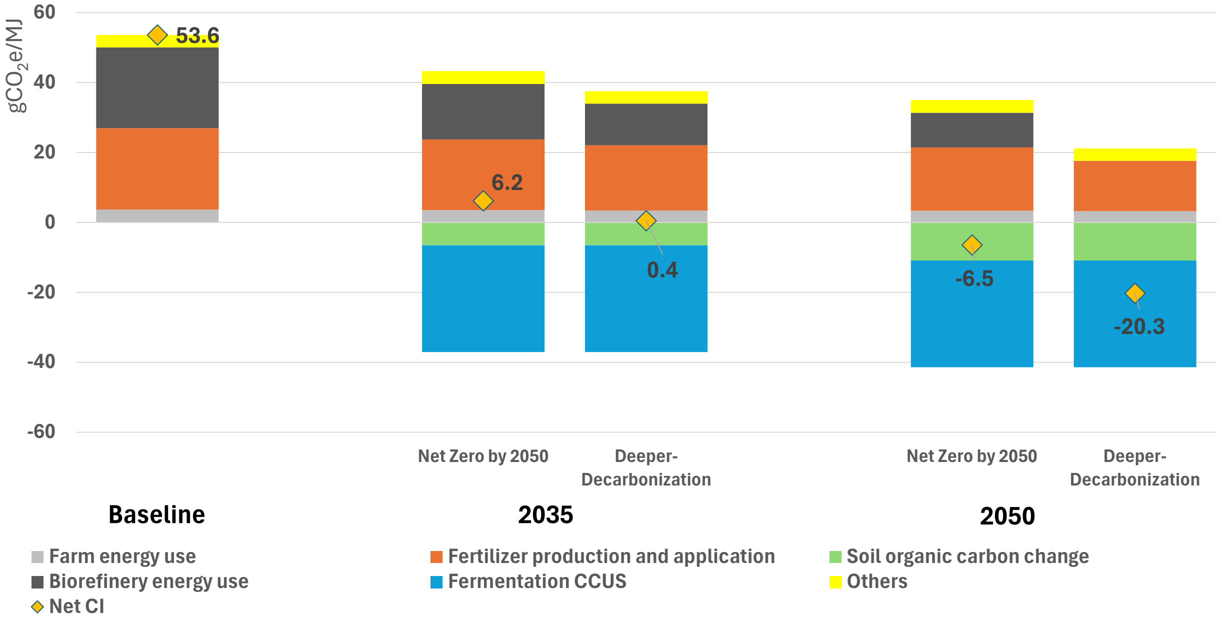
Renewable diesel was assumed to replace 5% and 10% of diesel use in farm machinery, corn transport, and ethanol transport in 2035 and 2050, respectively, reflecting the limited current resource supply base. This estimate of market penetration for on-farm use is consistent with the national projection that renewable diesel could reach market penetration of about 6% and 8% of total current diesel use in 2035 and 2050, respectively.[123]

Lastly, in the pathway with Deep-Decarbonization Options, in addition to biomass, renewable natural gas (RNG), blue hydrogen, and green hydrogen were assumed to be used in the CHP system in a biorefinery. Since RNG and clean hydrogen are limited in replacing 100% of natural gas, they were assumed to be used as a mix with other fuels.[124] Given the rising demand for RNG for other industry applications, the ethanol industry may secure a much smaller share of the RNG market. Technically, hydrogen can be blended up to 20% without significantly modifying facilities.

Pathways of Carbon Intensity Reductions

Under the Net Zero by 2050 Pathway, a biorefinery can reduce almost 90% of the ethanol CI by 2035 and reach net-zero emissions by 2050. With the Deeper-Decarbonization Options, a biorefinery can reach almost net-zero by 2035, and negative emissions in 2050 (Figure 12).

Figure 12. Ethanol carbon intensity in the baseline, Net Zero by 2050 Pathway, and Deeper-Decarbonization, 2035 and 2050

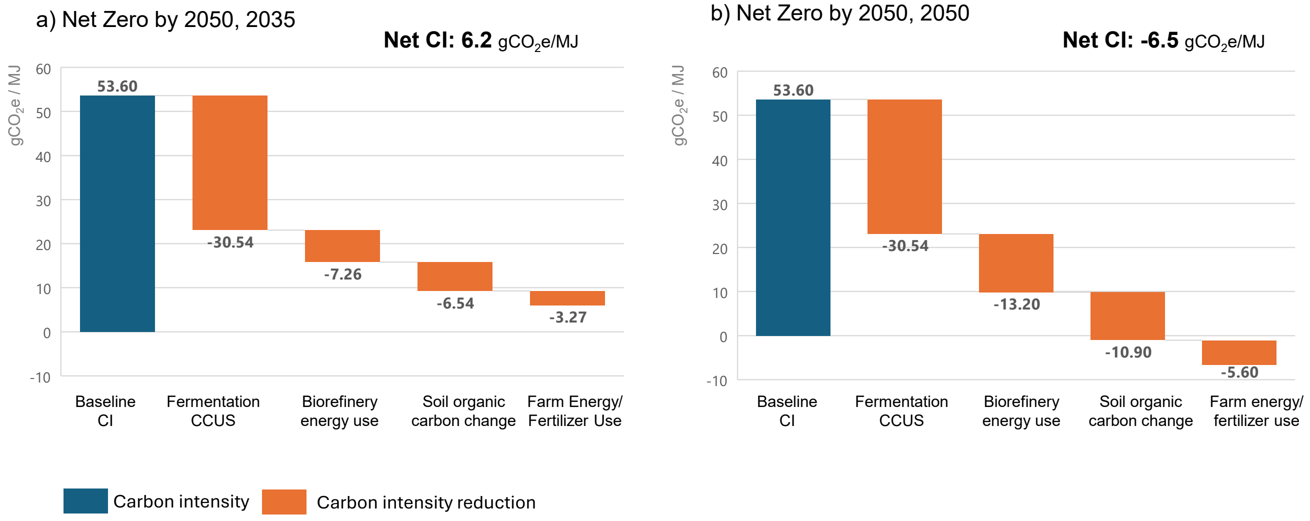


The Net Zero Pathway and Deeper-Decarbonization Options achieve major CI reductions by 2035 and both have negative or net zero emissions by 2050. Source: EFI Foundation analysis.

Net Zero by 2050 Pathway

Under the Net-Zero by 2050 Pathway, the ethanol CI reaches 6.2 gCO_2e/MJ by 2035, and -6.5 gCO_2e/MJ by 2050. The largest reduction comes from CCUS in the fermentation process, which reduces the CI by 30.5 gCO_2e/MJ, a 60% reduction. Decarbonizing the energy use in a biorefinery is the second largest source of reduction. Decarbonizing electricity use reduces the CI by 3.3 gCO_2e/MJ in 2035 and 2050, while decarbonizing thermal energy use reduces 4 gCO_2e /MJ and 9.9 gCO_2/MJ in 2035 and 2050, respectively. Increasing soil organic carbon (SOC) stocks by planting cover crops reduces the CI by 6.5 gCO_2e /MJ and 10.9 gCO_2e /MJ in 2035 and 2050, respectively. Decarbonizing farm energy and fertilizer uses cause significant but relatively small CI reductions (Figure 13).

Figure 13. Sources of CI reduction, Net-Zero by 2050 Pathway, 2035, 2050

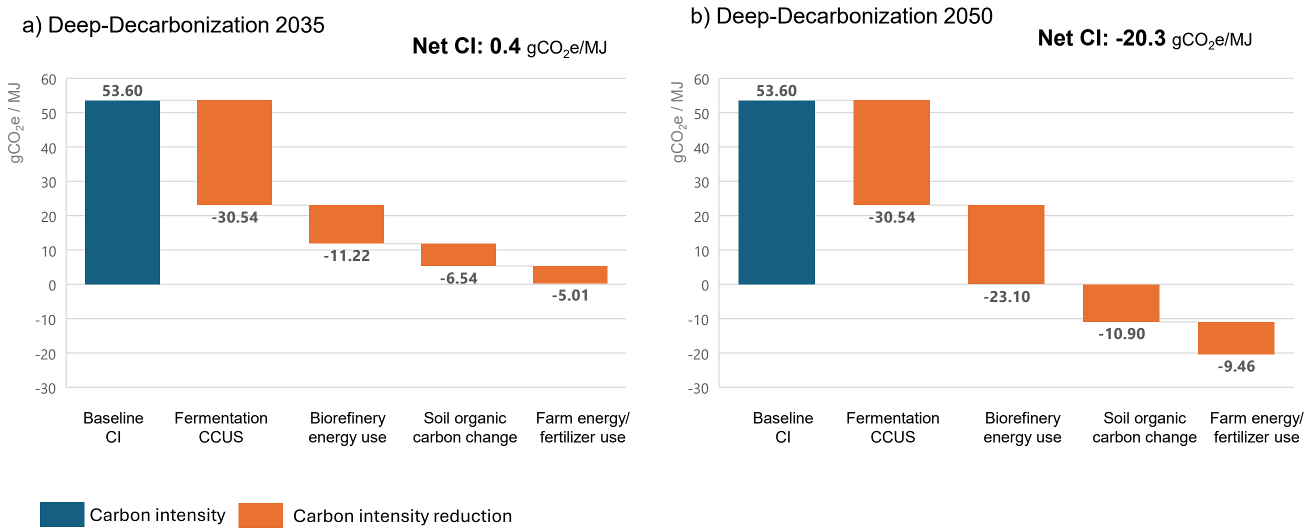


Under the Net Zero by 2050 Pathway, ethanol CI drops to 6.2 gCO_2e/MJ by 2035 and -6.5 gCO_2e/MJ by 2050, with the largest reduction coming from CCUS in fermentation (30.5 gCO_2e/MJ). Source: EFI Foundation analysis.

Pathway with Deeper-Decarbonization Options

Under this pathway, the ethanol CI reaches 0.4 gCO_2e/MJ by 2035 and -20.3 gCO_2e/MJ by 2050. Like in the Net Zero Pathway, the largest reduction comes from CCUS in the fermentation process, which reduces the CI by 30.5 gCO_2e/MJ, a 60% reduction. Compared to the cost-effective pathway, decarbonizing energy use in a biorefinery reduces a larger amount of the CI as natural gas use for thermal energy generation is completely replaced by a mix of low-carbon fuels by 2050. Decarbonizing thermal energy use reduces 7.9g CO_2e/MJ and 19.8 gCO_2e/MJ in 2035 and 2050, respectively. Decarbonizing farm energy and fertilizer uses reduces a larger amount of the CI because of decarbonizing fertilizers using blue and green ammonia (Figure 14).

Figure 14. Sources of CI Reduction with Deeper-Decarbonization Options, 2035, 2050.



With the Deeper-Decarbonization Options, ethanol CI drops to 0.4 gCO_2e/MJ by 2035 and -20.3 gCO_2e/MJ by 2050. The largest reduction comes from CCUS in fermentation, while replacing natural gas with low-carbon fuels for thermal energy further reduces CI. Source: EFI Foundation analysis.

5. Enabling Decarbonization of the Transportation Sector

As this roadmap outlines, decarbonizing ethanol can increase its contribution to a future low-carbon economy. Ethanol's value proposition lies in its established infrastructure and widespread availability. These make ethanol a practical and immediate solution for reducing carbon emissions in transportation by complementing the growing electric vehicle (EV) market and as a feedstock for sustainable aviation fuels (SAF).

Transportation emissions are currently the largest source of GHG emissions in the United States (29% in 2021).[125] To decarbonize light-duty passenger vehicles weighing less than 10,000 pounds,[126] the Biden-Harris administration set a goal that half of all new vehicles sold by 2030 be EVs, with most vehicles expected to be electric by 2050.[127]

On the path to reaching such climate milestones, lower-CI ethanol blended with gasoline can help reduce overall light-duty transportation emissions for the remaining gasoline vehicles in the fleet as vehicle electrification progresses.[27] Currently, blending ethanol with gasoline reduces GHGs by roughly 3%.[128] A gallon of gasoline emits approximately 8.887 kg of CO_2 per gallon, while a gallon of E10 emits 8.346kgCO_2/gallon.[129] Implementing the decarbonization technologies proposed in this roadmap can further reduce this.

Ethanol also can contribute to decarbonizing remaining emissions that cannot be mitigated with electrification, such as in aviation, a sector that relies heavily on liquid fuels and faces significant barriers to electrification.[130]

The DOE SAF Grand Challenge is a coordinated effort launched in 2021 to advance SAF production and achieve significant emissions reductions in the aviation sector by 2050. The Grand Challenge aims to produce SAF to fulfill 100% of U.S. aviation fuel demand by 2050, or 35 billion gallons annually.[131] In addition, SAF produced from low-carbon feedstocks qualify for the clean fuel tax credit under the Inflation Reduction Act (IRA). Also known as 45Z, this tax credit is awarded to transportation fuels whose carbon intensity is no more than 47.4 gCO_2e/MJ, or, as detailed in the IRA text, 50 kg CO_2e per million British thermal units (MMBtu).[132]

Sustainable Aviation Fuel (SAF)

SAF is a synthetic, drop-in fuel with properties similar to jet fuel but with lower emissions.[133] As such, using SAF does not require aircraft or supply chain infrastructure changes, avoiding substantial logistical, safety, and cost challenges.[134]

SAF is produced from renewable resources including ethanol, municipal waste, hydrogenated fats, and oils. In order for SAF to be blended and used as a drop-in fuel, safety certification is required. The most common certification standard for SAF is the

American Society for Testing and Materials (ASTM) D7566. Once SAF has received ASTM D7566 certification, it can be blended up to 50% with standard jet fuel, which then receives ASTM D1655. This certifies that SAF meets all the necessary technical specifications of jet fuel, including density, flash point, freezing point, sulfur content, aromatics content, and net heat of combustion.[135]

SAF has similar GHG emissions characteristics during combustion, but its emissions reduction potential lies in its use of renewable biogenic feedstocks in lieu of conventional fossil fuel energy sources. Table 2 lists the existing approved SAF production pathways.

Table 2

SAF Production Pathways

Production method	Blending limitation	Possible feedstocks
Fischer-Tropsch synthetic paraffinic kerosene (FT-SPK)	50%	Woody biomass (municipal solid waste, agricultural and forest wastes, wood, energy crops)
FT-SPK with aromatics[w]	50%	Same as above
Hydroprocessed esters and fatty acids (HEFA-SPK)	50%	Oil-based feedstocks (jatropha, algae, camelina; plant oil; yellow/brown greases; animal oil; waste fat, oil, and greases)
Hydrocarbon-hydroprocessed esters and fatty acids (HC-HEFA-SPK)	10%	Algal oil
Hydroprocessed Fermented Sugars to Synthetic Isoparaffins (HFS-SIP)	10%	Sugars, cellulosic biomass feedstocks (herbaceous biomass and corn stover), pretreated waste fat, oil, and greases
Alcohol-to-jet synthetic paraffinic kerosene (ATJ-SPK)	50%	Cellulosic or starchy alcohol (isobutanol and ethanol—ATJ E-SAF), including from lignocellulosic biomass (e.g., corn stover)
Catalytic hydrothermolysis synthesized kerosene (CH-SK or CHJ)	50%	Fatty acids or fatty acid esters or lipids from fats, oils, and greases
Fats, oils, and greases (fog) co-processing	5%	Fats, oils, and greases (e.g., cooking oil and waste animal fats) coprocessing with petroleum intermediates
FT co-processing	5%	Biocrude (5% Fischer-Tropsch syncrude coprocessing with petroleum crude oil)

Adapted from: U.S. Department of Energy (DOE), "Alternative Fuels Data Center: Sustainable Aviation Fuel," accessed May 16, 2024, https://afdc.energy.gov/fuels/sustainable-aviation-fuel.

Ethanol SAF is produced through the alcohol-to-jet, or ATJ pathway (ATJ E-SAF), which transforms ethanol into hydrocarbons suitable for blending with jet fuel. ATJ E-SAF's carbon intensity is currently 70.36 gCO_2e/MJ, compared to conventional jet fuel's CI of

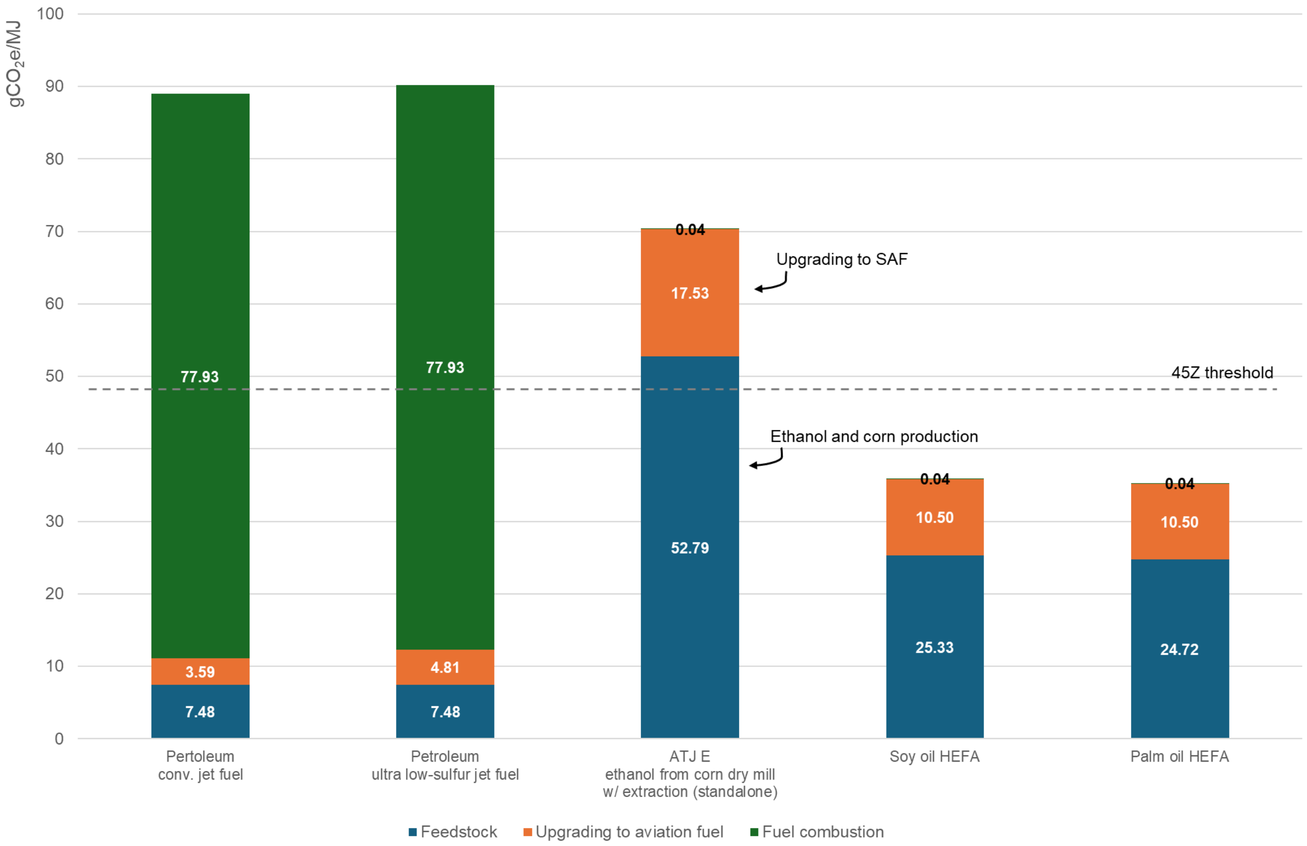
---

[w] Aromatics are hydrocarbons derived from crude oil or coal. The main aromatics are benzene, toluene, and xylenes, and are used in many consumer products.

89 gCO_2e/MJ. The CI of ethanol SAF is roughly 40% to 60% higher than the CI of the original ethanol feedstock (53.6 gCO_2e/MJ), primarily because of the energy-intensive nature of the conversion process and the loss of efficiency during the transformation.[136]

Figure 15 compares the carbon intensity (gCO_2e/MJ) of different types of jet fuels and SAF production pathways. The carbon intensity of SAF likewise depends on the feedstock used. ATJ E-SAF is above the 45Z tax credit threshold. Therefore, U.S. corn ethanol must significantly reduce its CI score to be competitive as a SAF pathway.

Figure 15. Current GREET default carbon intensity of jet fuel, ATJ E-SAF, palm oil and soy oil HEFA SAF



The carbon intensity (gCO_2e/MJ) of various jet fuels and SAF production pathways highlights that SAF's CI varies depending on the feedstock used. Notably, ATJ E-SAF exceeds the 45Z tax credit threshold, emphasizing the need for U.S. corn ethanol to significantly reduce its CI to remain competitive as a SAF production pathway. Data from: Argonne National Laboratory, “Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model,” accessed September 11, 2024. https://greet.anl.gov/.

SAF Market

The U.S. ATJ E-SAF industry is still in its early stages. In 2024, U.S. companies producing ATJ E-SAF primarily rely on Brazilian sugarcane ethanol because of its lower CI score, which makes it compatible with international SAF certification.[137]

SAF demand is expected to grow significantly in the coming years as U.S. airlines intensify their need for sustainable fuel options. Global SAF production reached only 158 million gallons in 2023 and is expected to triple to 480 million gallons in 2024, meeting just 0.53% of the aviation fuel demand and representing 6% of the total renewable fuel capacity.[138] Airlines and shipping companies have contracted more than 100 SAF offtake agreements since 2013, amounting to a cumulative volume of about 14 billion gallons.[139] As mandates and decarbonization targets are pursued in the coming years, the SAF market is projected to grow at a compound annual growth rate (CAGR) of nearly 50% by 2030, reaching a value of $16.8 billion globally by 2030.[140]

Current SAF production levels are far below projected demand, and the limited SAF is expensive. In the United States, SAF costs around $6.69/gallon, or 235% more than fossil-based jet fuel, which costs around $2.85/gallon.[141] After considering the full 45Z tax credit, the cost of SAF could decrease to $4.94/gallon. If used in a Minnesota or Illinois airport—states that also have SAF incentives (see next section)—SAF's cost could decrease further to $3.44/gallon.

Most SAF produced in the U.S. today is made from waste fats, oils, and greases (commonly referred to as FOGs), as well as other bio-based feedstocks like corn oil and used cooking oil.[142] However, few feedstocks have the necessary scalability and available infrastructure to reach projected demand in the coming years. SAF will rely heavily on economies of scale to offset the high costs associated with the necessary infrastructure, energy inputs, and processing technologies. As a result, continued innovation and scale-up are needed in the sector to reach production and sustainability goals.

SAF Cost Reduction Incentives in the United States

The IRA established the SAF blending tax credit (40B) to foster SAF production. The 40B tax credit starts at $1.25/gallon of SAF, with an additional $0.01 per percentage point over 50% emissions reductions and a maximum value of $1.75/gallon.[143] To qualify for the credit, SAF must meet ASTM SAF requirements and have estimated emissions reductions of at least 50% compared to conventional jet fuel. [143, 144]

Climate-smart agriculture (CSA) practices are included in the determination of whether SAF meets the 50% reduction target. Three CSA practices under the USDA CSA Pilot Program[x]—no-till farming, planting cover crops, and applying enhanced efficiency nitrogen fertilizer—must be adopted in conjunction on the same acreage for SAF produced from corn ethanol ATJ to receive a 10 gCO_2e/MJ reduction in its life cycle emissions. For SAF produced from soybean hydroprocessed esters and fatty acids

---

[x] The USDA Climate-Smart Agriculture (CSA) Pilot Program aims to promote agricultural practices that reduce GHG emissions and increase carbon sequestration. The program focuses on no-till farming, cover cropping, and the use of enhanced-efficiency fertilizers. A specific emphasis is placed on crops used as feedstocks for bioenergy, including biofuels like ethanol and SAF. Recognizing the significant emissions reduction potential of CSA and the existing challenges in verifying these benefits, the program grants life cycle emissions reduction credits to crops grown with CSA methods.

(HEFA), two CSA practices must be adopted on the same acreage for a 5 gCO_2e/MJ life cycle emissions reduction: no-till farming and planting cover crops.[144] These practices must be bundled, and other CSA practices currently do not qualify.

The 40B credit is short-lived, however, expiring in December 2024. Beginning in 2025, SAF incentives will immediately fall under the technology-neutral 45Z clean fuel production tax credit (PTC).[145] The 45Z PTC value starts at $0.2/gallon of clean fuel and $0.35/gallon of SAF, with a maximum value of $1/gallon and $1.75/gallon, respectively, depending on emissions factor and meeting wage and apprenticeship (W&A) requirements (Table 3).[146] Under 45Z, SAF must emit no more than 50 kilograms of CO_2 (or CO_2 equivalent) per MMBtu, based on the forthcoming SAF GREET model methodology, which DOE is currently developing.[144]

Table 3

Estimated §45Z clean fuel production credit values

Assumed kg of CO_2e/MMBtu	Emissions factor[y]	Does not meet W&A requirements ($/gal)	Meets W&A requirements ($/gal)
Nonaviation Fuels			
0	1.0	$0.20	$1.00
10	0.8	$0.16	$0.80
25	0.5	$0.10	$0.50
40	0.2	$0.04	$0.20
50	0.0	$0.00	$0.00
Aviation Fuels			
0	1.0	$0.35	$1.75
10	0.8	$0.28	$1.40
25	0.5	$0.18	$0.88
40	0.2	$0.07	$0.35
50	0.0	$0.00	$0.00
0	1.0	$0.35	$1.75

Data from: Congressional Research Service, "The Section 45Z Clean Fuel Production Source," https://crsreports.congress.gov/product/pdf/IF/IF12502.

The Treasury Department is expected to release further guidance on the 45Z PTC until the end of 2024. The 45Z tax credit will be available for SAF production over a three-year period, expiring on Dec. 31, 2027. Several states also have SAF-supporting policies.

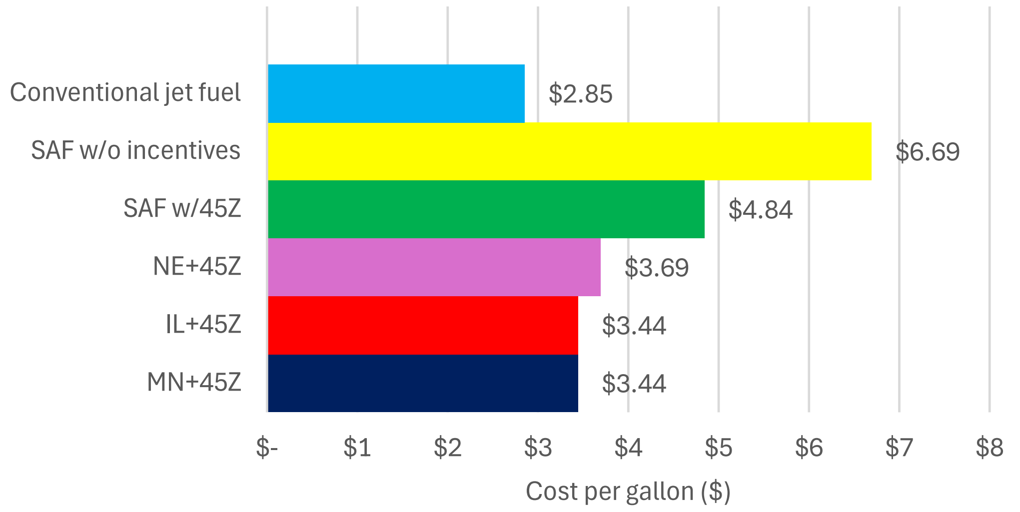
---

[y] To determine the credit size, the maximum credit value ($1.75) is multiplied by an emissions factor that is equal to: [(50 kg of CO2e per MMBtu) – (Fuel kg of CO2e per MMBtu)] / [50kg of CO_2e per MMBtu].

- Minnesota: a tax credit value of $1.50/gallon available to producers or purchasers departing from a Minnesota airport from June 30, 2024, to July 1, 2030.[147]
- Illinois: a credit of $1.50/gallon purchased in an Illinois airport from July 1, 2023, to Dec. 31, 2032.[148]
- Nebraska: a credit up to $1.25/gallon available to producers starting in 2027 based on the fuel's life cycle greenhouse gas emissions reduction.[149]
- Washington: Revenue from the Climate Commitment Act (CCA), the state's "cap-and-invest program," will be used to promote and accelerate SAF production.[150]

Figure 16 compares estimates of SAF costs with and without state and federal incentives. Without incentives, SAF costs $6.69/gallon, significantly higher than conventional jet fuel at $2.85. With the 45Z federal tax credit, SAF costs drop to $4.84. When combined with state-level incentives in Nebraska, Illinois, and Minnesota, the cost further decreases to $3.69, $3.44, and $3.44 per gallon, respectively, making SAF more competitive with conventional jet fuel.

Figure 16. Cost estimates for SAF with state and federal incentives



Stacking 45Z with emerging state SAF incentives boosts chances for the SAF market to be cost-effective with traditional jet fuel. Illinois, Nebraska, and Minnesota have implemented legal incentives in recent years. Data from Illinois General Assembly (2023), Bose (2023), Nebraska Legislature (2024), Minnesota Legislature (2023).

International Policies Supporting SAF

Other countries have taken a more proactive stance on reducing aviation emissions by establishing SAF mandates as part of their broader climate goals. The United Kingdom

SAF mandate, for example, will be effective on Jan. 1, 2025. It requires that SAF achieves at least a 40% reduction in carbon intensity compared to standard jet fuel and fulfills 10% and 22% of U.K. aviation fuel demand by 2030 and 2040, respectively. The mandate is technology agnostic and does not differentiate between domestic or international SAF origin. Although it encourages diverse SAF feedstocks, eligibility excludes food, feed, or energy crops.[151]

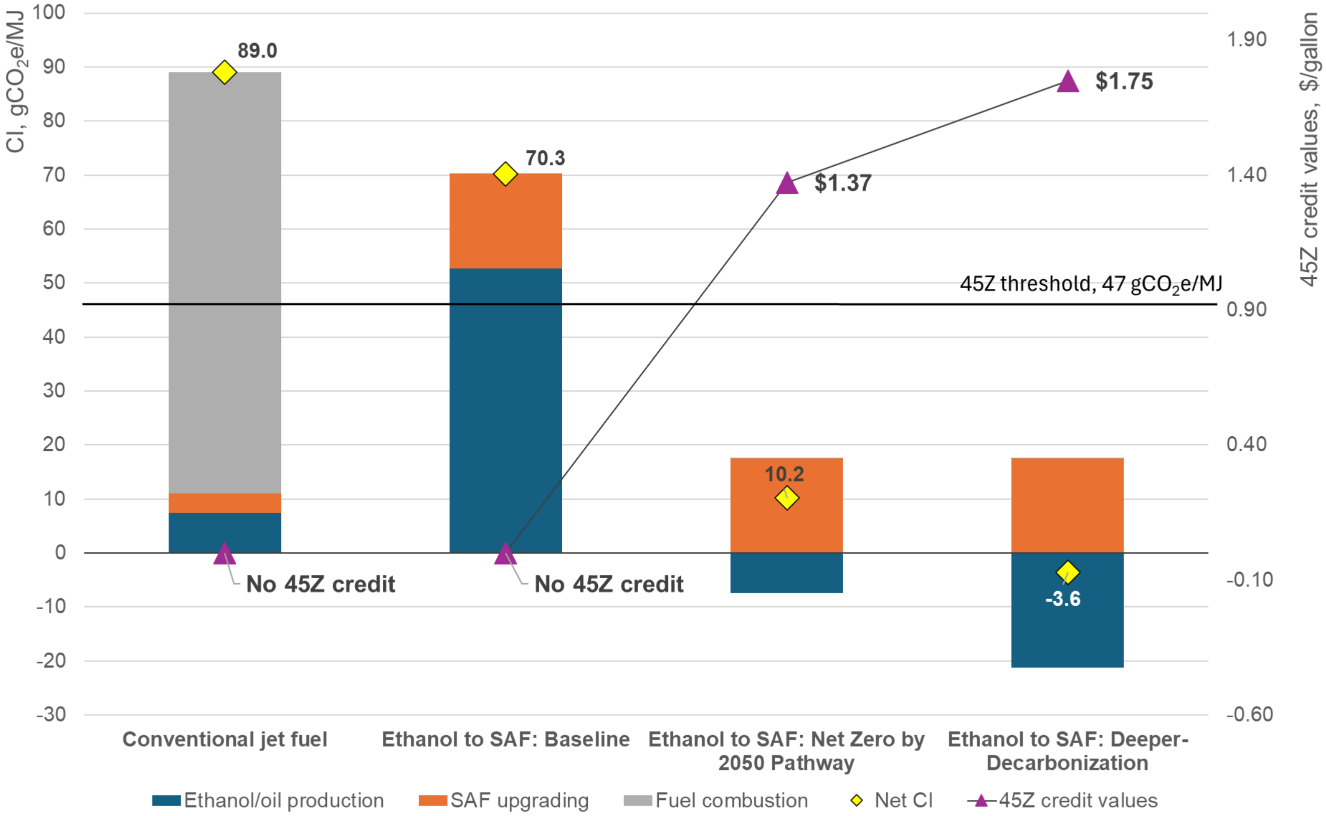
Similarly, the EU's "ReFuelEU Aviation" initiative has introduced a gradual mandate requiring airlines to blend an increasing percentage of SAF with conventional jet fuel. Starting in 2025 with a mandate of 2% SAF, the required blend will progressively increase to 6% by 2030, 20% by 2035, and is expected to reach 70% by 2050.[152]

If the U.S. were to require a similar percentage of SAF blended with conventional jet fuel, approximately 360 million gallons of SAF would be needed by 2025, 1 billion gallons by 2030, 4 billion gallons by 2035, and 24.5 billion gallons by 2050.

SAF CI and Cost Reduction Analysis

Figure 17 compares the carbon intensity and 45Z credit values for conventional jet fuel and various ethanol-to-SAF production pathways. The figure illustrates that SAF produced from current ethanol supplies (i.e., conventional ATJ E-SAF) does not qualify for the production tax credit under the current 45Z guidelines. In contrast, in the future decarbonization scenarios outlined above, ethanol SAF can qualify for between $1/gallon and $1.75/gallon. As suggested in the figure, deep decarbonization is needed to reach the maximum credit value under 45Z, but significant credit savings exist with all of the pathways EFIF has identified. The 45Z credit values were estimated with the assumption of meeting prevailing wage and registered apprenticeship requirements.

Figure 17. Comparative analysis of carbon intensity and 45Z credit values in ethanol-to-SAF pathways



While current ethanol-based SAF does not qualify for 45Z tax credits, future decarbonization efforts could enable it to earn credits of up to $1.75 per gallon, with significant savings across all identified pathways. Source: EFI Foundation analysis.

The potential for decarbonized ethanol to become a feedstock for SAF will open the door to a new market for ethanol to complement its role in reducing emissions in gasoline for light-duty vehicles (LDVs). As electrification of the LDV fleet increases (Box 2), the current ethanol production level can support increased blend rates in gasoline as well as significant market penetration of SAF.

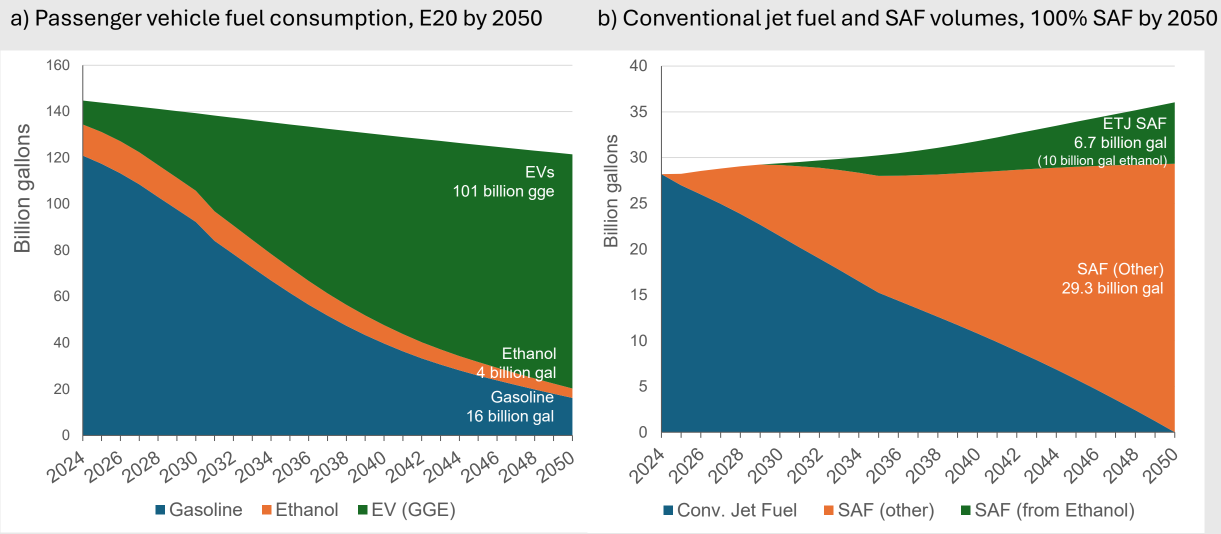
To fully realize this potential, substantial efforts are needed to reduce the carbon intensity of ethanol to enable scale-up of SAF production, ensuring that ethanol remains a competitive and sustainable option in the evolving energy landscape. The continued development of supportive policies, innovation and technological advancements, and market growth will be crucial to overcoming these challenges and unlocking the full potential of ethanol to contribute to global climate goals.

Box 2

The U.S. ethanol industry’s contribution to gasoline blending and SAF production volumes

The existing U.S. ethanol market—15 billion gallons per year—has the potential to contribute to both emerging SAF markets and gasoline blending, helping to close the transportation emissions gap. If EVs become 84% of the light-duty vehicle fleet and ethanol blending with gasoline increases to 20% by 2050, the vehicle market will consume approximately 4 billion gallons of ethanol annually.[z] The remaining 11 billion gallons could serve as feedstock for SAF, potentially covering 20% to 25% of the market if SAF replaces all jet fuel in the United States by 2050, as outlined in the DOE SAF Grand Challenge target (Figure 18).[153] Currently, 1 gallon of SAF requires 1.7 gallons of ethanol. Meeting 100% of the SAF Grand Challenge goal of 35 billion gallons would require approximately 59.5 billion gallons of ethanol per year, an amount nearly four times larger than current U.S. ethanol production levels of about 15 billion gallons a year.

Figure 18. Ethanol’s potential role in gasoline blending and SAF production in the 2050 time frame



a) Passenger vehicle fuel consumption, E20 by 2050

b) Conventional jet fuel and SAF volumes, 100% SAF by 2050

In a future fuel market with high EV uptake, the current ethanol production capacity (15 billion gallons per year) can be deployed for gasoline blending (E15 by 2035 and E20 by 2050) and SAF production. Note: GGE/gge: gasoline gallons equivalent. Source: EFI Foundation estimates using the GREET model.

---

[z] For this scenario, we assume that E20 will be introduced in the United States by 2035.

6. Current Incentives Provide a Foundation for Ethanol Decarbonization

The ethanol life cycle is complex, and the implementation of a strategic decarbonization roadmap requires coordinated action among five major players: corn growers, ethanol bio refiners, energy suppliers (electricity and fuels), fertilizer producers, and an emerging carbon management industry. Government policy is needed to provide the glue to enable players to integrate their actions effectively and efficiently.

Although some decarbonization efforts are occurring, most strategies are not yet widely adopted by ethanol producers and corn growers. Existing policies help incentivize ethanol producers and corn growers to start decarbonizing the ethanol supply chain, but additional policies are necessary to accelerate decarbonization efforts and motivate major players to invest in new strategies.

Before diving into the roadmap recommendations, this section will list existing policies supporting ethanol decarbonization efforts, such as renewable fuel standards, low carbon fuel standards, and various tax incentives that have created and sustained the existing ethanol market.

Since the late 1970s, proactive U.S. policies have fostered ethanol production, consumption, and exports, driven by key legislation, including the Energy Tax Act of 1978[154] and the Renewable Fuel Standard (RFS) of 2005[155] (See Appendix A for more details). The RFS, expanded under the Energy Independence and Security Act of 2007, mandated blending ethanol with gasoline, significantly increasing ethanol use in transportation fuels. By 2010, E10 was sold nationwide, doubling ethanol production and consumption from 2005 to 2023. The RFS created a guaranteed market for ethanol, spurring investment in production capacity and cementing ethanol's role in reducing dependence on oil imports and lowering greenhouse gas emissions.

Further support came from state-level low-carbon fuel standards (LCFS), which incentivized ethanol use and carbon intensity reductions in the ethanol supply chain. The 2022 Inflation Reduction Act (IRA) added more incentives, including tax credits for carbon capture and SAF production. Additionally, while no specific tax incentives exist exclusively for corn used in ethanol, various agricultural and renewable energy programs, along with federal farm subsidies, indirectly support ethanol production by promoting corn farming. This comprehensive policy landscape has enabled the U.S. ethanol industry to thrive, contributing significantly to a cleaner, more sustainable energy future.

There has been a growing number of industry actions and various types of policy support for decarbonizing the ethanol supply chain. These ongoing efforts should be continued and accelerated for more significant CI reduction.

45Z Clean Fuel Production Tax Credit

The IRA introduced the new 45Z clean fuel production tax credit, a technology-neutral credit for transportation fuels that, beginning in 2025, will replace all existing fuel-related tax credits (including the 40B credit) as well as other credits affecting production of biodiesel, renewable diesel, second-generation biofuel, sustainable aviation fuel (SAF), and alternative fuels.[156, 157] As written, 45Z will expire on Dec. 31, 2027. Treasury has yet to release final guidance or a 45Z GREET model to determine the guidelines for evaluating and quantifying life cycle emissions under the tax credit.

While 45Z provides a clear financial incentive of up to $1.75/gallon for SAF, as Chapter 5 outlines, its current timeline is insufficient to incentivize fuel decarbonization at the necessary scale to reach net zero. Stakeholders interviewed for this report highlighted the short life of the 45Z tax credit as their primary concern in using this tool in decarbonizing ethanol.

The 45Z tax credit is calculated based on a fuel's life cycle GHG emissions, which must have a carbon intensity of no more than 50 kg CO_2e/MMBtu, or 47.4 gCO_2e/MJ, in order to qualify. The performance-based design of the 45Z credit incentivizes to seek and adopt a wide range of decarbonization measures across all stages of ethanol production, including cleaner production technologies, use low-carbon and carbon-free energy sources, and implement sustainable agricultural practices.

The 45Z credit could also spur investment in clean fuels such as biodiesel and renewable diesel, which in turn contribute to lower-carbon ethanol production. Switching from diesel to renewable fuels for vehicles used in the ethanol value chain can contribute to decreasing ethanol's CI, as outlined in Chapter 3. Additionally, the 45Z credit can be used for ethanol blending, incentivizing higher ethanol concentrations in gasoline blends, such as E15. For non-aviation fuels, such as ethanol blends, the base credit amount is $0.20/gallon, which can increase to $1.00/gallon if the production facility meets prevailing wage and registered apprenticeship requirements.[158]

The 45Z tax credit is currently available for three years (2025 to 2027), which is insufficient for large-scale projects to be financially viable, given high capital expenditures and long payback periods. First-of-a-kind low-carbon fuel projects will require an extended production tax credit (PTC) to remain competitive with traditional fossil fuel alternatives that will remain in widespread use over the lifetime of the 45Z projects.[159]

State-Level Low-Carbon Fuel Standards

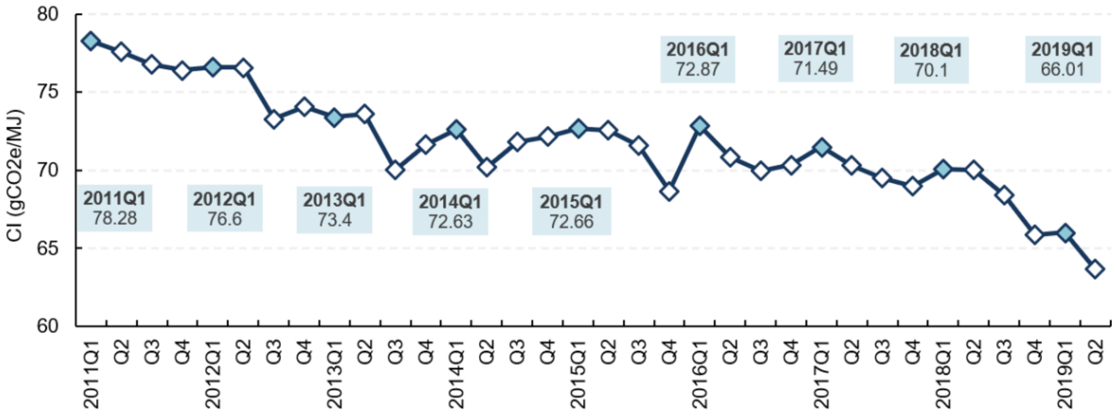
The low-carbon fuel standard (LCFS), also known as a clean fuel standard (CFS), requires the production and use of lower-carbon fuels through credits paid to fuels with CI scores below a baseline value, usually the CI of gasoline or diesel fuel. Through mandated reductions in CI scores, state-level LCFS programs provide an effective mechanism for gradually decarbonizing transportation fuels such as ethanol, spurring supply chain innovation and technology deployment.

Apart from reducing the CI value of ethanol, state LCFS have: led to reductions in the CI of other alternative fuels, including renewable natural gas (RNG), provided flexible and technology-neutral compliance options, spurred private investment in lower-CI technologies, and incentivized cleaner production beyond state borders.[160]

Currently, four U.S. states have an LCFS in place or pending: California, Oregon, Washington, and New Mexico.

California's LCFS has been used as a model for similar state and country-wide clean fuel standards in Oregon, Washington, New Mexico, and Canada. Evidence from California indicates that the LCFS is a powerful incentive for ethanol decarbonization (Figure 19). Since the policy's implementation in 2011, California's LCFS has driven ethanol CI reductions of over 25%.[161] Oregon's LCFS has reported similar results, spurring ethanol CI reductions of approximately 18%.[162]

Figure 19. Average low-carbon fuel standard (LCFS) ethanol carbon intensity, 2011-2019



California's Low Carbon Fuel Standard has been shown to reduce the CI of ethanol from 2011-2019. Showing it as a powerful incentive for ethanol decarbonization. Source: U.S. Department of Agriculture, California's Low Carbon Fuel Standard: Incentivizing Ethanol Industry Greenhouse Gas Mitigation, 2022, accessed August 28, 2024, https://www.usda.gov/sites/default/files/documents/CA-LCFS-Incentivizing-Ethanol-Industry-GHG-Mitigation.pdf.

Twelve states have introduced or discussed LCFS legislation (MN, IL, MI, NY, VT, MA, NE, OH, PA, NJ, HI, CO). Three of these states (NY, MI, and IL) are among the top ethanol consumers.

USDA Funding for CSA Practices and On-Farm Energy Use

The IRA provided $19.5 billion of additional funds over a five-year period to a portfolio of USDA conservation programs targeted to support adoption of climate-smart agricultural practices. The $19.5 billion in funds was allocated among six separate programs: the Environmental Quality Incentive Program ($8.45 billion), Regional Conservation Partnership Program ($4.95 billion), Conservation Stewardship Program ($3.25 billion), Agricultural Conservation Easement Program ($1.4 billion), Conservation Technical Assistance ($1 billion), and measuring, evaluating, and quantifying GHG emissions reductions ($300 million).[163]

The USDA has allocated $2.1 billion of these funds in 2022 and 2023, is estimated to allocate $3.1 billion by the end of 2024, and plans to allocate $5.6 billion in 2025, though farmer interest to date has far exceeded the available funds. When the USDA made $850 million of these funds available in 2023, applicants requested almost $3 billion in total.[164]

The USDA also is responsible for administering two other programs that can provide financial incentives for helping decarbonize on-farm energy use. The Rural Energy for America Program (REAP) provides guaranteed loan financing and grant funding to agricultural producers and rural small businesses for renewable energy systems or to make energy efficiency improvements. Funds can be used to purchase and install renewable energy systems such as biomass, geothermal, hydropower, hydrogen, wind and solar generation, or ocean generation. Funds can also be used to buy, build, and install energy efficiency improvements such as switching from a diesel to an electric irrigation motor.[165] Since the start of the Biden-Harris administration, the USDA has invested more than $1.8 billion via REAP in 6,000 renewable energy or energy efficiency projects.[166]

The Rural Energy Savings Program (RESP) provides zero-interest loans to rural utilities and other companies that provide loans to qualified consumers to implement energy efficiency measures. From 2017 to 2023, the USDA approved 44 loans via RESP.[167] This program does not include mandatory funds. Congress appropriated $75 million in discretionary funds in 2023, but only $3.6 million has been made available in 2024. A $3.6 million fund is limited in serving the increasing demand. Among the $500 million awarded since 2016, more than $200 million in loans were obligated in the past year, requiring more than $20 million in federal appropriations.[168] Lower appropriation in 2024 is expected to leave many prospective borrowers waiting until more funds become available.

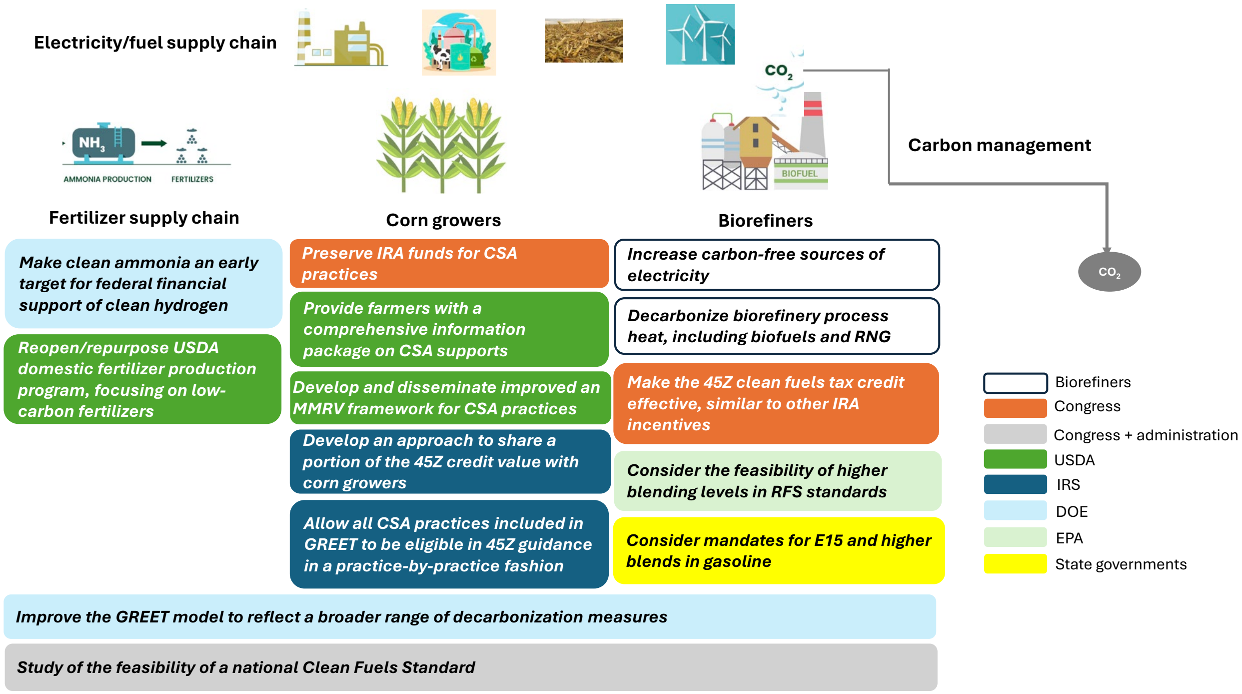
7. Additional Policies Are Necessary to Accelerate the Decarbonization of Ethanol Supply Chains

Currently available incentives are helpful starting points for leveraging the roadmap's decarbonization options, but they are not enough on their own. Additional policy measures will accelerate the adoption of a strategic decarbonization roadmap for the ethanol industry to reach net-zero CI and move beyond to net-negative CI. Employing ready-to-adopt and modest-cost decarbonization measures will enable the ethanol industry to reach net-zero emissions. But even these measures face barriers to implementation, such as lack of infrastructure, the need for upfront investment, and uncertain implementation outcomes. To lower these barriers, a range of industry actions and policy changes are required.

A key factor in the design of additional policy measures is the need to address the roles of all major players mentioned above, including ways to encourage cooperative and mutually reinforcing actions. The recommendations that follow are intended to comprehensively address decarbonization actions across all the players in the ethanol life cycle (Figure 20).

Although CCUS is often considered a low-hanging fruit for ethanol decarbonization, it faces various challenges for implementation. Capturing CO_2 emissions from the biorefining process is technologically feasible at a relatively modest cost of capture of about \$37/tCO_2. This cost could be covered by the 45Q tax credit of \$85/tCO_2; however, transportation and sequestration of CO_2 are challenging. As most ethanol plants are located in areas unsuitable for geologic sequestration of CO_2, the captured CO_2 in ethanol plants would have to be transported via pipelines to suitable sites. Uncertainties surrounding permitting of the CO_2 pipeline infrastructure and geologic storage (GS) site (Class VI) have been the most significant barriers to scaling up CO_2 transportation and sequestration infrastructure. The permitting issues are complex because the pipeline infrastructure would cross multiple states (e.g., five states in the Summit pipeline project, three states in the Tallgrass Energy Gas-to-CO_2 project) and require permit approvals by state and local governments. Because both the Summit and the Tallgrass projects are in the middle of state and local government proceedings, this report does not recommend any additional specific policy changes regarding CCUS at this time.

Figure 20. Summary of recommended policy measures to support implementation of the ethanol decarbonization roadmap



Recommended policy measures directed at the five key players in the ethanol industry: corn growers, ethanol biorefiners, energy suppliers (electricity and fuels), fertilizer producers, and an emerging carbon management industry, with support from Congress, the administration, USDA, IRS, DOE, EPA, and state governments. Source: EFI Foundation analysis.

USDA Support for Expanding Farmers' Adoption of Climate-Smart Agricultural (CSA) Practices

CSA adoption rates are low because of economic challenges and uncertain outcomes because of variation in environmental factors like soil type and climate. [42, 43, 44] In some instances, CSA practices require significant upfront investments, such as purchasing specialized equipment that does not necessarily result in an immediate increase in productivity. Further, the lack of a robust measuring, monitoring, reporting, and verification (MMRV) framework for CSA practices is another critical barrier preventing farmers from ensuring the outcome of their investment. Additional policy support is needed to provide farmers with CSA data and funding.

- ***Recommendation 1.*** *Congress should preserve the existing IRA funds for conservation programs so the USDA can proceed with the full multiyear funding allocations to expand the adoption of CSA practices.*

It is critical that the multiyear funding provided in the IRA continue to be focused on the adoption of CSA practices. Currently, the IRA fund is dedicated to the programs that generate climate mitigation benefits. If the current IRA funds are broadened to include conservation practices that do not provide comparable CSA benefits, maintaining the momentum of surging farmer interest in CSA practices would be diminished.

- ***Recommendation 2.*** *The USDA should provide farmers with a comprehensive information package, including grants, loan programs, technical support, tools and contracts, which can be used to invest in CSA practices.*

The USDA has provided a wide range of financial and technical support for farmers, but many farmers are still not benefiting from the programs because many grants are popular and oversubscribed. Meanwhile, several loan programs have been underutilized even though they support investment in agricultural operations, such as purchasing equipment for precision agriculture. For example, the Conservation Loan Program has disbursed no loans since 2017.[44] The USDA should provide comprehensive information to farmers, including about its grants and loan programs, as well as tools and best practices. Beyond making the information package publicly available, the USDA should raise awareness of the package among corn growers via outreach and educational activities.

- ***Recommendation 3.*** *The USDA should accelerate collecting field-based data on CSA practices, develop an MMRV framework for CSA practices, and disseminate the data and framework to stakeholders, including federal agencies designing incentive programs, GREET modelers, farmers, and the ethanol industry.*

The lack of a robust MMRV framework is a barrier to accelerating the adoption of CSA practices. The IRS adopted a bundling approach for CSA practices under the 40B SAF credit, rather than basing it on the actual carbon intensity of each practice partially because of limitations in verification mechanisms. The IRA provided $300 million over eight years to expand USDA MMRV programs to improve data, models, and tools for quantifying the impact of agricultural practices on GHG emissions and carbon sequestration. The USDA should work to improve these efforts, and disseminate widely to relevant federal agencies, farmers, and the ethanol industry.

- ***Recommendation 4.*** *The IRS, working with DOE, should expand the portfolio of CSA practices that can be considered in qualification for the 45Z credit to include all GREET options. Also, the IRS should allow flexibility in letting farmers select individual measures in a practice-by-practice fashion, rather than require bundling of measures–as has been done with the current SAF tax credit (40B).*

The 45Z credit is designed to incentivize the adoption of CSA practices that contribute to emissions reductions. However, requiring the bundling of CSA practices (specifically, no-till farming, cover-cropping, and enhanced efficiency nitrogen management) as a prerequisite for qualification could limit the flexibility of farmers, potentially discouraging participation. Not all CSA practices may be relevant or feasible for every farm, and bundling could impose unnecessary constraints.

Instead, allowing credit qualification based on the emissions reductions achieved for each practice individually would provide a stronger incentive for farmers to consider the appropriate portfolio of actions. This approach would encourage innovation and tailor CSA adoption to the unique circumstances of each farm, ultimately leading to more significant and verifiable emissions reductions.

- ***Recommendation 5.*** *The IRS, in collaboration with the USDA, should consider ways to help ethanol producers share the value of these credits with corn growers who contributed to reducing the carbon intensity of ethanol by adopting CSA practices.*

Assigning a portion of the 45Z credit value to corn growers who adopt CSA practices would recognize and reward their critical role in reducing the CI of ethanol production. By collaborating with the USDA to develop a framework for assigning credit value to these growers, the IRS would incentivize broader adoption of CSA practices and ensure that the benefits of the 45Z credit are equitably distributed across the supply chain.

Production Tax Credits

The 45Z production tax credit, which becomes effective in 2025, can provide a powerful incentive for the production of lower-CI ethanol for use as a gasoline blending agent and to significantly expand SAF supplies. It also could further reduce the CI of ethanol blends in gasoline. Under current law, the 45Z credit will apply only until Dec. 31, 2027. This period of time is insufficient to incentivize the capital investment needed to reduce the CI throughout the ethanol life cycle.

- ***Recommendation 6.*** *Congress should modify the 45Z clean fuels tax credit in a manner similar to other IRA incentives, i.e., extend it for 10 years to facilities that commence production of qualified transportation fuels by Jan. 1, 2033.*

Extending the 45Z tax credit is essential for ensuring ethanol decarbonization efforts are able to get off the ground and are profitable in early years. Currently, the credit expires in three years, on Dec. 31, 2027. By comparison, the 45Q tax credit for carbon sequestration and the 45V clean hydrogen production tax credit are eligible for 10 to12 years for the facilities built prior to 2033. Extending 45Z will help build the SAF market and facilitate adoption of renewable fuels for vehicles used in the ethanol value chain.

- ***Recommendation 7.*** *DOE, in collaboration with the USDA, should continue improving the GREET model to reflect a broader range of emissions-reduction practices, such as options for combined heat and power. These practices should be incorporated into the IRS 45Z guidance.*

Continuing to improve the GREET model in collaboration with the USDA and DOE is essential for accurately reflecting the full spectrum of emissions-reduction practices in agriculture and biofuel production. By incorporating a broader range of measures for decarbonizing the energy use in the ethanol supply chain into the model, the emissions reductions achieved through diverse technologies and practices could be fully recognized and rewarded. This provides more precise incentives for adopting low-carbon practices by aligning federal tax credits with the latest advancements in sustainability. Updating the GREET model to include these practices in the IRS 45Z guidance will enhance the model's utility as a comprehensive measure of carbon intensity and drive more significant emissions reductions across the biofuel supply chain.

Decarbonizing Energy Use in Biorefineries

Natural gas accounts for 91% of energy consumption at biorefineries, contributing significantly to ethanol’s carbon intensity. Alternatives such as renewable natural gas and clean hydrogen blended with natural gas can be used as drop-in fuels to reduce ethanol’s CI score. Both agricultural and landfill biogas resources are abundant in the Midwest but conversion to RNG production has been limited. The impediments include large upfront capital investment requirements, lack of transportation infrastructure, and fragmented market demand. Other options that could also significantly lower ethanol’s CI from electricity use are procuring carbon-free electricity from utilities that are decarbonizing their generation portfolio, seeking direct power purchase agreements (PPAs) with clean electricity generators, or purchasing renewable energy certificates, such as energy attribute certificates (EACs), with independent power producers.

- ***Recommendation 8.*** *Ethanol producers should seek opportunities to increase carbon-free sources of electricity for use at biorefineries—including electricity from biomass and other renewables, hydrogen, nuclear, hydropower, and others—in cases where the grid is not being decarbonized fast enough.*

Ethanol producers should consider opportunities to boost supplies of carbon-free electricity for use at biorefineries, including from renewables, hydrogen, nuclear, and other low-carbon sources. These should include working with current electric utilities (investor-owned, municipal utilities and cooperatives) to support their efforts to decarbonize their generation mix. Producers also could include seeking opportunities to solicit direct power purchase agreements (PPAs) for clean electricity. Finally, they could investigate options for on-site generation. Long-Term PPAs, for example, could provide ethanol producers with more stable and predictable electricity costs while enhancing supply security by securing longer-term access to clean electricity.

- ***Recommendation 9****. Ethanol producers should consider measures to decarbonize process heat, including biofuels and RNG—for example, facilitating demand aggregation that could incentivize expanded RNG production while mitigating financial risks. Market demand formation measures could range from establishing RNG certificate programs to forming buyers' cooperatives.*

Ethanol producers should consider opportunities for encouraging formation of clean fuels markets that can support the use of clean fuels such as RNG and hydrogen, as this collective approach, such as a purchasing collective, could provide the market certainty that RNG producers would need to finance new RNG conversion facilities. This cooperative strategy would strengthen the financial stability of individual producers and support the broader goal of reducing carbon intensity in ethanol production. Agreements to purchase RNG certificates, in instances where physical delivery is not feasible, also could provide the necessary incentive for RNG market formation.

Decarbonizing Fertilizers

Decarbonizing the production of fertilizers could significantly reduce ethanol's CI, as the emissions from fertilizer production account for about 11% of ethanol's carbon intensity. Low-carbon fertilizer production from either blue hydrogen or green hydrogen currently is more costly than conventional fertilizer supplies. Farmers are not motivated to pay a significant premium for low-carbon fertilizers, given their small profit margins and uncertain incentives for using them. Implementation of the new 45V tax credit for clean hydrogen, as well as DOE's hydrogen hubs program and the Hydrogen Demand Initiative,[aa] could potentially close this gap.

- ***Recommendation 10.*** *DOE's hydrogen hubs program and the Hydrogen Demand Initiative (H2DI) should consider making clean ammonia one of their early targets for financial support.*

In October 2023, DOE selected seven regional clean hydrogen hubs to receive $7 billion in funding to accelerate clean hydrogen market formation. In January 2024, DOE selected a consortium, the Hydrogen Demand Initiative (H2DI), to design and implement demand-side support mechanisms for unlocking the potential of regional hydrogen hubs. The proposed Heartland Hydrogen Hub, located in Montana, North Dakota, and

---

[aa] The Hydrogen Demand Initiative is a consortium selected by DOE and led by the EFI Foundation to help accelerate the commercial liftoff of the clean hydrogen economy.

South Dakota, plans to supply clean fertilizer to local farmers.[169] DOE and H2DI should work closely with hub developers to ensure the successful development and operation of hubs focused on clean ammonia.

- ***Recommendation 11.*** *The USDA should re-open and repurpose its domestic fertilizer production program, focusing on retrofitting existing facilities to produce low-carbon fertilizers using funds from the Commodity Credit Corporation (CCC). Congress should not restrict the USDA's authority to use CCC funds for this purpose in pending farm bill legislation.*

The USDA provided grants to business owners to help boost domestic fertilizer production and provide affordable fertilizers to U.S. farmers through the Fertilizer Production Expansion Program (FPEP) with the CCC funds. Since the start of the Biden-Harris administration, the USDA has invested more than $166 million in 40 domestic fertilizer production projects nationwide.[170] Although the USDA requires applicants of the FPEP to show that their projects reduce GHG impact, the program focuses more on expanding the capacity of domestic production. Among the selected projects, only a few described expected climate impacts, which were mostly indirect, such as purchasing climate-smart equipment for more efficient use of fuel, rather than producing low-carbon fertilizer.[171]

Reopening and repurposing the domestic fertilizer production program to focus on decarbonizing fertilizer production could provide the additional boost to scale the clean fertilizer market.

Demand-Side Mandates for Clean Fuels

Demand-side mandates can have a synergistic effect when added to production incentives. State-level low-carbon fuel standard (LCFS) policies, for example, have proven effective in reducing the carbon intensity of ethanol. California's LCFS, has led to a 25% reduction in ethanol's carbon intensity since its implementation in 2011.[172]

However, creating a national clean fuel standard (CFS) requires further investigation into policy design options, as the specifics of the standard substantially shape its efficacy. State-level LCFS programs have been evolving to address challenges such as fluctuating prices. For example, the California Air Resources Board (CARB) considered adjusting near-term targets to address the growing oversupply of credits and the decline in prices this year.[173] A national CFS should be designed by carefully considering the lessons learned from the experience of state-level LCFSs policies.

In addition, a key issue in the design of a national CFS is the interplay between a CFS and the existing federal Renewable Fuel Standard (RFS) program. The current RFS target implicitly considers the blend rates of ethanol in gasoline when setting the target. A CFS could encourage higher blend rates reflecting the fact that today, the vast majority of on-road vehicles are capable of using blends up to 15%.[174]

- ***Recommendation 12.*** *The administration should launch an interagency study of the feasibility of a national CFS, including a process for broad public engagement.*

The success of state-level LCFS suggests that similar benefits could be realized on a larger scale, promoting cleaner fuel production and contributing to national decarbonization goals. A nationwide CFS could harmonize efforts across states, provide a consistent regulatory framework, encourage investment in low-carbon technologies and fuels, and ultimately lead to a significant reduction in the carbon footprint of transportation fuels across the country. Further, when combined with the technology-neutral 45Z tax credit, a federal CFS would create a robust financial and regulatory environment that encourages the use of, production of, and investment in low-carbon technologies and fuels. This dual approach ensures that ethanol producers have immediate and long-term incentives to reduce emissions, fostering innovation and investment in cleaner production methods and ultimately contributing to national climate goals.

However, further analysis is needed to fully develop and optimize this approach. A comprehensive assessment of regional variations in fuel production and consumption, as well as the potential economic impacts on different sectors, is essential. Additionally, understanding the infrastructure and technological advancements required to support a national CFS will be crucial in ensuring its feasibility and effectiveness. Finally, the interplay between a proposed CFS and the existing RFS program is needed to understand areas of overlap. Such analysis will help tailor the policy to address specific challenges and opportunities, maximizing its benefits while minimizing any adverse effects.

- ***Recommendation 13.*** *The U.S. Environmental Protection Agency (EPA) should consider the feasibility of higher blending levels in the formulation of RFS standards, and states should consider expanding current mandates, including establishing requirements for E15 and higher blends in gasoline.*

Lastly, the EPA should explore options for incorporating higher blending levels in the formulation of RFS targets, focusing on increasing the proportion of low-carbon fuels in the national fuel mix to drive greater emissions reductions.

8. Next Steps

EFIF’s roadmap identifies key pathways for transforming the U.S. ethanol industry into a net-zero, sustainable biofuel industry capable of meeting the demands of a net-zero economy. By focusing on decarbonizing farming and biorefinery processes and fostering an environment for net-zero ethanol through a national CFS and technology-neutral SAF production tax credit, this roadmap outlines the steps necessary to reduce the ethanol industry’s carbon intensity. These efforts will enable the ethanol industry to support the broader transition to a sustainable, low-carbon energy system.

This roadmap also identifies additional research areas that require further exploration. They are listed below.

How can stakeholders share the cost of decarbonizing the ethanol supply chain?

Decarbonizing the ethanol supply chain is costly, and determining effective cost-sharing mechanisms among stakeholders is crucial to ensure sustainable implementation. This is important because it reduces the financial burden on ethanol producers and farmers, facilitating the adoption of decarbonization practices. Potential research areas should focus on identifying and evaluating various cost-sharing strategies, such as government funding, loans, and collaborative industry investments. Pilot programs and case studies can provide valuable insights, helping to refine these mechanisms and promote the widespread adoption of sustainable practices.

What is the role of ethanol in sustainable aviation fuel?

Understanding the potential of sustainable aviation fuel (SAF) requires examining the competition for bioenergy feedstocks among sectors such as power, heavy-duty transportation, and building heating. This is crucial because each feedstock presents unique challenges and benefits in terms of availability, cost, and life cycle emissions, impacting the scalability of SAF production. Potential research areas should analyze these competitive dynamics and their implications for SAF, focusing on optimizing feedstock use and developing strategies for effective SAF integration into the aviation sector. Energy systems modeling and case studies can provide essential data to inform policies and strategies aimed at achieving net-zero emissions.

How can the cost gap between SAF and conventional jet fuel be filled?

There is a significant cost gap between SAF and conventional jet fuel, which is also observed between ATJ E-SAF and SAF produced with other feedstocks.[175] Such cost gaps can be addressed by tax credits, subsidies, and mandates for SAF usage. For instance, this roadmap recommends extending the 45Z tax credit, whose value could also be increased to make SAF more economically viable. Subsidies for SAF producers can lower production costs, while mandates for SAF blending in aviation fuel can create a guaranteed market, driving demand and encouraging investment in SAF production. These policy measures can help bridge the cost gap, which is crucial because it directly impacts the economic viability and widespread adoption of SAF. Further research could focus on economic models to assess the effectiveness of these policies in bridging the cost gap and accelerating SAF adoption in the aviation sector.

References

[1] Uisung Lee et al., "Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions," *Biofuels, Bioproducts and Biorefining* 15, no. 5 (2021): 1318-1331, https://doi.org/10.1002/bbb.2225.

[2] Argonne National Laboratory, "R&D GREET Model," Energy Systems and Infrastructure Analysis, accessed September 4, 2024, https://greet.anl.gov/index.php.

[3] U.S. Environmental Protection Agency, Greenhouse Gas Inventory Data Explorer, https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

[4] Rhodium Group. "Closing the *Transportation Emissions Gap* with Clean Fuels." January 14, 2021, https://rhg.com/wp-content/uploads/2021/01/Closing-the-Transportation-Emissions-Gap-with-Clean-Fuels-1.pdf.

[5] U.S. Department of Energy, Alternative Fuels Data Center, "Global Ethanol Production by Country or Region," accessed July 22, 2024, https://afdc.energy.gov/data/10331.

[6] U.S. Energy Information Administration, March 2024 Monthly Energy Review, Table 10.3 "Fuel Ethanol Overview," https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.03.

[7] Renewable Fuels Association, "Ethanol Industry's Impact on the U.S. Economy Strengthened in 2022," accessed February 6, 2024, https://ethanolrfa.org/media-and-news/category/news-releases/article/2023/02/new-study-ethanol-industry-s-impact-on-the-u-s-economy-strengthened-in-2022.

[8] U.S. Department of Agriculture, "What is agriculture's share of the overall U.S. economy?" April 19, 2024, https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58270#:~:text=Agriculture%2C%20food%2C%20and%20related%20industries,0.7%20percent%20of%20U.S.%20GDP.

[9] U.S. Department of Energy, "Alternative Fuels Data Center, Ethanol Fuel Basics," accessed February 9, 2024, https://afdc.energy.gov/fuels/ethanol_fuel_basics.html.

[10] Rita H. Mumm et al., "Land Usage Attributed to Corn Ethanol Production in the United States: Sensitivity to Technological Advances in Corn Grain Yield, Ethanol Conversion, and Co-Product Utilization," *Biotechnology for Biofuels* 7, no. 61 (April 2014): https://doi.org/10.1186/1754-6834-7-61.

[11] Statista, "U.S. Farming: Total Land in Farms 2022," accessed June 8, 2023, https://www.statista.com/statistics/196104/total-area-of-land-in-farms-in-the-us-since-2000/.

[12] Renewable Fuels Association, "Contribution of the Ethanol Industry to the Economy of the United States in 2022," accessed February 6, 2024, https://d35t1syewk4d42.cloudfront.net/file/2428/Ethanol%20Industry%20Contribution%20to%20the%20US%20Economy%20in%202022.pdf.

---

[13] Krista Swanson, "Qualifying Acres in the 40B Conservation Programs," National Corn Growers Association, July 18, 2024, https://ncga.com/stay-informed/media/the-corn-economy/article/2024/07/qualifying-acres-in-the-40b-conservation-programs.

[14] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," planted corn, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/E68171F8-6E5B-3BA8-959E-2BD06DBEA74E.

[15] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," yield corn, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/E68171F8-6E5B-3BA8-959E-2BD06DBEA74E.

[16] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," planted barley, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/3501331A-FEFF-3E4A-B825-6A3768A0954E.

[17] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," planted rice, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/CAC86491-9916-3EDC-AA01-F0366E2CFC4D.

[18] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," planted wheat, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/8CDCF8FE-E9C1-3D90-9A07-AB7CD068A3A3.

[19] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," planted soybean, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/7DCA61AE-5725-3FC9-B991-6B5573FD7D39.

[20] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," yield barley, accessed August 22, 2024, https://quickstats.nass.usda.gov/#3501331A-FEFF-3E4A-B825-6A3768A0954E.

[21] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," yield rice, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/432606ED-9C30-37B2-A634-E8FD3010D409.

[22] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," yield wheat, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/92A993E7-CB85-3863-AAC6-F6D5B7CC33C8.

[23] U.S. Department of Agriculture, National Agricultural Statistics Service, "Quick Stats," yield soybean, accessed August 22, 2024, https://quickstats.nass.usda.gov/results/98C856E2-C640-367F-B858-8921BC53F3F6.

[24] U.S. Environmental Protection Agency, *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*, June 2018, https://www.epa.gov/sites/default/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf.

---

[25] U.S. Department of State and U.S. Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, p. 30, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

[26] Felix Creutzig et al., “Towards Demand-Side Solutions for Mitigating Climate Change,” *Nature Climate Change* 8 (April 2018): 260–63, https://doi.org/10.1038/s41558-018-0121-1.

[27] U.S. Energy Information Administration, Annual Energy Outlook 2023, High IRA Uptake case, https://www.eia.gov/outlooks/aeo/.

[28] International Energy Agency, “*Global EV Outlook 2024: Trends in Electric Cars,”* accessed August 29, 2024, https://www.iea.org/reports/global-ev-outlook-2024/trends-in-electric-cars.

[29] Deloitte, *Electric Vehicles: Setting a Course for 2030*, Deloitte Insights, accessed August 29, 2024, https://www2.deloitte.com/content/dam/insights/us/articles/22869-electric-vehicles/DI_Electric-Vehicles.pdf.

[30] Joseph White, “US automakers race to build more hybrids as EV sales slow,” *Reuters*, March 15, 2024, https://www.reuters.com/business/autos-transportation/us-automakers-race-build-more-hybrids-ev-sales-slow-2024-03-15/.

[31] Sourasis Bose, "U.S. sustainable aviation fuel production target faces cost, margin challenges," *Reuters*, November 1, 2023, https://www.reuters.com/sustainability/us-sustainable-aviation-fuel-production-target-faces-cost-margin-challenges-2023-11-01/.

[32] Inflation Reduction Act of 2022, Pub L. No. 117-169, 136 Stat. 1818, 2022.

[33] Berkeley Center for Law and the Environment, “California Climate Policy Fact Sheet: Low Carbon Fuel Standard,” https://www.law.berkeley.edu/wp-content/uploads/2019/12/Fact-Sheet-LCFS.pdf.

[34] Oregon Department of Environmental Quality, *Oregon Clean Fuels Program: Program Review*, February 1, 2022, https://www.oregon.gov/deq/ghgp/Documents/CFPProgramReview.pdf.

[35] State of Washington, Engrossed Substitute Senate Bill 5447, April 19, 2023, https://lawfilesext.leg.wa.gov/biennium/2023-24/Pdf/Bills/Senate%20Passed%20Legislature/5447-S.PL.pdf?q=20230502125608.

[36] J. Rosenfeld et al., *The California Low Carbon Fuel Standard: Incentivizing Greenhouse Gas Mitigation in the Ethanol Industry,* U.S. Department of Agriculture Office of the Chief Economist, November 2020, https://www.usda.gov/sites/default/files/documents/CA-LCFS-Incentivizing-Ethanol-Industry-GHG-Mitigation.pdf.

[37] David M. McCulough et al., "Revving Up: Eight States in Gear with Low Carbon Fuel Standard Legislation," Pillsbury Law Review (2024): 1-6, https://www.pillsburylaw.com/print/v2/content/1042127/eight-states-low-carbon-fuel-standard-legislation.pdf.

[38] U.S. Department of Agriculture Natural Resources Conservation Service, “Inflation Reduction Act Investments,” accessed July 1, 2024, https://www.nrcs.usda.gov/about/priorities/inflation-reduction-

---

act#:~:text=The%20Inflation%20Reduction%20Act%20provides,yield%20climate%20change%20mitigation%20benefits.

[39] U.S. Department of Agriculture, “As USDA Sees Record Interest in Conservation and Clean Energy Programs, Swift Implementation of Inflation Reduction Act Funding Continues,” accessed September 4, 2024, https://www.usda.gov/media/press-releases/2023/09/19/usda-sees-record-interest-conservation-and-clean-energy-programs.

[40] U.S. Environmental Protection Agency, Renewable Fuel Standard (RFS) Program: Standards for 2023, 2024, and 2025, Federal Register, July 12, 2023, https://www.govinfo.gov/content/pkg/FR-2023-07-12/pdf/2023-13462.pdf.

[41] U.S. Energy Information Administration, “Almost all U.S. gasoline is blended with 10% ethanol,” accessed September 5, 2024, https://www.eia.gov/todayinenergy/detail.php?id=26092.

[42] Scott Richman, “Ag Census Confirms Cropland Decline, Adoption of Environmental Practices,”, Renewable Fuels Association, February 15, 2024, https://ethanolrfa.org/media-and-news/category/blog/article/2024/02/ag-census-confirms-cropland-decline-adoption-of-environmental-practices#:~:text=No%2Dtill%20has%20increased%20to,38%25%20(Figure%203).

[43] Qu Zhou et al., "Recent Rapid Increase of Cover Crop Adoption Across the U.S. Midwest Detected by Fusing Multi-Source Satellite Data," *Geophysical Research Letters* 49, no. 22 (2022): e2022GL100249, https://doi.org/10.1029/2022GL100249.

[44] U.S. Government Accountability Office, Precision Agriculture: Benefits and Challenges for Technology Adoption and Use, January 2024, https://www.gao.gov/products/gao-24-105962.

[45] UC Davis Institute of Transportation Studies, "Status Review of California’s LCFS," September 2018, accessed August 7, 2024, https://its.ucdavis.edu/research/californias-low-carbon-fuel-standard/.

[46] U.S. Environmental Protection Agency, “E15 Fuel Registration,” Fuels Registration, Reporting, and Compliance Help, accessed September 4, 2024, https://www.epa.gov/fuels-registration-reporting-and-compliance-help/e15-fuel-registration.

[47] Caley Johnson et al, *History of Ethanol Fuel Adoption in the United States: Policy, Economics, and Logistics*, National Renewable Energy Laboratory, November 2021, p.1-14. https://www.nrel.gov/docs/fy22osti/76260.pdf .

[48] U.S. Department of Energy, "Maps and Data,” Alternative Fuel Data Center, accessed August 22, 2024, https://afdc.energy.gov/data

[49] Renewable Fuels Association, “Ethanol Industry Contribution to the U.S. Economy in 2022,” 2022, p. 1-16, https://d35t1syewk4d42.cloudfront.net/file/2428/Ethanol%20Industry%20Contribution%20to%20the%20US%20Economy%20in%202022.pdf.

[50] Renewable Fuels Association, “Ethanol Industry’s Impact on the U.S. Economy Strengthened in 2022”, Renewable Fuels Association,” February 28, 2023,accessed February 6, 2024,

---

https://ethanolrfa.org/media-and-news/category/news-releases/article/2023/02/new-study-ethanol-industry-s-impact-on-the-u-s-economy-strengthened-in-2022

[51] U.S. Department of Agriculture, “What is agriculture's share of the overall U.S. economy?” Economic Research Service, April 19, 2024, https://www.ers.usda.gov/data-products/chart-gallery/gallery/chart-detail/?chartId=58270#:~:text=Agriculture%2C%20food%2C%20and%20related%20industries,0.7%20percent%20of%20U.S.%20GDP .

[52] Renewable Fuels Association, “Ethanol Industry’s Impact on the U.S. Economy Strengthened in 2022,” February 28, 2023, accessed February 6, 2024, https://ethanolrfa.org/media-and-news/category/news-releases/article/2023/02/new-study-ethanol-industry-s-impact-on-the-u-s-economy-strengthened-in-2022

[53] U.S. Energy Information Administration. "Ethanol Can Be Used As A Transportation Fuel" Biofuels Explained: ethanol, accessed September 12, 2024. https://www.eia.gov/energyexplained/biofuels/ethanol-use.php .

[54] U.S. Energy Information Administration. "Biofuels Explained," accessed September 12, 2024. https://www.eia.gov/energyexplained/biofuels/#:~:text=In%202022%2C%20about%2018.7%20billion,17.6%20billion%20gallons%20were%20consumed.

[55] U.S. Energy Information Administration , “Petroleum Supply Annual, Volume 1,” Petroleum’s & Other Liquids, accessed September 12, 2024, https://www.eia.gov/petroleum/supply/annual/volume1/.

[56] U.S. Energy Information Administration,“Table 10.3” Fuel Ethanol Overview,” March 2024 Monthly Energy Review, accessed September 12, 2024, https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T10.03 .

[57] U.S. Energy Information Administration , “Table 17. Renewable Energy Consumption by Sector and Source,” Annual Energy Outlook 2023”, accessed September 12, 2024. https://www.eia.gov/outlooks/aeo/data/browser/#/?id=24-AEO2023&region=0-0&cases=ref2023&start=2021&end=2050&f=A&linechart=ref2023-d020623a.4-24-AEO2023~ref2023-d020623a.16-24-AEO2023~ref2023-d020623a.36-24-AEO2023~ref2023-d020623a.37-24-AEO2023~ref2023-d020623a.38-24-AEO2023~ref2023-d020623a.39-24-AEO2023&map=&ctype=linechart&sourcekey=0

[58] U.S. Energy Information Administration, “U.S. Exports of Fuel Ethanol,” Petroleum’s & Other Liquids, accessed April 18, 2024 https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=m_epooxe_eex_nus-z00_mbbl&f=a .

[59] Renewable Fuels Association ,“Ethanol Trade & Exports.” accessed February 21, 2024, https://ethanolrfa.org/policy/trade-and-exports.

[60] U.S. Department of Agriculture, “Ethanol 2021 Export Highlights” Foreign Agricultural Service, accessed February 13, 2024, https://fas.usda.gov/ethanol-2021-export-highlights.

[61] U.S. Department of Energy, “Ethanol Fuel Basics.” Alternative Fuels Data Center, accessed February 9, 2024. https://afdc.energy.gov/fuels/ethanol_fuel_basics.html.

---

[62] Rita H. Mumm et al., "Land Usage Attributed to Corn Ethanol Production in the United States: Sensitivity to Technological Advances in Corn Grain Yield, Ethanol Conversion, and Co-Product Utilization," Biotechnology for Biofuels 7, no. 1, (April 12, 2014): page 61, https://doi.org/10.1186/1754-6834-7-61.

[63] Statista, "U.S. Farming: Total Land in Farms 2022," Statista, accessed June 8, 2023, https://www.statista.com/statistics/196104/total-area-of-land-in-farms-in-the-us-since-2000/.

[64] Renewable Fuel Association, "2022 Pocket Guide to Ethanol,"2022, p.1-16 accessed February 7, 2024 https://d35t1syewk4d42.cloudfront.net/file/2144/RFA%202022%20Pocket%20Guide.pdf.

[65] U.S. Department of Agriculture, National Agricultural Statistics Service. "USDA Prospective Plantings Report 2024." March 28, 2024. https://www.nass.usda.gov/Newsroom/2024/03-28-2024.php.

[66] U.S. Department of Energy, "Global Ethanol Production by Country or Region," Alternative Fuels Data Center accessed February 6, 2024, https://afdc.energy.gov/data/10331

[67] International Energy Agency, "Ordinance No 75/2015 on Ethanol Blending Mandate " July 9, 2024, accessed July 16, 2024, https://www.iea.org/policies/2021-ordinance-no-752015-on-ethanol-blending-mandate?s=1 .

[68] Mingho Li et al.,"China's New Nationwide E10 Ethanol Mandate and Its Global Implications," Agricultural Policy Review, accessed July 16, 2024, https://agpolicyreview.card.iastate.edu/fall-2017/chinas-new-nationwide-e10-ethanol-mandate-and-its-global-implications.

[69] U.S. Department of Agriculture, "Biofuel Mandates in the EU by Member State," July 5, 2022, https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuel%20Mandates%20in%20the%20EU%20by%20Member%20State%20-%202022_Berlin_European%20Union_E42022-0044.pdf .

[70] U.S. Grains Council, 2024, "Ethanol Mission To Ottawa Focuses On Enhancing Blending," March 28, 2024. https://grains.org/ethanol-mission-to-ottawa-focuses-on-enhancing-blending/.

[71] Argonne National Laboratory. *Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model*, accessed September 11, 2024 https://greet.anl.gov/

[72] California Air Resources Board. "LCFS Pathway Certified Carbon Intensities." Accessed August 22, 2024. https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities. CARB ILUC values replaced with R&D GREET ILUC values.

[73] Hui Xu,"Life-Cycle Greenhouse Gas Emissions Reduction Potential for Corn Ethanol Refining in the USA," Biofuels, Bioproducts and Biorefining 16, no. 3 (2022): 671–81. https://doi.org/10.1002/bbb.2348.

[74] Argonne National Laboratory, "Summary of Expansions and Updates in Greet 2021," accessed July 11, 2024. https://greet.anl.gov/files/greet-2021-summary.

[75] U.S. Environmental Protection Agency, *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities*, June 2018, https://www.epa.gov/sites/default/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf

---

[76] Scott Irwin, "Trends in the Operational Efficiency of the U.S. Ethanol Industry: 2023 Update." *farmdoc daily* University of Illinois Urbana-Champaign, February 8, 2024, https://farmdocdaily.illinois.edu/2024/02/trends-in-the-operational-efficiency-of-the-u-s-ethanol-industry-2023-update.html.

[77] Renewable Fuels Association, *Pathways to Net-Zero Ethanol: Scenarios for Ethanol Producers to Achieve Carbon Neutrality by 2050* , February 2022, p. 1-47, https://d35t1syewk4d42.cloudfront.net/file/2146/Pathways%20to%20Net%20Zero%20Ethanol%20Feb%202022.pdf

[78] Global CCS Institute, “Global Status of CCUS Report 2023,” https://status23.globalccsinstitute.com/

[79] EFI, Turning CCUS Projects in Heavy Industry and Power into Blue Chip Financial Investments, February 14, 2023, https://efifoundation.org/reports/turning-CCUS-projects-in-heavy-industry-into-blue-chip-financial-investments/

[80] Corey Lavinsky,“Cancellation of Navigator CO2 Pipeline Raises Critical Issues for Several Industries,” S&P Global Commodity Insights, October 25, 2023, https://www.spglobal.com/commodityinsights/en/market-insights/blogs/energy-transition/102523-navigator-co2-carbon-capture-heartland-greenway-pipeline-cancellation.

[81] Summit Carbon Solutions, “Project Footprint,” accessed June 26, 2024, https://summitcarbonsolutions.com/project-footprint/

[82] Bold Nebraska, "Tallgrass, Bold Alliance, and Key Agricultural and First Responder Organizations Announce a Community Benefits Agreement," accessed August 22, 2024, https://boldnebraska.org/tallgrass-bold-alliance-and-key-agricultural-and-first-responder-organizations-announce-a-community-benefits-agreement/.

[83] U.S. Energy Information Administration, “How much carbon dioxide is produced per kilowatthour of U.S. electricity generation?” Frequently Asked Questions (FAQs), accessed September 10, 2024. https://www.eia.gov/tools/faqs/faq.php?id=74&t=11

[84] Lawrence Berkeley National Laboratory, *Wind Technologies Market Report*, accessed August 22, 2024, https://emp.lbl.gov/wind-technologies-market-report/.

[85] Lawrence Berkeley National Laboratory, *Utility-Scale Solar: 2023 Edition*, accessed August 22, 2024, https://emp.lbl.gov/publications/utility-scale-solar-2023-edition.

[86] U.S. Energy Information Administration, “Wholesale U.S. electricity prices were relatively low in 2023,” Today in Energy, accessed September 10, 2024, https://www.eia.gov/todayinenergy/detail.php?id=61445

[87] U.S. Environmental Protection Agency, "U.S. Renewable Electricity Market," accessed August 22, 2024, https://www.epa.gov/green-power-markets/us-renewable-electricity-market.

[88] U.S. Department of Energy, “CHP Installations”, U.S. Department of Energy Combined Heat and Power and Microgrid Installation Databases, accessed September 11, 2024. https://doe.icfwebservices.com/chp

---

[89] U.S. Department of Energy, “There Is a Cornucopia of Feedstock Options for Making Biofuels,”accessed September 10, 2024, https://www.energy.gov/eere/articles/there-cornucopia-feedstock-options-making-biofuels#:~:text=Corn%20Husks%20and%20Stalks,DuPont's%20biorefinery%20in%20Nevada%2C%20Iowa.

[90] Clean Air Taskforce, “Fact Sheet: Hydrogen Blending – Not a serious decarbonization pathway,” May 2, 2024, https://www.catf.us/resource/hydrogen-blending-not-serious-decarbonization-pathway/

[91] Kevin Topolski, et al., *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology*, National Renewable Energy Laboratory, 2022, NREL/TP5400-81704, https://www.nrel.gov/docs/fy23osti/81704.pdf.

[92] Frank Jossi, “California clean fuel standard sparks renewable gas boom in Midwest” *Energy News Network*, May 13, 2021, https://energynews.us/2021/05/13/california-clean-fuel-standard-sparks-renewable-gas-boom-in-midwest/

[93] U.S. Environmental Protections Agency, *Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities, 2018, p.1-11,* https://www.epa.gov/sites/default/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf

[94] U.S. Department of Agriculture, “Climate-Smart Agriculture and Forestry,” accessed June 26, 2024, https://www.farmers.gov/conservation/climate-smart

[95] U.S. Department of Agriculture, “NRCS Climate-Smart Mitigation Activities,” accessed September 11, 2024, https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/climate/climate-smart-mitigation-activities

[96] U.S. Department of the Treasury, “U.S. Department of the Treasury, IRS Release Guidance to Drive American Innovation, Cut Aviation Sector Emissions”, Press Releases, accessed September 11, 2024, https://home.treasury.gov/news/press-releases/jy2307

[97] J. S. Bergtold et al., “A review of economic considerations for cover crops as a conservation practice,” (2017), *Renewable Agriculture and Food Systems*, 34(1), 62–77, https://doi.org/10.1017/S1742170517000278

[98] Jennifer B. Dunn et al., “Energy Consumption and Greenhouse Gas Emissions from Enzyme and Yeast Manufacture for Corn and Cellulosic Ethanol Production," *Biotechnology for Biofuels* 6, no. 1 (2013): 1-15. https://doi.org/10.1016/j.biombioe.2013.01.041 .

[99] U.S. Department of Agriculture, “As USDA Sees Record Interest in Conservation and Clean Energy Programs, Swift Implementation of Inflation Reduction Act Funding Continues,” September 19, 2023, https://www.usda.gov/media/press-releases/2023/09/19/usda-sees-record-interest-conservation-and-clean-energy-programs .

[100] Ziqi Qin et al., "Assessing long-term impacts of cover crops on soil organic carbon in the central US Midwestern agroecosystems," *Global change biology* 29, no. 9 (2023): 2572-2590, https://doi.org/10.1111/gcb.16632 .

---

[101] President’s Council of Advisors on Science and Technology, Report to the President, “Accelerating Effective Reduction of Greenhouse Gas Emissions,” February 2024, PCAST_Greenhouse-Gas-Report_Feb2024-Letter-ExecSumm.pdf (whitehouse.gov)

[102] U.S. Department of Agriculture, Economic Research Service, "Trends in Production Practices and Costs of the U.S. Corn Sector," July 2021, accessed August 2, 2024 https://www.ers.usda.gov/webdocs/publications/100000/err-294.pdf.

[103] U.S. Department of Agriculture, National Agricultural Statistics Service, "Crop Production 2022 Summary," January 2023, accessed August 2, 2024, https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan22.pdf .

[104] Levi, Peter G., and Jonathan M. Cullen, "Mapping global flows of chemicals: from fossil fuel feedstocks to chemical products," *Environmental science & technology* 52, no. 4 (2018): 1725-1734, https://doi.org/10.1021/acs.est.7b04573

[105] Xinyu Liu et al., "Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products," Green Chemistry 22, no. 17 (2020): 5751-5761, https://doi.org/10.1039/D0GC02301A .

[106] A. Venkatesh, “U.S. Low-Carbon Ammonia: Costs and Resource Requirements, Low Carbon Resources Initiative,” Marcy 2024, https://www.epri.com/research/products/000000003002028977

[107] BloombergNEF, Scaling Up Hydrogen: The Case for Low-Carbon Ammonia, accessed January 11, 2024, https://www.bloombergneweconomy.com/news/scaling-up-hydrogen-the-case-for-low-carbon-ammonia/ .

[108] David Pimentel et al., “Ethanol production: energy, economic, and environmental losses," *Reviews of Environmental Contamination and Toxicology: Continuation of Residue Reviews* (2007): 25-41, https://doi.org/10.1007/978-0-387-35368-5_2 .

[109] Brittany Stale et al., Pathways for Agricultural Decarbonization in the United States, National Renewable Energy Laboratory (NREL), January 2024, https://www.nrel.gov/docs/fy24osti/86071.pdf

[110] Daniel L. Northrup et al, “Novel Technologies for Emission Reduction Complement Conservation Agriculture to Achieve Negative Emissions from Row-Crop Production,” Proceedings of the National Academy of Sciences 118 (28): e2022666118. https://doi.org/10.1073/pnas.2022666118.

[111] Jacob Whitson, “Study predicts steady growth in electric farm tractors,” June 1, 2023, https://www.farmprogress.com/farming-equipment/study-predicts-steady-growth-in-electric-farm-tractors

[112] U.S. Department of Energy, “Alternative Fuel Price Report,” Alternative Fuels Data Center, accessed September 11, 2024, https://afdc.energy.gov/fuels/prices.html

[113] U.S. Energy Information Administration, “Weekly Retail Gasoline, and Diesel Prices” Petroleum & Other Liquids, accessed September 11, 2024, https://www.eia.gov/dnav/pet/pet_pri_gnd_dcus_r20_m.htm

---

[114] U.S. Energy Information Administration, “Annual Energy Outlook 2023,” March 2023, accessed September 11, 2024, https://www.eia.gov/outlooks/aeo/ .

[115] Min Chen, and Paul M. Smith, "The US cellulosic biofuels industry: Expert views on commercialization drivers and barriers," *Biomass and Bioenergy* 102 (2017): 52-61, https://doi.org/10.1016/j.biombioe.2017.05.002

[116] U.S. Energy Information Administration, “What is U.S. electricity generation by energy source?,” accessed September 11, 2024, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

[117] Scott Irwin, "Trends in the Operational Efficiency of the U.S. Ethanol Industry: 2023 Update," *farmdoc daily*, University of Illinois Urbana Champaign, February 8, 2024, https://farmdocdaily.illinois.edu/2024/02/trends-in-the-operational-efficiency-of-the-u-s-ethanol-industry-2023-update.html.

[118] U.S. Department of Agriculture, National Agricultural Statistics Service, "Crop Production 2022 Summary," January 2023, accessed August 2, 2024, https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan22.pdf .

[119] David R. Kanter, and Timothy D. Searchinger, "A technology-forcing approach to reduce nitrogen pollution," Nature Sustainability 1, no. 10 (2018): 544-552, https://doi.org/10.1038/s41893-018-0143-8

[120] Global CCUS Institute, “Global Status of CCUS Report 2023,” https://status23.globalccsinstitute.com/

[121] U.S. Department of Energy, *2023 Billion-Ton Report: Assessment of U.S. Renewable Carbon Resources*, accessed August 22, 2024, https://www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources.

[122] International Energy Agency, *Ammonia Technology Roadmap Towards more sustainable nitrogen fertiliser production*, October 2021, p.1-160, https://www.iea.org/reports/ammonia-technology-roadmap .

[123] U.S. Energy Information Administration, “Annual Energy Outlook 2023”, Analysis and Projections, accessed September 11, 2024, https://www.eia.gov/outlooks/aeo/ .

[124] U.S. Environmental Protection Agency. *AgSTAR Market Opportunities for Biogas Recovery Systems at U.S. Livestock Facilities: 2018*. June 2018. https://www.epa.gov/sites/default/files/2018-06/documents/epa430r18006agstarmarketreport2018.pdf.

[125] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks Explorer*, accessed August 22, 2024, https://cfpub.epa.gov/ghgdata/inventoryexplorer/.

[126] U.S. Department of Energy, “Vehicle Weight Classes & Categories,” Alternative Fuels Data Center accessed September 20, 2021, https://afdc.energy.gov/data/10380#:~:text=EPA%20defines%20vehicle%20categories%2C%20also,(GVWR%20%3E%208%2C501%20lb).

[127] The White House, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, October 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

---

[128] Argonne National Laboratory, *Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model*,. ,A accessed August 22, 2024. https://greet.es.anl.gov/.

[129] U.S. Environmental Protections Agency, “Greenhouse Gas Emissions from a Typical Passenger Vehicle,” Overviews and Factsheets, January 12, 2016, https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle .

[130] Emily Wimberger et al., Closing the *Transportation Emissions Gap* with Clean Fuels, Rhodium Group. January 14, 2021, https://rhg.com/wp-content/uploads/2021/01/Closing-the-Transportation-Emissions-Gap-with-Clean-Fuels-1.pdf.

[131] The White House, "Fact Sheet: Biden Administration Advances the Future of Sustainable Fuels in American Aviation," last modified September 9, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/.

[132] U.S. Congress, *House Bill 5376: Build Back Better Act*, 117th Congress (2021-2022), accessed August 22, 2024, https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

[133] U.S. Department of Energy, "Sustainable Aviation Fuel," *Alternative Fuels Data Center*, accessed August 22, 2024, https://afdc.energy.gov/fuels/sustainable-aviation-fuel.

[134] International Civil Aviation Organization, "FAQs on Sustainable Aviation Fuels," *Global Framework for Aviation Alternative Fuels*, accessed August 22, 2024, https://www.icao.int/environmental-protection/GFAAF/Pages/FAQs.aspx.

[135] International Civil Aviation Organization, *Sustainable Aviation Fuels Guide*, December 2018, https://www.icao.int/environmental-protection/Documents/Sustainable%20Aviation%20Fuels%20Guide_100519.pdf

[136] International Civil Aviation Organization, "CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels," ICAO Environmental Protection, June 2022, https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2006%20-%20Default%20Life%20Cycle%20Emissions%20-%20June%202022.pdf.

[137] Carneiro, Isis Almeida, and Tarso Veloso Ribeiro, "Brazil Makes First Shipment of Ethanol to US Jet Fuel Plant," *Bloomberg*, April 22, 2024, https://www.bloomberg.com/news/articles/2024-04-22/brazil-makes-first-shipment-of-ethanol-to-us-jet-fuel-plant?embedded-checkout=true.

[138] International Air Transport Association, “SAF Volumes Growing but Still Missing Opportunities,” IATA, 6 December 6, 2023, IATA - SAF Volumes Growing but Still Missing Opportunities

[139] The United Nations Civil Aviation Organization. “SAF Offtake Agreements,” ICAO, accessed March 22, 2024. https://www.icao.int/environmental-protection/GFAAF/Pages/Offtake-Agreements.aspx

[140] Markets and Markets, “Sustainable Aviation Fuel Market,” accessed March 22, 2024. https://www.marketsandmarkets.com/Market-Reports/sustainable-aviation-fuel-market-70301163.html?gad_source=1&gclid=CjwKCAjwzN-

---

vBhAkEiwAYiO7oCHp9c5PhSSCLmmyzNToPsg_eTxZk686NCnUh3c0MaSfNO5ljwABhBoCZSMQAvD_BwE

[141] Raditya Haryanto and Laura Sanicola, "U.S. Sustainable Aviation Fuel Production Target Faces Cost, Margin Challenges," *Reuters*, November 1, 2023, https://www.reuters.com/sustainability/us-sustainable-aviation-fuel-production-target-faces-cost-margin-challenges-2023-11-01/.

[142] International Air Transport Association, "Sustainable Aviation Fuels," accessed August 22, 2024, https://www.iata.org/en/programs/sustainability/sustainable-aviation-fuels/#:~:text=What%20is%20SAF%3F,waste%20and%20non%2Dfood%20crops.

[143] Internal Revenue Service, “Sustainable Aviation Fuel Credit,” accessed 22 March 2024, https://www.irs.gov/credits-deductions/businesses/sustainable-aviation-fuel-credit#:~:text=Amount%20of%20Credit,that%20the%20reduction%20exceeds%2050%25.

[144] Internal Revenue Service, “Sustainable Aviation Fuel Credit; Lifecycle Greenhouse Gas Emissions Reduction Percentage and Certification of Sustainability Requirements Related to the Clean AirnAct; Safe Harbors,” Notice 2024-6, December 2023, p. 10-11, https://www.irs.gov/pub/irs-drop/n-24-06.pdf

[145] Internal Revenue Service, “Section 45Z Clean Fuel Production Credit; Registration,” Notice 2024-49, May 31, 2024, https://www.irs.gov/pub/irs-drop/n-24-49.pdf

[146] Congressional Research Service*, The Section 45Z Clean Fuel Production Credit*, September 27, 2023, https://crsreports.congress.gov/product/pdf/IF/IF12502 .

[147] Minnesota Department of Revenue, “Sustainable Aviation Fuel Credit,” November 11, 2023, https://www.revenue.state.mn.us/sustainable-aviation-fuel-credit.

[148] Illinois General Assembly, *Invest in Illinois Act, Senate Bill 2951*, 102nd General Assembly (2021-2022), accessed August 22, 2024, https://www.ilga.gov/legislation/102/SB/10200SB2951lv.htm.

[149] Bill Track 50, NE LB937, “Provide for tax credits, tax exemptions, and certain grant programs and change provisions relating to tax credits and fuel taxes,” https://www.billtrack50.com/billdetail/1658826

[150] State of Washington, Engrossed Substitute Senate Bill 5447, April 19, 2023, https://lawfilesext.leg.wa.gov/biennium/2023-24/Pdf/Bills/Senate%20Passed%20Legislature/5447-S.PL.pdf?q=20230502125608

[151] UK Department of Transportation, *Pathway to net zero aviation: developing the UK sustainable aviation fuel mandate*, April 25, 2024, https://www.gov.uk/government/consultations/pathway-to-net-zero-aviation-developing-the-uk-sustainable-aviation-fuel-mandate

[152] European Council, “RefuelEU Aviation Initiative: Council adopts new law to decarbonize the aviation sector,” October 9, 2023, https://www.consilium.europa.eu/en/press/press-releases/2023/10/09/refueleu-aviation-initiative-council-adopts-new-law-to-decarbonise-the-aviation-sector .

[153] U.S. Department of Energy, "Sustainable Aviation Fuel Grand Challenge," accessed August 22, 2024. https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.

---

[154] International Energy Agency, “Energy Tax Act of 1978 – Policies,” IEA, accessed March 29, 2024, https://www.iea.org/policies/4248-energy-tax-act-of-1978 .

[155] U.S. Department of Energy, “Alternative Fuels Data Center: Renewable Fuel Standard,” accessed March 29, 2024, https://afdc.energy.gov/laws/RFS .

[156] Nicholas Buffie, “The Section 45Z Clean Fuel Production Credit,” Congressional Research Service, September 27, 2023, https://crsreports.congress.gov/product/pdf/IF/IF12502

[157] Inflation Reduction Act of 2022, Pub L. No. 117-169, 136 Stat. 1818, 2022.

[158] U.S. Department of Energy, “Ethanol Laws and Incentives in Federal,” Alternative Fuels Data Center, accessed August 2, 2024, https://afdc.energy.gov/fuels/laws/ETH?state=US .

[159] International Energy Agency, *Emissions from Oil and Gas Operations in Net Zero Transitions: A World Energy Outlook Special Report on the Oil and Gas Industry and COP 28*, 2023, https://iea.blob.core.windows.net/assets/2f65984e-73ee-40ba-a4d5-bb2e2c94cecb/EmissionsfromOilandGasOperationinNetZeroTransitions.pdf.

[160] Berkeley Center for Law and the Environment, “California Climate Policy Fact Sheet: Low Carbon Fuel Standard,” https://www.law.berkeley.edu/wp-content/uploads/2019/12/Fact-Sheet-LCFS.pdf .

[161] J. Rosenfeld et al., “The California Low Carbon Fuel Standard: Incentivizing Greenhouse Gas Mitigation in the Ethanol Industry,” USDA, Office of the Chief Economist, November 2020, https://www.usda.gov/sites/default/files/documents/CA-LCFS-Incentivizing-Ethanol-Industry-GHG-Mitigation.pdf

[162] Oregon Department of Environmental Quality, “Oregon Clean Fuels Program: Program Review,” February 1, 2022, https://www.oregon.gov/deq/ghgp/Documents/CFPProgramReview.pdf

[163] USDA Natural Resources Conservation Service, “Inflation Reduction Act,” accessed July 1, 2024, https://www.nrcs.usda.gov/about/priorities/inflation-reduction-act#:~:text=The%20Inflation%20Reduction%20Act%20provides,yield%20climate%20change%20mitigation%20benefits .

[164] U.S. Department of Agriculture, “As USDA Sees Record Interest in Conservation and Clean Energy Programs, Swift Implementation of Inflation Reduction Act Funding Continues,” accessed September 4, 2024, https://www.usda.gov/media/press-releases/2023/09/19/usda-sees-record-interest-conservation-and-clean-energy-programs.

[165] Congressional Research Service, “Overview of the 2018 Farm Bill Energy Title Programs,” April 2, 2024, https://crsreports.congress.gov/product/pdf/IF/IF10288.

[166] U.S. Department of Agriculture, “Biden-Harris Administration Invests in Clean Energy and Fertilizer Production to Strengthen American Farms and Businesses as Part of Investing in America Agenda,” March 28, 2024, https://www.usda.gov/media/press-releases/2024/03/28/biden-harris-administration-invests-clean-energy-and-fertilizer.

---

[167] U.S. Department of Agriculture, “Rural Energy Savings Program (RESP),” accessed July 11, 2024, https://www.rd.usda.gov/sites/default/files/UEP_RESP_Report.pdf.

[168] Daniel Bresette, “Support for the Rural Energy Savings Program,” Outside Witness Testimony for Fiscal Year 2025, U.S. Senate Committee on Appropriations, Subcommittee on Agriculture, Rural Development, Food and Drug Administration, and Related Agencies, May 8, 2024, https://www.naseo.org/Data/Sites/1/documents/tk-news/multi-group-fy23-usda-resp-support-letter.pdf.

[169] Energy & Environmental Research Center, “Heartland Hydrogen Hub,” accessed June 26, 2024, https://undeerc.org/research/projects/heartland-h2-hub.html

[170] U.S. Department of Agriculture, “Biden-Harris Administration Invests $207 Million in Clean Energy and Domestic Fertilizer Projects to Strengthen American Farms and Businesses as part of Investing in America Agenda,” January 22, 2024, accessed September 20, 2024, https://www.usda.gov/media/press-releases/2024/01/22/biden-harris-administration-invests-207-million-clean-energy-and

[171] U.S. Department of Agriculture, “USDA Rural Development FPEP and REAP Final Chart,” January 22, 2024, https://www.rd.usda.gov/media/file/download/usda-rd-reap-fpep-chart-01162024.pdf

[172] Julie Witcover, “Status Review of California’s Low Carbon Fuel Standard, 2011–2018 Q1,” UC Davis Institute of Transportation Studies, September 2018, accessed August 7, 2024, https://escholarship.org/uc/item/445815cd .

[173] SRECTRade, “LCFS Credit Surplus Grows, Prices Decline as CARB Mulls Changes”, accessed September 11, 2024, https://www.srectrade.com/blog/low-carbon-fuel-standard/lcfs-credit-surplus-grows-prices-decline-as-carb-mulls-changes

[174] U.S. Environmental Protection Agency, “E15 Fuel Registration,” Fuels Registration, Reporting, and Compliance Help, accessed September 4, 2024, https://www.epa.gov/fuels-registration-reporting-and-compliance-help/e15-fuel-registration.

[175] M.J. Watson et al., “Sustainable Aviation Fuel Technologies, Costs, Emissions, Policies, and Markets: A Critical Review,” *Journal of Cleaner Production* 449 (April 10, 2024): 141472, https://doi.org/10.1016/j.jclepro.2024.141472.