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Life cycle greenhouse gas emissions and carbon intensity of U.S. fuel use and projection for the next 10 years-based on built capacity and expansion plans

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The U.S. Inflation Reduction Act of 2022 supports biofuel production expansion through the 45Z clean fuel production tax credit, replacing previous 40A and 40B credits. This follows on the Renewable Fuel Standard from the Energy Policy Act of 2005 and its expansion in 2007. States like California, Oregon, and Washington also offer clean fuel credits. Meanwhile, federal agencies, including the U.S. Department of Energy, have advanced alternative fuel technologies through research and development funding. The surging interest in the biofuel industry has spurred the demand for biofuel supplies in the markets, although achieving profitability for advanced biofuels and low-carbon e-fuels remains challenging. This study aims to track U.S. alternative fuel production capacity expansion plans over the next 10 years and estimate impacts on greenhouse gas (GHG) emissions. By tracking built capacity and industry announcements of planned expansion, this study complements other studies which use models to predict changes in energy technologies and the associated GHG implications. Modeled projections of future technologies are often criticized for over or underestimating the cost and potential role of new technologies. The study focuses on sustainable aviation fuel, renewable diesel, ethanol, biodiesel, and renewable natural gas. Using facility-level data, we conducted a bottom-up analysis linking biofuel production pathways with corresponding pathways and parameterizations in the Argonne R&D GREET model. Results indicate that biofuel capacity could reach 3.8 exajoules in 2035, potentially reducing U.S. GHG emissions by 179 million tonnes, including the full life cycle. This corresponds to a 20% reduction in transportation and 5% in industry sector emissions by 2035, or a 3.6% reduction in economy-wide emissions. Overall, this study shows that while biofuel production capacity in the U.S. is expanding, the capacities remain limited compared to fuel demand. Uncertainty regarding the durability and extension of incentives may be dampening the pace of growth. Meanwhile, demonstrating the commercial potential for alternative fuels and climbing the learning curve for new technologies could lead to an increased pace of expansion in later years. This study offers insights for bioenergy stakeholders, highlighting biofuel technologies' contribution to U.S. energy system and emissions reduction over time based on producers' plans.

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1. Introduction

Biofuels will play a pivotal role in the transition to a low emissions economy, serving as an interim solution for some sectors before full electrification and as a long-term solution for hard-to-electrify sectors and those relying on fossil-based feedstocks. Additionally, biofuels could enhance energy security by mitigating the impact of global price fluctuations in traditional fuel markets, and foster energy innovation through increased domestic fuel production, generating export revenues.[1] In 2021, the U.S. Government set the ambitious goal to reduce U.S. economy-wide greenhouse gas (GHG) emissions to a certain level by 2050.[2,3] To achieve this goal, the U.S. Government released a series of emissions reduction strategies, including energy efficiency, energy transition, non-CO_2 reduction, land sink, and CO_2 removal technologies. While the larger share of the reductions in early years was anticipated to come from low emissions electricity, transitioning to lower carbon energy sources including biofuels, hydrogen, and electrification are necessary steps to achieving the goals. As low carbon fuels, biofuel was projected to contribute ∼14–22% of the emission reduction under the energy transition category.[3] In 2025 under the new administration, implementing solutions that enable abundant, reliable and affordable energy future through development and use of domestic energy resources is one of the priorities. Accordingly, a series of executive orders were recently

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signed, including biofuels amongst the U.S. areas of focus for energy.[4,5] Over the past years, various policies have been implemented to incentivize biofuel manufacturers to reduce carbon emissions and promote biofuels use. The Inflation Reduction Act (IRA) incentivizes low carbon transportation fuels such including increasing the blend ratios for biodiesel (BD) and ethanol (EtOH) and sustainable aviation fuel (SAF) production and investment support.[6] The Renewable Fuel Standard (RFS) and the California Air Resource Board (CARB) Low Carbon Fuel Standard (LCFS) subsidize domestic biofuel producers by awarding carbon credits to reduce emissions, lower production costs and encourage biofuel adoption in transportation.[7,8] These measures underscore the biofuel industry's critical role in meeting U.S. future energy goals. Hence, its trajectory will significantly influence bioenergy progress over the coming decades.

Biofuel production technologies encompass a range of conversion pathways that transform biomass/feedstocks into liquid and gaseous fuels. EtOH is primarily derived from sugar and starch rich crops through fermentation; but lignocellulosic biomass can also be converted to ethanol *via* pretreatment, enzymatic hydrolysis, and fermentation.[9,10] While EtOH production from corn is a mature technology, EtOH production from lignocellulosic feedstocks is an emerging pathway. Fatty acid methyl ester (FAME) BD is produced *via* transesterification of triglyceride oils (*e.g.*, soybean, canola, corn oil, tallow, used cooking oil *etc.*) with methanol typically over base or heterogeneous catalysts, yielding glycerol as a co-product. The process is relatively low temperature/pressure and is widely commercial. FAME is not a fully "drop-in" fuel and faces blending limits in current diesel specs (typically up to B20 in many markets).[11,12] The hydroprocessed esters and fatty acids (HEFA) pathway is the predominant commercial route for renewable diesel (RD) and SAF production. RD and HEFA-derived SAF are produced by hydroprocessing lipid feedstocks (*e.g.*, used cooking oil, tallow, vegetable oils) *via* hydrodeoxygenation, hydroisomerization, and mild hydrocracking followed by fractionation of the RD/SAF cuts and at many hydroprocessing sites operators can adjust ("swing") the product split between RD and jet fuel based on market and specification requirements.[13,14] SAF can be produced through other routes, including Fischer–Tropsch (FT) synthesis, alcohol-to-jet (ATJ), catalytic hydrothermolysis to jet (CHJ) and others.[15] ATJ converts alcohols (notably ethanol or isobutanol) *via* dehydration to olefins, oligomerization, hydrogenation, and fractionation to jet-range hydrocarbons using starch, sugar-based or cellulosic feedstocks. FT to synthetic paraffinic kerosene (FT-SPK) from gasification converts lignocellulosic biomass or municipal solid wastes (MSW) to cleaned syngas followed by FT synthesis and upgrading to jet/diesel fractions. CHJ processes lipid feedstocks under hydrothermal conditions followed by hydrotreating/isomerization and fractionation to jet-range hydrocarbons. Power-to-Liquids (PtL) is an advanced electrofuels pathway that uses renewable electricity, water, and carbon dioxide (CO_2) to produce liquid hydrocarbons such as synthetic diesel, gasoline, jet fuel, or intermediates like methanol. For aviation fuels, PtL typically synthesizes jet-range hydrocarbons from green hydrogen (*via* electrolysis) and captured CO_2 either biogenic or from direct air capture through FT synthesis (often after reverse water–gas shift to form syngas) or *via* methanol-to-jet conversion routes.[15–19] Renewable natural gas (RNG) is produced by anaerobic digestion (AD) and upgrading of landfill gas, manure, food waste, or wastewater sludge to pipeline-quality biomethane. During AD, microorganisms break down organic matter in the absence of oxygen, to produce biogas. The biogas primarily methane and CO_2 can be cleaned and upgraded by removing CO_2, and other impurities to yield pipeline-quality RNG with a high methane content comparable to fossil natural gas.[20]

Several previous studies provide pieces of the overall picture of U.S. biofuel production capacity and near-term expansion plans, while a comprehensive accounting of biofuel supply across fuel types and end use sectors has not previously been available. Most of the available literature is focused on a short time frame and limited biofuel types, especially BD and RD.[21–28] There is also a need to update previous studies which have become outdated. Recent research by Gerveni *et al.* tracked U.S. 2022 BD capacity and RD production capacity from 2010 to 2025 and later.[22–24] The International Civil Aviation Organization (ICAO) tracks future RD/SAF coproduction capacity and SAF offtake agreements between producers and purchasers.[29] The National Renewable Energy Laboratory (NREL) assessed the existing, under construction, and planned RD/SAF HEFA facilities and its available feedstocks to meet 2030 SAF targets.[14] There are also several papers that evaluated biofuel production potential through optimization, integrated assessment models, or government targets.[16,30–40] Nevertheless, comprehensive and up-to-date analyses of biofuel production capacity and sustainability are still limited, underscoring the need for further research in this rapid evolving field. This study complements other studies that project changes to the energy system over time based on estimated costs and projected technological learning by specifically focusing on analysis of the current market and concrete plans for capacity expansion. Projections of future technologies are frequently criticized for either overestimating or underestimating their costs and potential impact.[41–44] The study provides a rigorous dataset describing U.S. alternative fuel production across multiple pathways including renewable diesel, biodiesel, sustainable aviation fuel and renewable natural gas (RNG).

Tracking the scale-up of bioenergy production, its benefits, and trade-offs can provide valuable insights into the potential of biofuels for sustainably meeting economy-wide emissions reduction and future energy goals. Production capacity expansion and fuel carbon intensity (CI) data are usually collected by different groups without analyzing the interaction between production and emissions reduction potential. The U.S. Energy Information Administration (EIA) tracks historical biofuel production capacities for ethanol, RD, and BD but does not track SAF and RNG production capacities and future biofuel expansion plans. ICAO tracks RD/SAF capacities and offtake agreements for SAF only. Meanwhile, programs like the CARB LCFS and the U.S. Environmental Protection Agency (EPA) Renewable Fuel Standard Program (RFS) set facility-specific carbon intensity (CI) standards to estimate carbon credits with the total supply volume considered. This paper fills the gap by pulling together all the datasets, verified through company-level information, and putting the results in the context of the contribution to U.S. future energy production and emissions reduction.

This study tracks the U.S. facility-level alternative fuel production capacity and capacity expansion plans from various feedstock and conversion technologies, quantifies the life cycle GHG emissions and CIs of biofuels supplied to the U.S. market, and the potential emissions reduction across all sectors over the next 10 years, based on the planned expansion of alternative fuels production capacity and fuel use projections. This is achieved by connecting fuel pathway analysis and biofuel industry developments to harmonize a bottom-up analysis with industry statistics. The study examines future trends in biofuel production based on producers' plans and assesses the potential GHG reduction achievable through biofuel deployment. The findings provide valuable insights enabling stakeholders to track the impact of bioenergy technologies on the future energy production, emissions reduction and sustainability of U.S. fuel use. In addition, it provides a detailed understanding of the connection between total national GHG emissions and contributions from individual bioenergy pathways. This study's novelty lies in providing an empirically anchored, facility-level, multi-pathway assessment that (i) integrates publicly disclosed capacity expansions with feedstock and process details, (ii) harmonizes facility-specific LCFS carbon intensities with Argonne R&D GREET/ICAO GREET and synthesizes land-use change across multiple models, and (iii) maps the resulting biofuel supply into economy-wide energy use and lifecycle GHG emissions through 2035. In contrast to optimization or IAM-based forecasts, our projections are grounded in built capacity and announced expansions, offering a transparent, data-driven complement to modeled scenarios and state-of-industry reports.

2. Methods

2.1. Establishing a facility-level information database

This study examines fuel use across all U.S. economic sectors, starting with fuel categories and end uses from the EIA's Annual Energy Outlook (AEO)[45] and going on to include additional alternative fuel pathways. EIA tracks fuels including natural gas, jet fuel, diesel/distillate fuel, gasoline, residual fuel oil, liquefied petroleum gases, kerosene, propane, ethanol (E85 and ethanol content of conventional gasoline), hydrogen, and coal. While EIA discusses biofuels broadly as biofuel heat and coproducts, this study refines the analysis by specific pathways, detailing end-use fuels, feedstocks, and conversion technologies. To understand the trajectory of change in the industry, the scope also includes 10 year projections of alternative fuel production capacity based on biofuel producers' disclosed plans, focusing on SAF, BD, RD, EtOH, and RNG.

Data was synthesized from public and industry sources to characterize fuel production pathways being used in the market, capacity expansion projects, and facility-level operations.[29,46–52] These datasets were compiled into a biofuel facility-level database categorized by operational status: existing, under construction, and planned facilities. It includes details such as location, biofuel type, feedstock, production capacity, and import/export data (adjusted using 2019–2023 averages).[53,54] Since EIA aggregates RD and other biofuels, it was assumed most imports/exports are RD.[53,54] Biofuel import, and export datasets are shown in the SI Section S2.

Biodiesel, RD, and ethanol historical capacity datasets are collected from EIA, and future capacity and feedstock datasets are derived from Biodiesel Magazine and other sources.[47–49] The SAF dataset is from ICAO's SAF facility database and the Airline Offtake Agreement.[29,46] RNG/biogas datasets are from the Argonne RNG Database[50] and the EPA Landfill Gas and Livestock Anaerobic Digester Database.[51,52] Other sources include the Environmental, Social, and corporate Governance (ESG) report, company disclosures, news, and intelligence regarding biofuel and feedstock capacity expansion (through interaction with biofuel industry stakeholders).[53–60]

2.2. Carbon intensity of fuel pathways: comparison and harmonization

This study employs a cradle-to-grave (or so-called well-to-wheel, well-to-wake, and well-to-hull for vehicles, aviation, and marine fuels, respectively) approach to quantify the environmental impacts of biofuel production, transport, and use. The system boundary encompasses feedstock production, pretreatment, conversion, combustion, co-products, biogenic CO_2, and land use change (LUC) emission stages. The functional unit is g CO_2e per MJ of biofuel use.

To achieve the closest estimate of the CI for each fuel pathway for a particular facility, facility-specific CI values are sourced from CARB's LCFS certified pathways;[61] however, if a facility does not have a certified pathway, Argonne's R&D Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model standard CIs are used.[62] The LCFS program incentivizes biofuel producers who are willing to reduce GHG emissions of their biofuel product and the biofuel used in California, encouraging the disclosure of facility-specific CIs adjusted for operational conditions.[63] The LCFS program applies the California (CA)-GREET3.0 model, which is a GREET derivative product originally based on GREET1 2016.[64] For facilities outside the LCFS program or lacking data disclosure, the R&D GREET model standard CI datasets are used to compensate for the missing facility datasets based on their feedstock and fuel pathway information. Major biofuel pathways exist in the R&D GREET model that make the analysis across a larger number of pathways tractable. Alternative frameworks include the EU Renewable Energy Directive methodology and default values,[65] and process-integration LCA/TEA studies such as Sadhukhan *et al.*[9] and Martinez-Hernandez *et al.*[66] RED II prescribes EU-focused calculation rules, energy-allocation co-product treatment, and default (I)LUC adders, while the latter studies emphasize integrated biorefinery design with system-expansion credits and combined heat and power

(CHP) integration. Due to methodological differences, CIs can vary across accounting frameworks due to co-product allocation, electricity mix, and ILUC treatment among others. GREET underpin major U.S. programs (LCFS, EPA analyses) and offer comprehensive, feedstock- and pathway-specific CIs required to map facility-level U.S. projects across SAF, RD, BD, ethanol, and RNG. GREET is publicly available, widely used by U.S. agencies and industry, and directly comparable to LCFS-certified facility pathways we employ. We therefore use GREET for its policy alignment, pathway breadth, and ability to harmonize multiple LUC sources relevant to U.S. facility-level assessment. In addition, we compare and harmonize bottom-up R&D GREET pathways with industry-reported CIs of fuel pathways to identify possible differences and key contributing factors.

LUC impacts are adopted from models including the CARB LCFS, ICAO, EPA Set Rule Analysis, and Carbon Calculator for Land Use and Land Management Change from Biofuels Production (CCLUB)-GREET models.[67–72] Variability in LUC estimates arises due to model differences, potentially leading to uncertainty. To address this, we compared LUC emissions (g CO_2e per MJ) from multiple sources and back-calculated impacts per dry tonne of biomass using feedstock-to-biofuel yield ratios.[62] The presented results used the average LUC emission value with range bars to show the variation in those models. Details for LUC calculations are in the SI Section S4.

2.3. Facility-level biofuel production and GHG emissions

For some facilities, a specific biofuel can be produced from a mix of feedstocks (*e.g.*, RD from HEFA using soybean oil, canola oil, corn oil, and/or tallow). For such facilities, we divide production capacity equally among the disclosed feedstocks due to the lack of explicit and publicly available data on specific feedstock inputs by type. After allocating capacity by feedstock and matching a certified CI to each feedstock-specific pathway, facility-level biofuel production capacities and CIs were combined to estimate the GHG emissions from biofuel production by feedstock in each facility. The estimated GHG emissions of biofuel production by feedstock are summed to get the total GHG emissions within the facility scale. Based on this, we estimated the economy-wide potential biofuel production and GHG emissions (tonne CO_2e per year) (eqn (1)) for the next 10 years, where i denotes each individual facility, j represents each feedstock within the facility. Production_{ij} and CI_{ij} represent the production capacity (million gal per year) and CI (g CO_2e per MJ) by feedstock in a facility. LHV_{fuel} is the low heating value of the biofuel in MJ gal^{-1}.

$$\text{Total biofuel GHG emisisons} = \sum_{i=\text{facility}}^{i} \sum_{j=\text{feedstock}}^{j} \text{production}_{ij} \times \text{LHV}_{\text{fuel}} \times \text{CI}_{ij} \quad (1)$$

2.4. Economy-wide energy demand, emissions reduction potential, and modeling

To contextualize facility-level biofuel production volumes within the U.S. economy-wide energy demand over the next decade, we conducted a bottom-up analysis based on different cases of future U.S. economy-wide fuel use from the Argonne Decarbonization Scenario Analysis Model (Decarbonization Model).[73] This model quantifies the effect of mitigation measures on energy use and GHG emissions across U.S. sectors, encompassing the agricultural, commercial, residential, industrial, and transportation sectors. It includes both a reference case and a mitigation case with the emissions reduction measures ranging from low carbon electricity grid and energy efficiency improvement to sector-specific measures such as

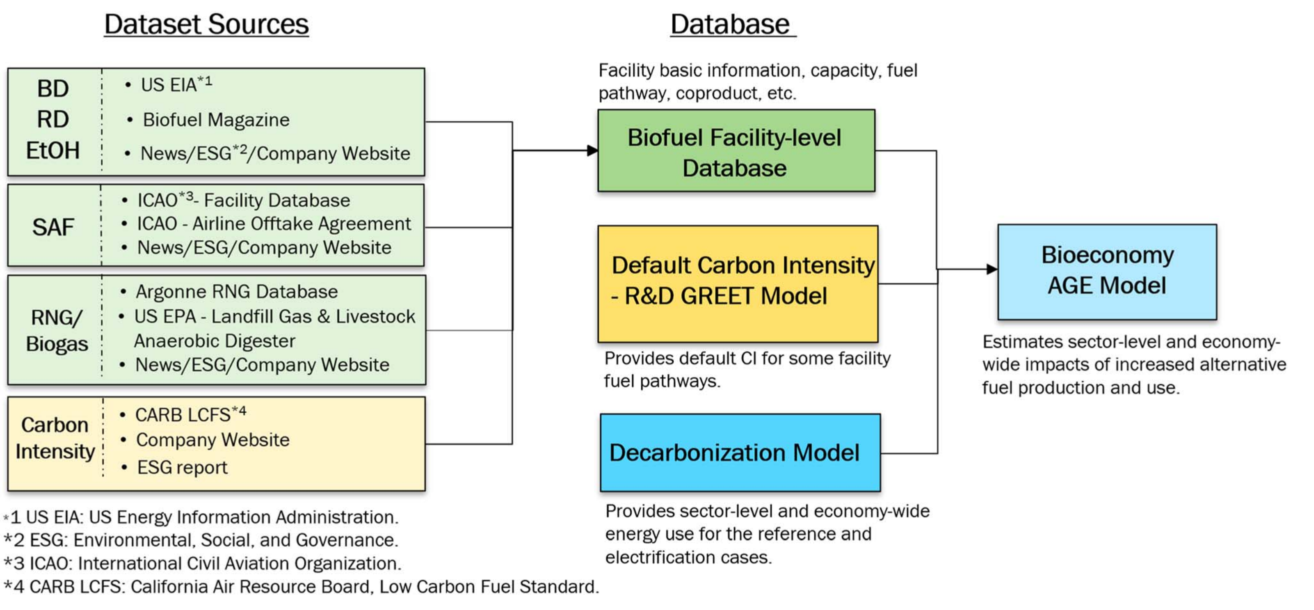

Fig. 1 Biofuel facility-level dataset and model framework.

technology upgrade and fuel switching from natural gas to hydrogen application.

Based on this, we established three cases to capture the impact of increased biofuel supply/use based on producers' plans. The first, a business-as-usual or reference case, is based on the Decarbonization Model as established based on the reference case of the EIA AEO 2022 energy demand projection.[45] The second case integrates increased electrification on U.S. economy-wide future fuel use as reflected in the Decarbonization Model. It is worth noting that although the focus of the study is on biofuels, we're leveraging part of an earlier study to put the results in context including potential electrification.[73] The third case incorporates increased use of biofuel based on biofuel producers' plans using the existing and planned biofuel expansion facility-level data above the electrification case. Each end-use GHG emission is calculated using the energy-demand data and the respective temporal emission factors obtained from the R&D GREET model using the Air emissions, Greenhouse gas emissions, and Energy use for the Bioeconomy (Bioeconomy AGE) model.[16,35–37,74] This model integrates temporally explicit life cycle profiles from R&D GREET for each of the selected fuel pathways, and information regarding the three cases under consideration (including increased biofuel production based on capacity expansion plans and annual economy-wide energy demand by type) to calculate energy and GHG emissions through 2035. This approach ensures a robust analysis of how biofuel deployment based on the biofuel producers' plans, combined with other mitigation measures, could influence energy use and emissions across the economy. This study identifies potential replacements for conventional fuels by biofuels including BD/RD for diesel, ethanol for gasoline, SAF for jet fuel, and RNG for natural gas (details in SI Section S5). Biofuel use is proportionally distributed across sectors according to their conventional fuel usage ratios. The overall framework is outlined in Fig. 1.

3. Results and discussion

3.1. Existing and future biofuel facility capacity trends by fuel type

As indicated by the compiled facility-level dataset based on producers' plans, the next 10 years will see a surge in RD and SAF production driven by biofuel subsidies and increasing demand. SAF and RD are produced currently and in the near term from the same feedstocks and *via* similar processes, with the main difference being further hydroprocessing to produce SAF. Hence, it is challenging to predict these independently of one another, as facilities could swing their production from one to the other. SAF production capacity is projected to grow at an annual rate of 21% from 2020 levels, increasing from 0.023 billion gal per year (2.9 PJ per year) in 2021 to 8.0 billion gal per year (1013 PJ per year) by 2035. This exceeds the SAF Grand Challenge goal of 3 billion gallons by 2030 (Fig. 2 and additional details in the SI Section S1).[75] SAF production before 2023 is limited, roughly 0.71 billion gal per year (90 PJ per year) with 5 facilities. Since 2023, more and more SAF producers released their expansion plans, including an additional 5 billion gal per year (630 PJ per year) from 40 facilities under construction and another ∼3 billion gal per year (∼378 PJ per year) from 19 planned projects by 2035. According to the EIA 2023 facility datasets, RD has 22 operational projects with 4.3 billion gal per year (557 PJ per year) in 2023. Based on available datasets, some existing RD facilities in 2023 coproduced SAF/RD, which led to a 1.3 billion gal per year (168 PJ per year) RD reduction (depending on SAF/RD ratio). Based on expansion plans, 16 facilities are under construction with a potential 2.2 billion gal per year (285 PJ per year) capacity, and 12 new projects are being proposed with a potential 0.7 billion gal per year (91 PJ per year) capacity. Total RD capacity by 2035 will be 5.83 billion gal per year (755 PJ per year). Most SAF and RD facilities either under construction or planned are in California, Louisiana, and the Pacific Northwest (Oregon/Washington) (SI Fig. S6). This distribution pattern reflects incentives from CARB's LCFS and similar programs in Oregon and Washington. In addition, RD facilities can use existing petroleum refining technology and infrastructure, making them suitable for co-location within refining complexes.[23]

The United States had 56 BD facilities with a 2.9 billion gal per year (366 PJ per year) capacity in 2023 (2.1 billion gal per year from EIA datasets,[25] additional capacity is based on other sources[47]). According to the U.S. EIA, BD production capacity declined by 0.17 billion gallons between January 2022 and January 2023 with renewable diesel (RD) surpassing BD.[21] RD production will continue to grow as previously outlined, driven by its compatibility with existing infrastructure, diesel engines having no blending limitations, higher state and federal targets for RD/SAF production, incentives from credits, and the conversion of existing petroleum refineries into RD/SAF production (*e.g.*, Philips 66's San Francisco oil refinery in Rodeo and Marathon's Marinez refinery are being converted to produce renewable fuels).[76,77] It is anticipated that the overall BD production capacities will decrease by 2035 as some facilities plan to produce less BD or convert to feedstock pretreatment facilities for renewable diesel (SI Section S1).[22,47]

The United States had 187 ethanol facilities with a 18 billion gal per year (1450 PJ per year) capacity in 2023 (SI Fig. S8–S10).[49] Multiple pressures on the ethanol market make predicting future production levels challenging. With broadly increased electrification in the light-duty sector, it is anticipated that future ethanol production capacity might reduce or remain unchanged. However, it could rise again due to the transition of some ethanol facilities to producing low-carbon aviation fuel and the potential for permanent year-round E15 sale in the U.S. midcontinent.[5,78] Given the methodology employed in this study, tracking the closure or conversion of biodiesel/ethanol production capacity to RD or SAF has been a challenge, as these events often occur unexpectedly.

RNG had 252 operational projects, 141 under construction, and 36 planned projects in 2022. RNG production capacity will increase from 870 to 1140 million GGE per year (104 to 137 PJ per year, about a 31% increase from 2022) by 2035. Most growth is expected from landfill gas feedstocks, with government- and institution-owned facilities playing a significant role (Fig. S17). Facility-level details for RD, SAF, BD, EtOH, and RNG are in the SI, Section S1.

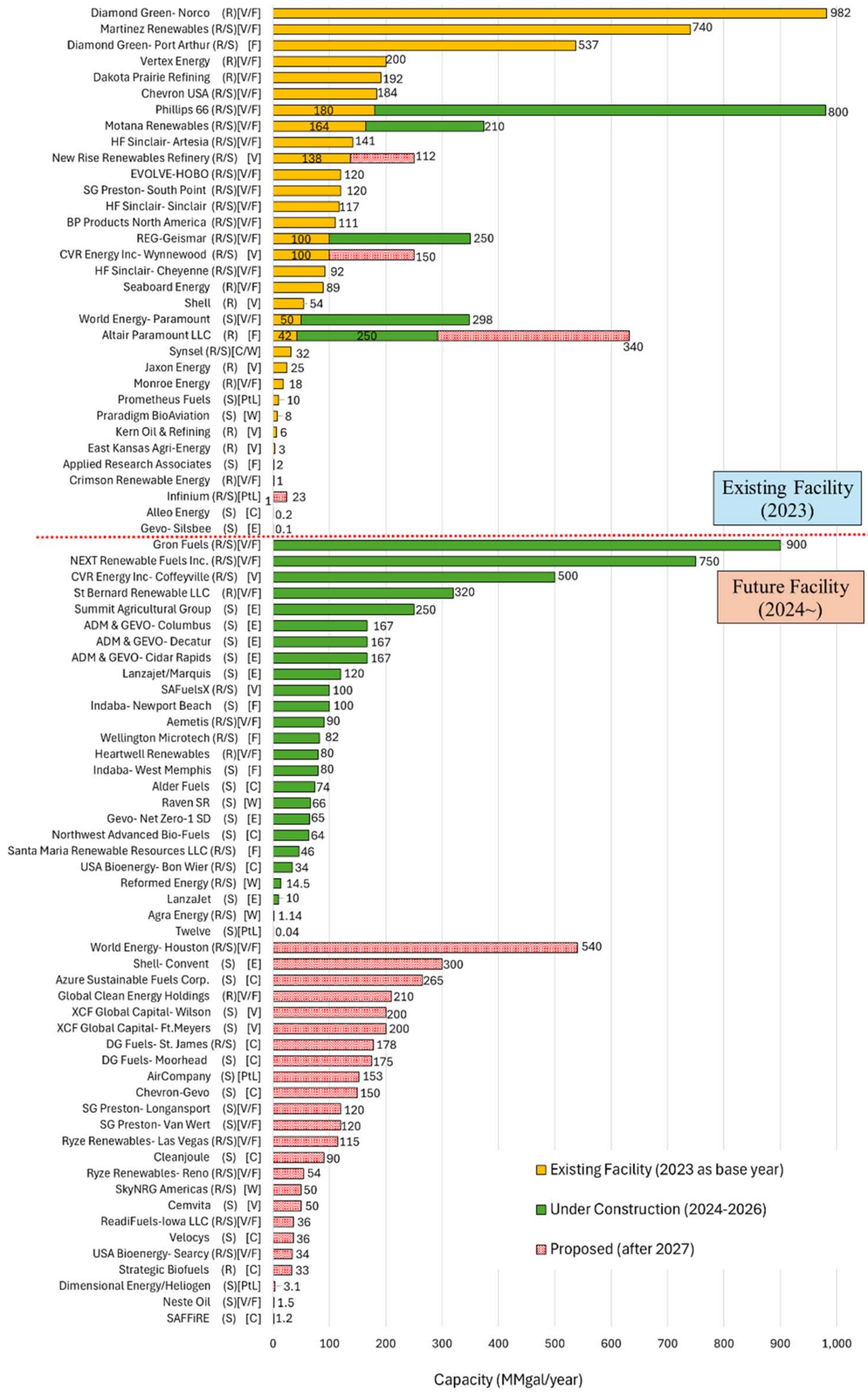

Fig. 2 RD/SAF facility existing capacity and expansion plans. Figures for other biofuels are in the SI. R: RD; S: SAF; V: vegetable oils to jet; F: fats, oils, and grease (FOG) (includes tallow and used cooking oil [UCO]) to jet; PtL: power to liquid; C: cellulosic biomass to jet; E: ethanol to jet; W: waste to jet.

3.2. Overall feedstock consumption trend by type

Based on producers' capacity expansion plans and potential feedstock use, we estimated biofuel capacity expansion by feedstock type as shown in Fig. 3. Corn provides three types of biofuel feedstocks – corn grain (corn starch and part of the cellulose portions of the grain), corn oil (extracted at most dry

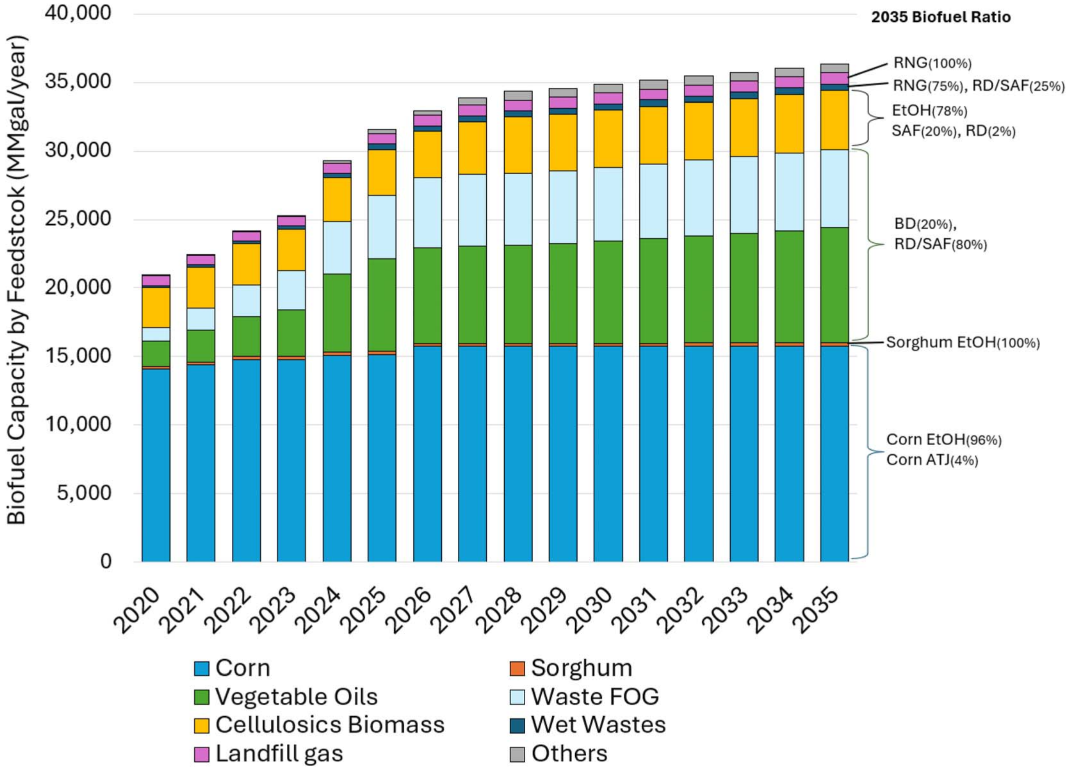

Fig. 3 Biofuel capacity trend by feedstocks between 2020 and 2035. Corn contributes 43% of biofuel production in 2035, especially for ethanol, followed by soybean oil (11%), tallow (9%), and corn stover (9%). Others include sugarcane, RNG/methanol, industrial CO_2, and undeclared feedstocks. Vegetable oils include soybean oil, corn oil, canola oil, and other vegetable oils. Waste FOG contains tallow and UCO. Wet wastes include municipal solid waste (MSW), manure, and sludge.

mill corn ethanol processes), and corn stover. Most corn grains are used for EtOH production; meanwhile, corn oil is used for BD and RD production with other vegetable oils. Corn stover is categorized as agricultural waste and is usually used for EtOH *via* fermentation or RD through the gasification process. Corn grain will contribute 16 billion gal per year (∼130 million dry ton corn grain) in 2035 with 96% for ethanol production and 4% for alcohol to SAF production.

The use of vegetable oils and waste fats, oils, and grease (FOG) like tallow and used cooking oil (UCO, also known as yellow grease) increased over the years and will potentially play an important role in future biofuel feedstock expansion. Waste FOG feedstocks are crucial to emissions reduction because of their low CIs with 5.7 billion gallons of biofuel production in 2035. However, there is a limited availability of FOG feedstocks in the United States, and this study estimated the waste feedstock required based on producers' plans (27 million dry ton) would be 3–4 times the available waste feedstock projected in the 2023 Billion-Ton Report (BT23) (Table 1).[79] This presents a great challenge for scaling up facilities that utilize waste as biofuel feedstocks, which implies that a majority of these facilities would potentially rely on imported waste feedstock to fulfill their needs.[14,80–82] Given the importance of waste feedstock, we explore a ‘feedstock-constrained’ sensitivity (SI) that caps domestic waste FOG at BT23 levels (SI Section S9).

It is estimated that about 62 million dry tons of cellulosic biomass such as agricultural residues (including corn stover) and forest residues would be required in 2035, based on facility expansion plans (producing 4.3 billion gallons biofuels). To place this in context, this is about 29% of the 217 million dry tons per year projected in the BT23 report in 2035. The BT23 estimates of cellulosic biomass indicate that these categories of feedstock are critical for large-scale fuel production, yet most of the facilities we tracked use first-generation or waste feedstocks. Hence, the investment in technologies to scale-up the use of cellulosic biomass will be essential for biofuel scale-up.

From a technological standpoint, SAF production, as an example, leverages diverse feedstocks and conversion processes, including HEFA, gasification with F–T synthesis, PtL, and ATJ pathways. While commercially available pathways like HEFA lead current production, technologies such as ATJ show promise for mid-term growth (Fig. S11). Ethanol, for example, serves as a viable feedstock for ATJ, promoting some ethanol facilities to transition to SAF production or serve as ethanol feedstock plants for SAF production. Notably, LanzaJet launched the world's first ATJ SAF commercial facility in Georgia in January 2024, with an anticipated first year output of 9 million gallons of SAF and 1 million gallons of RD.[83]

At the national scale, the RNG volumes implied by existing, under-construction, and announced projects are well within the technical resource base. In particular, our implied landfill gas (LFG) use in 2035 (Table 1) is substantially below the national LFG potential reported in BT23. The feedstock mix (Fig. S17) is dominated by landfill gas. While some streams (*e.g.*, manure)

Table 1 Comparison between estimated feedstock usage in 2035 and available feedstock from BT23 (data from the mature-market scenario)[79]

	Investigated feedstock usage in this study		
	Capacity (billion gal per year)	Amount (million dry tons per year)	Available feedstocks from BT23[f] (million dry tons per year)
First-generation agriculture biomass currently used for energy[a]	21	158	154
Cellulosic biomass[b]	4.3	62	217
Tallow	3.4	13	3.2
UCO and brown grease	2.3	14[c]	4.5
Landfill gas	0.81[d]	205 BCF[e]	836 BCF

[a] Agriculture biomass currently used for energy includes corn grain, sorghum grain, and vegetable oils (soybean and canola oil).[79] [b] Cellulosic biomass: agricultural waste and forest residue. [c] Higher FOG (tallow, UCO, and brown grease) estimate in this study compared to available feedstock estimates in BT23 can be attributed to two reasons: (1) for a given facility, we used the average allocation to divide production capacity equally among the disclosed feedstocks due to the lack of information, (2) the majority of these facilities may actually rely on imported waste feedstock to fulfill their needs. [d] Billion gge per year. [e] BCF: billion cubic feet of natural gas. [f] Data is derived from BT23 medium mature-market scenario.

exhibit seasonal variation, assessing such dynamics and their operational mitigation is outside the scope of this study.

3.3. Harmonization between facility-level and R&D GREET standard carbon intensities

This section shows the harmonization results between the LCFS facility-specific pathway CIs and the R&D GREET 2023 model general CIs by fuel pathway. Since LCFS uses the CA-GREET3.0 model (a revised version of GREET), variations in facility CIs are to be expected. Fig. 4 illustrates the SAF facility-level harmonization results, while the results for other biofuels are in the SI (Section S3). Currently, only three companies (REG Geismar, AltAir Paramount, and Montana Renewables) produce SAF under LCFS, using hydrotreating with feedstocks like UCO, tallow, soybean oil, and corn oil. GREET ICAO values were used for facilities under construction or planned.[84] Facility-level CIs differ from R&D GREET general CIs due to factors such as feedstock origin (*e.g.*, South America or Australia),

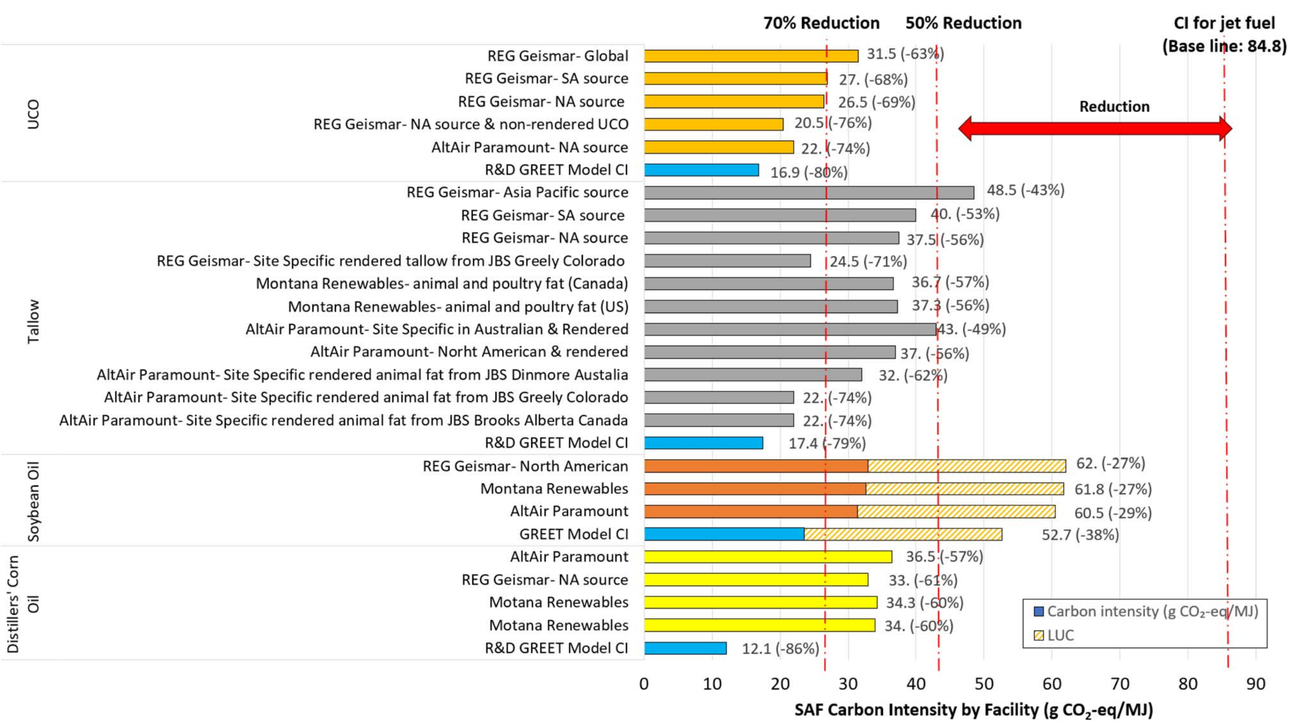

Fig. 4 SAF carbon intensity by facility. Blue bars represent R&D GREET model general CIs by feedstock. Other colors show facility-specific CIs by feedstock. Compared to the CI of conventional jet fuels (89 g CO_2e per MJ), every fuel pathway could achieve a 50% GHG reduction except for SAF from soybean oil. SA: South America; NA: North America. For consistency with facility-level CIs, the R&D GREET model CI reflects LCFS LUC values and not the default CCLUB.

transportation mode, and rendering status (rendered *vs.* non-rendered) (Fig. 4). The electricity mix used will also have an impact on the CIs depending on where the facility is located. LUC accounted for nearly half of the CI for soybean oil pathways.

Facility-level BD and RD CIs mostly align with the default Argonne's R&D GREET CIs, except for tallow, where differences arise from feedstock sourcing and rendering status and corn oil. For the soybean oil, and canola oil pathways, LUC contributes significant CI variability, with high uncertainty due to model differences (SI Section S4). CIs also vary based on hydrogen sources, *e.g.*, hydrogen from natural gas or electrolysis. In GREET, hydrogen can be sourced from several technologies, including natural-gas steam methane reforming (SMR), auto-thermal reforming (ATR) and electrolysis among others using grid or low-carbon electricity. Facilities may procure merchant hydrogen or produce hydrogen on-site; the choice materially affects fuel CI. Where LCFS facility-specific pathways disclose hydrogen sourcing, we used those data; otherwise, we used GREET defaults for the relevant hydrogen pathway. See also recent analyses of on-site hydrogen generation for SAF production.[85] EtOH CIs vary widely due to feedstock differences (corn, corn stover, grain sorghum) and production methods (*e.g.*, dry/wet milling, gasification, fermentation). Coproducts like dry distiller's grains with solubles or wet distiller's grains with solubles further contribute to CI variability.

RNG is primarily produced from landfill gas, animal waste, municipal solid waste, and wastewater sludge. Variations in CIs arise from feedstock type and AD methods. For instance, RNG from dairy manure has a CI of −152 g CO_2e per MJ due to avoided treatment emissions, while turkey manure results in 76 g CO_2e per MJ. The R&D GREET default CIs for animal waste pathways used dairy manure as the baseline. Please see the SI for facility-level information.

3.4. Economy-wide energy demand and biofuel use

Fig. 5 shows the economy-wide energy demand in 2035 based on the Decarbonization Model as established based on the reference case of the EIA AEO 2022 reference case projection (red line)[45,73] and the case that incorporates increased use of biofuel based on biofuel producers' plans above the electrification case (column chart). The difference between energy demand in the reference case and the column chart arises from emissions reduction measures such as widespread electrification and energy efficiency improvement. These measures collectively will reduce economy-wide energy demand by 11% by 2035 (Fig. 5). According to the EIA AEO,[45] diesel fuel is projected to be predominantly utilized in transportation (79%) and as industrial fuel (13%), with minor consumption in the residential and commercial sectors (4% each) by 2035. Non-transportation diesel is primarily used in construction/mining within the industry sector, as well as for heat/power in both the commercial and residential sectors. Based on capacity expansion plans, BD/RD will account for 15% of total diesel demand by 2035. Approximately 95% of gasoline demand is expected to be used by the transportation sector, with ethanol projected to replace 12% of it by 2035, primarily as E85 (85%) and low blend-in ratios in gasoline (10%).

In the aviation sector, jet fuel is projected to be utilized as follows: 48% for domestic passengers, 19% for international passengers, and 17% for dedicated freight services by 2035. SAF is anticipated to supply up to 24% of total jet fuel demand in 2035 based on capacity expansion plans.

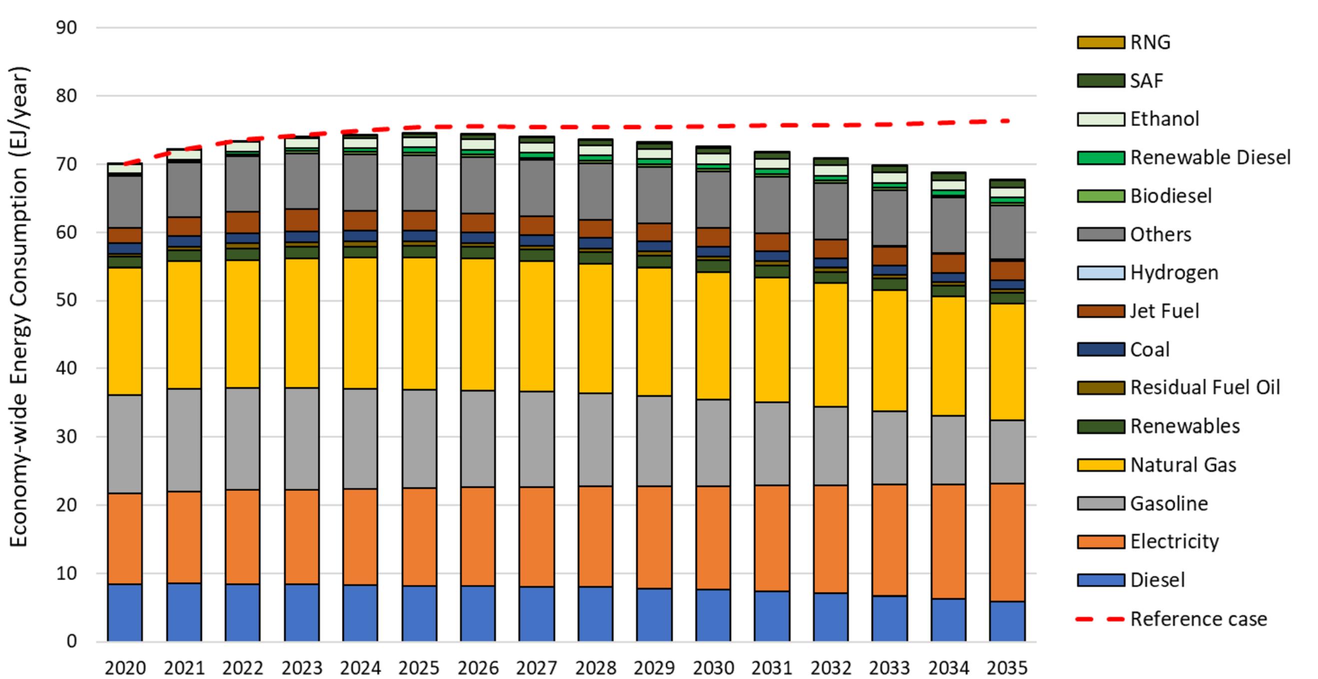

Fig. 5 Economy-wide energy demand by fuel type.

Natural gas consumption is forecasted to be distributed across industrial (53%), commercial (23%), residential (17%), and transportation (7%) sectors by 2035. However, RNG could replace only 1% of the total natural gas demand by 2035, reflecting a modest expansion relative to natural gas consumption. While RNG is a valuable fuel for its methane avoidance benefits and contribution to reducing natural gas use emissions, it stands to make only a small contribution to lowering emissions in NG use. With this, expanding the natural gas market to enable the use of RNG in transportation would likely not contribute to the goal of economy-wide emissions reduction.

Collectively, these expansions are expected to displace approximately 5.6% of conventional fuel use across the U.S. economy, which is equivalent to 3.8 EJ (around 31 billion GGE) out of the total 68 EJ fuel demand by 2035. Further details on these projections and sectoral distributions are provided in SI Section S5.

3.5. Estimated GHG emissions reduction from biofuels use

While this study aims to estimate the emissions reduction associated with replacing conventional fuels with biofuels based on producers' plans, emissions reduction measures such as low carbon electricity grid, electrification, and energy efficiency improvement were still considered in the background since these are essential to achieving greater emissions reduction by 2050. Fig. 6 shows the potential GHG emissions reduction associated with biofuel deployment between 2020 and 2035. The positive side represents emissions from biofuel consumption, while the negative side shows GHG emissions avoided from displacing conventional fuels. BD and RD demonstrate the potential to significantly reduce GHG emissions in the diesel category, with an 8% reduction projected by 2035. Similarly, SAF exhibits a notable impact, reducing emissions from jet fuel by 17% in 2035. LUC contributes about one-fourth of the positive GHG emissions from biofuel use, highlighting the sensitivity of the results to LUC factor selection. The LUC impact shown here is based on the average LUC value from four models (as indicated in the Method section) with a range bar indicating variability among the models. RNG has the smallest effect since RNG production is less than that of other biofuels. Overall, based on existing capacities and expansion plans, biofuel deployment could achieve GHG emissions reductions of up to 179 MMT CO_2e by 2035.

In this study, RD and RNG are drop in fuels that can be used at any blend level in existing engines and infrastructure. SAF is an American Society for Testing Materials (ASTM) D7566 approved synthetic blending component that, when blended within approved limits and certified to ASTM D1655, is a drop in finished jet fuel.[86] In the light-duty and heavy-duty vehicle sectors, RD offers a one-for-one replacement for traditional diesel fuel. However, concerns about criteria air pollutants emissions have contributed to a growing emphasis toward battery electrification due to its elimination of tailpipe emissions.[87] Notably, EPA emissions regulations have been quite effective in reducing tailpipe criteria air pollutant emissions[88,89]

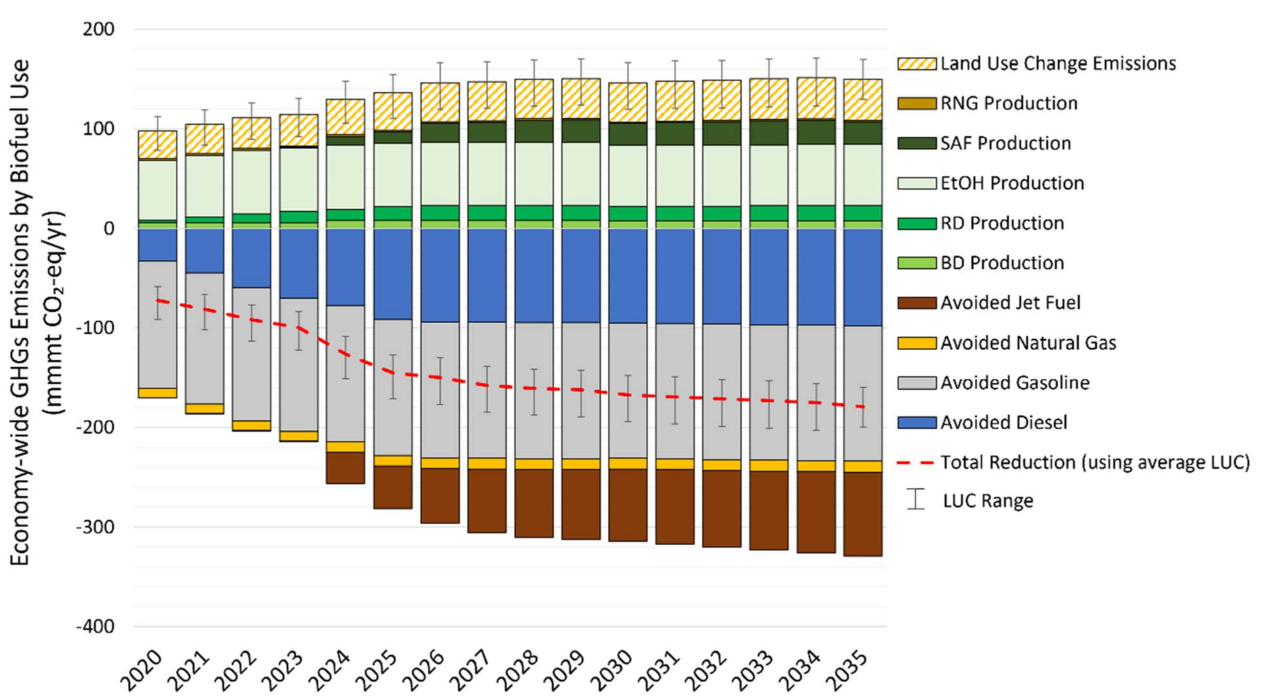

Fig. 6 Economy-wide GHG reduction from biofuel use in 2020–2035. The negative side shows avoided GHG emissions from conventional fuels that are replaced, and the positive side represents GHG emissions from biofuel consumption. The reductions include an assumed reduction for existing corn ethanol (45 MMT CO_2e per year) and biodiesel (14 MMT CO_2e per year) production; hence, the already negative value in 2020. The LUC emissions (hatched yellow bars) and total reduction (dashed red lines) show the results with the average LUC emissions.

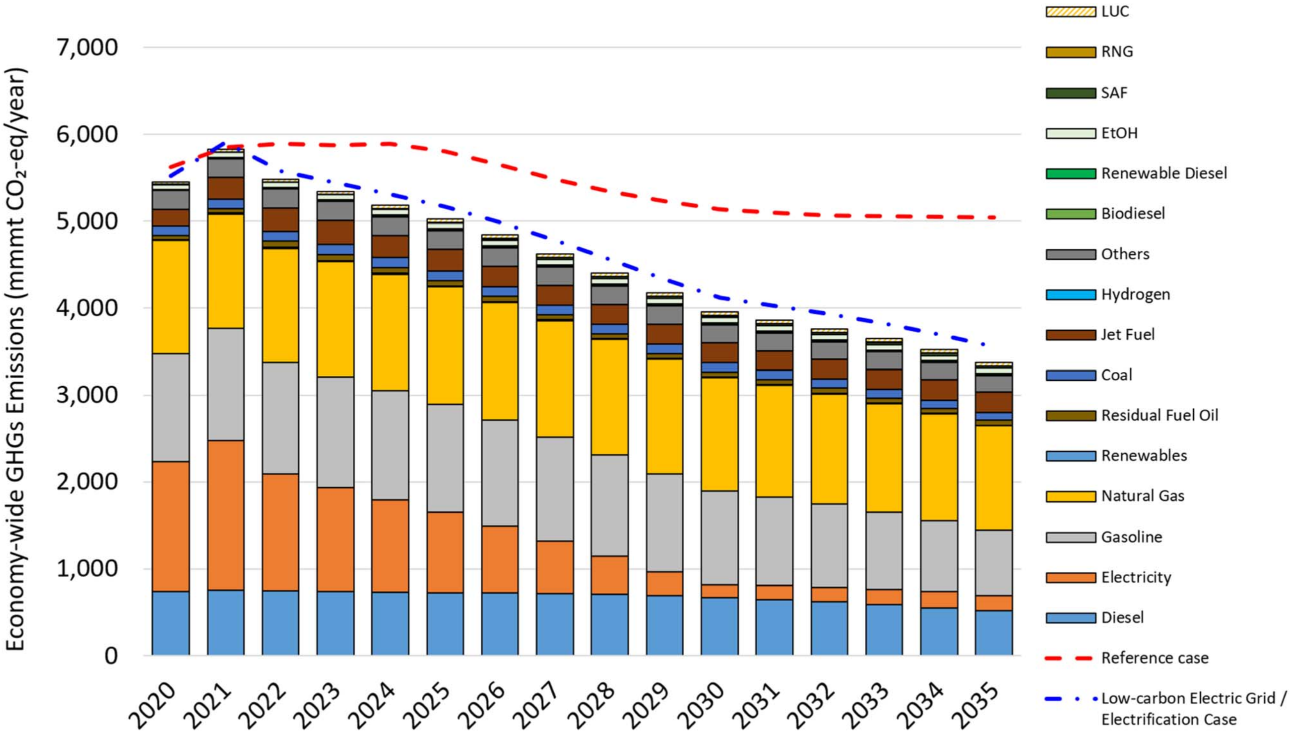

Fig. 7 U.S. economy-wide GHG emission contribution by fuel types. The red line shows the reference case emissions based on AEO 2022 energy demand projection, the blue line shows the case with electrification and low carbon electricity grid and the column chart shows the case with electrification, low carbon electricity grid and increased use of alternative fuels based on producers' plans.

and may be sufficient to allow the "market to decide" whether battery electric vehicles (BEVs) or drop-in RD is a better solution. Another concern is rebound and backfill; increases in biofuel supply or compliance mandates do not necessarily displace fossil fuel use one-for-one, particularly when average fuel prices fall or policy signals weaken. Empirical work under the RFS and low-carbon fuel programs shows that additional biofuel often displaces less than an energy-equivalent amount of petroleum because of price pass-through and demand elasticity, and because total liquid fuel use can expand—allowing fossil "backfill" when biofuel supply is insufficient to meet demand.[90–92] Strengthening regulatory or market-based instruments could help mitigate this phenomenon.

3.6. Estimated economy-wide GHG emissions for the next 10 years

The results indicate that biofuels could replace up to 3.8 EJ of conventional fuels by 2035, significantly addressing transportation sector emissions. Most GHG reductions occur through SAF replacing jet fuel and BD/RD displacing conventional diesel, contributing a 150 MMT CO_2e per year reduction in the transportation sector. In industry, electrification, low carbon electricity grid, and efficiency improvement drive most GHG reductions, with biofuel contributing a 15 MMT CO_2e per year reduction by 2035. The GHG reductions of both the commercial and residential sectors primarily stem from low carbon electricity, electrification, and efficiency improvement in end uses like heating/cooling, water heating, and washing/drying, contributing 298 and 450 MMT CO_2e reductions per year by 2035 with biofuel contributing 8.4 and 2.8 MMT CO_2e reductions, respectively. Biofuel deployment in the agricultural sectors is limited to a reduction of 2.9 MMT CO_2e per year by replacing diesel use in tractors. These results are in line with United States and state policy measures that have focused on biofuels for transportation uses. Please see the SI Sections S6–S8 for more details on sector-specific impacts.

Placing this in the context of overall U.S. GHG emissions, biofuels reduce economy-wide GHG emissions by 3.6%. While this study does not focus on estimating the effects of other emissions reduction measures, leveraging the findings of other studies,[73,93] we find that biofuels contribute roughly one-tenth of the overall reduction in GHG emissions in 2035 of 1700 MMT CO_2e, or a 33% reduction compared to the EIA reference case (Fig. 7). In addition to biofuels, these reductions include low carbon electricity grid, battery electrification of transport, and efficiency improvements in industrial, residential, and commercial energy uses.

4. Conclusions

This study examines the current and projected U.S. biofuel production capacity over the next decade, with a focus on sustainable aviation fuel, renewable diesel, biodiesel, ethanol, and renewable natural gas. By synthesizing facility-level data, it estimates the potential life cycle greenhouse gas emissions reductions achievable through planned biofuel expansions. The findings have highlighted that by 2035, biofuel capacity could reach 3.8 exajoules, primarily utilizing first-generation and waste feedstocks, potentially reducing U.S. GHG emissions by 179 million tonnes with significant impacts in transportation sectors. Despite this expansion, biofuel production capacity remains limited compared to overall U.S. fuel demand, indicating opportunities for further growth beyond 2035. The Bipartisan Infrastructure Law and Inflation Reduction Act (IRA) measures together with increasing industry and consumer commitments to reducing GHG emissions and enhancing domestic energy supply are accelerating the deployment of biofuels. We see this "first phase" of expansion as primarily in conventional and waste feedstocks, which offer lower cost opportunities for biofuel production while plans for expansion to cellulosic feedstocks and e-fuels using captured CO_2 remain limited.

The projections in this study are based on publicly available expansion plans announced by industry by 2024 and may be thought to reflect conservative or optimistic estimates of production in 2035 depending on the evolution of the market and policy measures between now and then. Under the current IRA incentives and assuming these incentives are extended, it is reasonable to believe that 2035 biofuel production may be higher than projected by this study, as additional projects could be planned and built between now and 2035 and some current plans may not be publicly announced. Meanwhile, inherent risks and changes in the market could also result in the cancellation or failure of planned projects.

There remains significant untapped opportunity for biofuels to enhance domestic energy supply and decrease GHG emissions that policymakers should pay attention to in the next phase of the energy transition to remain on track for the future goals. According to the U.S. Department of Energy Bioenergy Technologies Office's projection, it is estimated that 62 billion GGE per year of sustainable biofuel could be produced in the United States by 2050, driven by feedstocks including purpose-grown energy crops, algae, wet wastes, and forestry and agricultural residues.[94] Our study estimates that about 31 billion GGE of biofuel could be produced by 2035, based on publicly available data on expansion plans prior to publication. While first-generation and waste feedstocks dominate current and near-term production, scaling cellulosic biomass use is crucial for future growth. Mobilization of the cellulosic biomass resources projected by the 2023 Billion-Ton Report is key to achieving these levels of biofuel production and potential GHG reductions.

From an energy security and domestic productivity perspective, increased biofuel availability enhances the energy supply and could increase the U.S. Gross Domestic Product (GDP) and provide millions domestic jobs.[95] Furthermore, increased biofuel production could position the United States as a net energy exporter, enhancing its global geopolitical standing, particularly in BD/RD and EtOH, *e.g.*, around 1.5 billion gallons EtOH was exported in 2023.[53] Meanwhile, if emissions reduction is the goal, measures addressing the potential rebound effect of increased fuel supply should be considered, as biofuel supply might lower fossil fuel prices, potentially expanding the conventional fuel market.

It is worth noting that the growth in biofuel capacity expansion reported in this study represents nameplate capacity and not necessarily production volume as these are challenging to track. Plants can operate below nameplate capacity, and the mix of products can also change. Our results reflect annualized, facility level capacities harmonized with pathway CIs and should be interpreted as indicative of potential scale and timing rather than precise forecasts. Key uncertainties include (i) capacity realization/utilization and SAF-RD product slate choices, (ii) feedstock mix and distribution (iii) land use change (LUC) factors, and (iv) imports/exports (noting future trade patterns could shift U.S. market volumes and displacement effects). We quantify LUC variability, adjust imports/exports with 2019–2023 EIA averages, and constrain domestic waste FOG. While some uncertainties remain, the principal conclusion—that planned biofuel capacity can deliver emissions reductions by 2035, particularly in aviation and diesel uses holds. Biofuels impact not only GHG emissions but also water consumption, land use, criteria air pollutants emissions, and other environmental metrics. We plan to address these aspects in the next phase of this study.

Author contributions

Tai-Yuan Huang: conceptualization, methodology, software, validation, formal analysis, data curation, writing – original draft, writing – review and editing, visualization; Doris Oke: conceptualization, methodology, software, validation, formal analysis, data curation, writing – original draft, writing – review and editing, visualization; Troy R. Hawkins: conceptualization, methodology, validation, writing – original draft, writing – review and editing, visualization, supervision, project administration, funding acquisition.

Conflicts of interest

There are no conflicts to declare.

Data availability

Detailed facility-level biofuel data by type are provided in the supplementary information (SI). Facility-specific CI values are sourced from CARB's LCFS certified pathways and available at **https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities**.Other used CI data are available at **https://greet.anl.gov/greet_icao** and **https://greet.anl.gov/**. Data for energy demand projection are publicly available at **https://www.eia.gov/outlooks/archive/aeo22/** and **https://greet.anl.gov/tool_decarb**. Supplementary information is available. See DOI: **https://doi.org/10.1039/d5se00769k**.

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