TRANSPORTATION
ENERGY INSTITUTE

Decarbonizing Combustion Vehicles

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A PORTFOLIO APPROACH TO GHG REDUCTIONS

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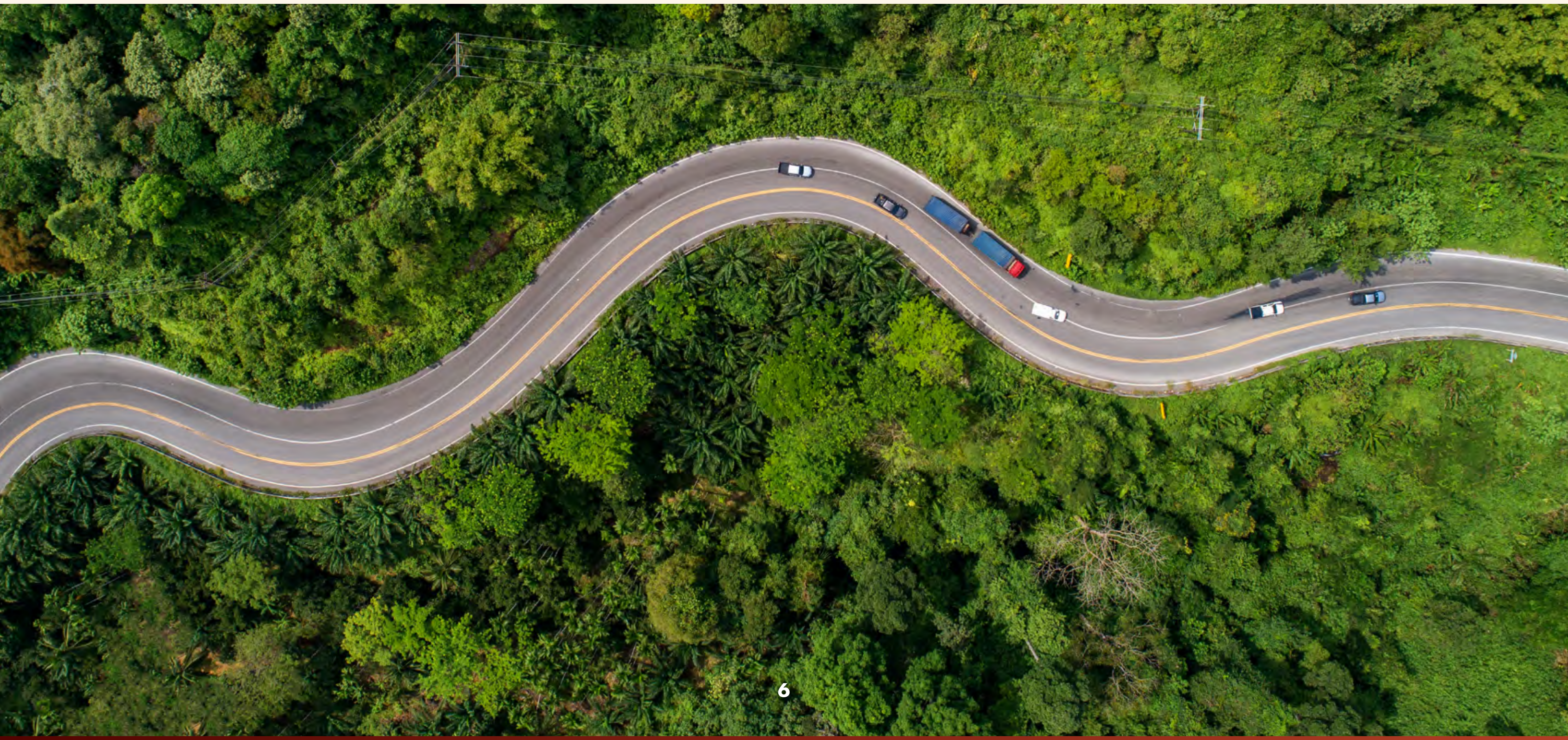

Executive Summary

Within the United States, federal and state policies are encouraging or requiring the adoption of zero-tailpipe emissions vehicles (ZEVs) like battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles. President Biden issued an executive order setting a goal that by 2030 50% of all light-duty vehicles (LDVs) sold in the U.S. will be ZEVs. BEV sales are projected to increase significantly in the coming years, but it will take decades to turn over the current vehicle fleet.

S&P Global Mobility[1] reports that in July 2021 BEVs represented only 0.42% of vehicles in operation, which left 282 million internal combustion engine vehicles (ICEVs) on the roads in the U.S. By 2030, it is projected there will be 290 million ICEVs in operation. That same year, BEV sales were projected to total nearly 2.8 million units. If LDV sales maintain their historical level of about 16.5 million vehicles per year, this would mean that, even in 2030, consumers will purchase nearly 14 million new ICEVs, and those vehicles can be expected to be on the road in the U.S. for at least fifteen years. Accordingly, large numbers of ICEVs consuming liquid fuels will be on the road in the U.S. for decades to come.

Given the objective to reduce carbon emissions from the transportation sector, waiting for the market to transition to ZEVs without seeking solutions for the dominant powertrain on the roads is a strategy

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[1] https://www.transportationenergy.org/research/reports/ev-charger-deployment-optimization

which ignores the substantial reductions which can be achieved in current and future ICEVs. Embracing strategies to reduce carbon emissions from the nearly 300 million ICEVs that will continue to operate in the U.S. for the next several decades is imperative.

Fortunately, total lifecycle, as well as tailpipe, emissions reductions are already being achieved by increasing use of biofuels and reducing the carbon intensity of the fuel mixtures used in ICEVs. Additional near-term steps to reduce the carbon intensity of fuels will play a critical role in limiting the expected increase in cumulative mobile source greenhouse gas (GHG) emissions. ICEV technologies and the associated fuels can continue to be employed over broad and energy-intensive transportation applications while making substantial contributions to near- and long-term GHG emissions reductions. In fact, substantial reductions in GHG emissions from LDVs in the near term can only be achieved by reducing emissions from ICEVs.[2]

Stillwater Associates was engaged by the Transportation Energy Institute to identify and analyze the potential opportunities to expand on this critical GHG-reduction strategy. In this report, we examine the benefits achievable through the decarbonization of the existing on-road U.S. ICEV fleet given the extended timeframe which will be required to transition that fleet to ZEVs.

This study was executed in four stages:

1. **Prelude** – An overview of the current U.S. vehicle market composition, fleet turnover rates, GHG and criteria pollutant emissions, and the duration of various GHG emissions in the atmosphere;
2. **Life Cycle Analysis of Options** – Identify a slate of options which could materially contribute to a lower carbon ICEV market;
3. **Biofuels** – Demonstrate how bio- and renewable fuels present the most promising near-term option for lowering the carbon emissions of the existing ICEV fleet; and
4. **Market Transition** – Evaluate the practical implications and requirements for transitioning the existing ICEV fuel supply to the decarbonized fuel mix identified.

IN THIS REPORT, WE ASSESS THE VEHICLE FLEET AND GHG REDUCTIONS REALIZED FROM 2011 THROUGH 2021 AND DISCUSS GHG-REDUCTION POTENTIAL FROM 2022 THROUGH 2050.

IN THIS TIMEFRAME, BIOFUELED ICEVs ARE LIKELY TO REMAIN COMPETITIVE WITH ELECTRIC VEHICLE (EV) EMISSIONS REDUCTIONS. TAKEN TOGETHER, DECARBONIZING THE ICEV FLEET AND GROWING THE EV FLEET WILL MAXIMIZE CUMULATIVE GHG REDUCTIONS.

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[2] U.S. Environmental Protection Agency (EPA) / Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Year 2022-2025.

The key findings of the prelude are:

1. **Biofueled ICEVs are reducing emissions now.** Since 2011, when California began tracking biofuel GHG reductions, biofueled ICEVs have reduced 76 million metric tons (MT) of GHG emissions while EVs have reduced 16 million MT. Biofueled ICEVs will continue generating more GHG reductions than EVs for at least the near term and likely into the longer term due to biofuels' low carbon intensities being used in the larger ICEV fleet.

2. **NOx and $PM_{2.5}$ emissions have been cut significantly from 2000 levels.** EPA estimates the national fleet of all vehicles (except motorcycles) reduced nitrogen oxide (NOx) emissions by 89% between 2000 and 2022. By 2030, the fleet's NOx emissions are projected to be reduced by up to 95% compared to the 2000 baseline. Today, diesel $PM_{2.5}$ emissions are 91% lower than 2000 levels, and by 2030 the fleet will be 97% lower than 2000 levels.

3. **New heavy-duty (HD) diesel vehicles provide substantial PM emissions reduction benefits.** The EPA emission inventories show new heavy-duty diesel vehicles' PM emissions in the laboratory are 99.86% lower than 1990 vehicles. When driven in air violation areas, the cleanest diesel ICEVs now operate 100.4% more cleanly than 1990s-era vehicles (i.e., modern ICEVs consume more air pollution than they emit).

4. **Fleet turnover to new technology vehicles will be slow due to higher vehicle costs and the required installation of new infrastructure.** This hinders progress towards replacing the oldest, dirtiest heavy-duty ICEVs and makes a single-track ZEV adoption approach a less economical and slower way to a cleaner vehicle fleet than reducing GHG emissions from ICEVs in the immediate term.

5. **GHG emissions reductions can be effected more immediately by incrementally reducing emissions with the current and future fleet of ICEVs than by waiting for the fleet to transition to ZEVs.** For example, if existing heavy-duty ICEVs were fueled with 100% renewable diesel (RD) starting in 2022, they would achieve GHG reductions four times greater than those achieved by EVs over the next decade. Heavy-duty ICEVs fueled with 20% biodiesel (BD) blended with 80% petroleum diesel (B20) would match expected heavy-duty EV GHG reductions over the decade. On the light- and medium-duty side, if gasoline with 15% ethanol (E15) replaced gasoline with 10% ethanol (E10), due to the significantly greater number of vehicles on the road that could use this fuel ethanol would provide twice the cumulative GHG reductions as the smaller market of EVs are expected to achieve over the decade.

The key findings of our lifecycle analysis of options are:

1. **GHG reduction options abound.** When considering the massive volume of ICEVs on the road for the decades to come, immediate solutions are necessary. There are at least 24 fuel sources for ICEVs that could provide equal or greater GHG reductions to the reduction seen in present US EVs charged using the average U.S. mix electricity (excluding coal). This demonstrates that, while the market for EVs expands, there is a diversity of biofuels sources to support significant GHG reductions from ICEVs into the future.

2. **ICEVs + biofuels is a winning immediate and long-term combo.** Conventional vehicles fueled with biofuels have the potential to provide at least 80% of total on-road transport GHG reductions through 2035 and 68% of GHG reductions through 2050.

3. **NOx emissions modeling falls short.** Applying laboratory testing results to real-world conditions results in an overestimation of realized NOx emissions from ICEVs as ambient NOx (i.e., the NOx concentration found in the air taken in by the ICEV engine) can be higher than the measured NOx in the exhaust. Thus, in real-world conditions, NOx emissions from the cleanest modern vehicles driven on the highway are a net negative. Put simply: ICEVs can clean NOx from the air.

4. **ICEVs' PM emissions have dramatically improved since 1980.** All vehicle options sold today reduce PM emissions within 3% of that logged by EVs charged using U.S. mix power. On the heavy-duty front, all properly operating (and non-coal-generated electricity charged) HD EV and HD diesel ICEVs provide equivalent PM reductions on a well-to-wheels or vehicle basis. However, high costs for newer and cleaner HD trucks often leaves older vehicles on the road for a prolonged period of time. Low carbon biofuels are necessary to improve overall emission reductions.

The key findings of the Biofuels analysis are:

1. **Biofuel benefits are not tapped out:** EIA projections indicate that the volume of biofuels used in ICEVs will hold steady through 2050 even as EVs displace ICEVs. With additional incentives for and approval of biofuels usage, these volumes and associated emissions reductions could grow.

2. **Easiest options:** Expanded usage of ethanol, RD, and BD is the lowest hanging fruit available to reduce the existing fleet's GHG emissions.

3. **Ethanol + carbon capture could provide significant benefits:** Demand for ethanol has been constrained by the absence of incentives under the current design of the federal Renewable Fuel Standard (RFS), biomass-based diesel blenders tax credit (BTC), and the cellulosic biofuel waiver credit, to price higher ethanol blends like E85 to be competitive with E10 at an energy equivalent level. The Inflation Reduction Act of 2022 (IRA)[3] expands the 45Q tax incentive for carbon capture, utilization, and storage (CCUS) and adds significant support for ethanol produced with CCUS.

4. **The food versus fuel debate is fading:** Ethanol and BD supply currently rely heavily on two feedstocks, corn and soybeans, respectively. The impact of using a growing share of corn for fuel instead of food has declined over time due to increasing crop yields, corn-to-biofuel conversion process efficiency, and improvements in the ability to extract coproducts like dried distillers grains with solubles and corn oil.

5. **Nonfood feedstocks show growth potential:** In addition to current and growing usage of inedible tallow, used cooking oil, and distillers corn oil, there is significant potential to use nonfood feedstocks, such as oilseeds from cover crops and dedicated energy crops, to produce biofuels with much less diversion of cropland to biofuel production and greater potential to reduce carbon intensity of transportation fuel. However, policy incentives that reward lower carbon fuels and improve their competitiveness and assured demand are critical to induce investment in these feedstocks. The transition from the BTC to the Clean Fuels Production Tax Credit (also referred to as 45Z) in 2025, as established by the IRA, provides increased incentive to utilize nonfood feedstocks for production of biofuels.

6. **State-level low-carbon fuel standard (LCFS) programs are driving low-carbon fuel innovation:** LCFS-style programs, as currently exist in California, Oregon, and Washington (with potential to expand into additional states), have accelerated the use of renewable fuels beyond what is required by the federal RFS. In addition to supporting the replacement of ICEVs with ZEVs, LCFS programs provide unique incentives to producers of all low-carbon fuel options to continually reduce the CI (carbon intensity) of their production. As a result, existing LCFS programs have driven deeper decarbonization of ICEV fuels than would have been achieved with the RFS alone. In California, for example, the LCFS has led to the displacement of over one-third of petroleum diesel fuel demand with RD and BD.

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[3] 117th Congress / Public Law 117-169.

The key findings of the Market Transition Requirements analysis are:

1. **Immediate carbon reductions yield both short- and long-term benefits:** Many near-term options for reducing the carbon intensity of ICEV fuels will have near-term reductions in carbon emissions since those ICE fuels will be used in the current fleet of ICEVs and will continue into the future. Improvements to ICEVs' fuel economy amplify these carbon reductions.
2. **All options faces challenges:** There are varying degrees of viability and timing uncertainties in each of the options for further decarbonizing ICEVs.
3. **There is no silver bullet:** Given these uncertainties and the fact that some of these alternatives are highly aspirational, a portfolio approach to ICEV decarbonization is advisable.
4. **ICEV carbon reductions are a crucial near-term step toward net zero:** Since full ZEV deployment is not without significant challenges and is not viable as a short-term solution, deployment of lower carbon ICE vehicle and fuel options provides real near-term carbon emissions reductions and can be a hedge against slower ZEV deployment.
5. **ICEV improvements can complement ZEV deployment**: A portfolio approach will maximize the reductions in on-road transportation carbon emissions in both the near and long term and result in both ICEVs' (near-term) and ZEVs' (longer term) roles in minimizing transportation carbon emissions being realized.
6. **A portfolio approach:** Based on our analysis and comparison of the alternatives discussed in this report, we propose a list of prioritized options to optimize the carbon reduction of the ICEV fleet based on the parameters evaluated. These parameters include potential fleet carbon reductions, ease of economic and consumer acceptance, technical viability, costs, and timing. The ranked options are listed in the table below. The first-tier options are the lowest hanging fruit with reasonable feasibility and relatively low cost-to-benefit ratios. The second-tier options are opportunities that need more time to develop, and the third-tier options require a significant breakthrough to become practical alternatives. (Table ES 1)

TABLE ES-1. TIERED ICEV CARBON-REDUCTION POTENTIAL OF ALTERNATIVE OPTIONS*

TIER	OPTION	PAIRED VEHICLE TECHNOLOGY	CARBON REDUCTION VS. CURRENT FLEET & FUELS	POTENTIAL IMPACT	INITIATIVES REQUIRED	
					REGULATORY	MARKETPLACE
0	Current ULSD & E10 Gasoline	Current Gas ICEV	base	N/A	N/A	N/A
1	Biodiesel (B5)	Current Diesel ICEV	<5%	small	N/A	Increased feedstock generation
1	Ethanol (E15)	Current Gas ICEV	3%	small	Wider EPA approval	Infrastructure build-out
1	Renewable Gasoline (RG)	Current Gas ICEV	50-70%	small	Continuation/expansion of existing regulatory incentives	Scalability of production
1	Renewable Natural Gas (RNG)	NGV	100+%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Renewable Propane (RP)	LPG ICEV	60-70%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Reduced CI Gasoline & Diesel	Current ICEVs	5-15%	small to medium	Strengthened regulations on upstream flaring and methane emissions; continued move to renewable marine fuels; continued regulatory incentives for CCUS and use of renewable energy at refineries	Refinery investment in CCUS and usage of renewable energy
1	Ethanol (E15)	Hybrids (HEV & PHEV)	20%	small to medium	E15 approval and increased incentives for hybrid expanded vehicle purchases	Conversion to hybrid vehicle fleet and expansion of E15 infrastructure
1	Biodiesel (B20)	Current Diesel ICEV	5-15%	small to medium	N/A	Increased feedstock generation
1	Ethanol (E85)	FFV	15-25%	small to medium	Increased incentives for FFV production and purchase (adjustments to CAFE) and potential aftermarket equipment certification program for FFV conversions	Fueling infrastructure expansion and increased vehicle and fuel availability
1	Renewable Diesel (R99)[3]	Current Diesel ICEV	50-70%	medium	Continuation/expansion of existing regulatory incentives	Increased feedstock generation
1	Renewable Diesel (R99)	Hybrids (HEV & PHEV)	55-85%	medium	Increased incentives for hybrid vehicles	Conversion to hybrid vehicle fleet and increased feedstock generation
2	Ethanol (Intermediate Blends)	Dedicated Vehicle	5-15%	small	New incentives for development of dedicated intermediate-ethanol-blend vehicle production	Expanded compatible fuel infrastructure
2	Biodiesel (B20+)	Current Diesel ICEV	40-60%	small	Establish ASTM standards	OEM warranty, expanded fueling infrastructure, and increased feedstock generation
2	ICEV Improvements	NA (current fuels)	20-50%	medium	Technology-neutral testing and CAFE standards	Broad OEM roll-out
2/3	Hydrogen (H_2)	H_2 ICEV	60-100%+	small	Substantial financial incentives	Build-out of hydrogen production hubs, expansion of dedicated fueling infrastructure, conversion of vehicle fleet to H_2
3	Cellulosic Ethanol (E10)	Current Gas ICEVs	5-10%	small	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Cellulosic Diesel	Current Diesel ICEVs	60-90%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	FT Diesel (BTL)	Current Diesel ICEVs	20-100+%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Pyrolysis Fuels	Current Gas & Diesel ICEVs	0-60%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	E-Fuels	Current Gas & Diesel ICEVs	40-100%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost

*For an explanation of the assigned tiers presented in this table, please refer to page 175.

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4 Renewable Diesel (RD) at 100% by volume (R100) can be placed into a vehicle without issue, but the Biomass-Based Diesel Blenders Tax Credit (BTC) requires blending of RD with petroleum diesel in order to generate the credit. As such, essentially all RD in the market is blended with at least a small amount of petroleum diesel.

Prelude

Vehicle Technologies and Emissions

In this report, we explore various vehicle technologies and their corresponding fuels as well as greenhouse gas (GHG) and criteria pollutant emissions. In this section, we level-set the vehicle technologies and emissions categories addressed in this four-part study.

1.1 VEHICLE TECHNOLOGIES

A zero-emission vehicle (ZEV) is a vehicle that does not emit exhaust gas or other pollutants from the onboard source of power. California's ZEV Program requires most vehicle manufacturers operating in the state to bring to and operate in California a certain percent of ZEVs such as battery electric vehicles (BEVs), gasoline plug-in hybrid electric vehicles (PHEVs), and hydrogen fuel cell electric vehicles (FCEVs).[5] Table 1 below differentiates between vehicle technologies that qualify as ZEVs and those that do not.

TABLE 1. VEHICLE TECHNOLOGIES

VEHICLE TECHNOLOGY TYPE	ZEV*
Gasoline (Conventional)	NO
Flexible-Fueled Vehicles (E85 FFVs)	NO
Diesel	NO
Gasoline Hybrid	NO
Natural Gas Vehicle	NO
Gasoline Plug-In Hybrid Electric Vehicle (PHEV)	YES
Battery Electric Vehicle (BEV)	YES
Hydrogen Fuel Cell Electric Vehicle (FCEV)	YES

**ZEV refers to criterion pollutants (hydrocarbons, carbon monoxide, NOx, and PM) and GHG emissions. PHEVs must have an all-electric range of at least 10 miles to qualify as a ZEV.*

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[5] California Air Resources Board (CARB) / Zero Emission Vehicle Program.

1.2 GREENHOUSE GAS EMISSIONS

Gases that absorb heat in the atmosphere are called greenhouse gases. The primary GHGs emitted by the transportation sector are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These GHGs are commonly measured in units of carbon dioxide equivalence (CO_2e). The impact of each on climate change depends on three main factors: how much of the gas is in the atmosphere, atmospheric lifetime (i.e., the average length of time a given gas resides in the atmosphere given its sources, sinks, and reactivity)[6], and potency. Each of these factors is displayed in Table 2 below. The global warming potential (GWP) of a given GHG is the ratio of that gas' global warming impact relative to that of CO_2 over a 100-year time horizon.[7] Atmospheric concentration, atmospheric lifetime, and GWP are presented in Table 2 for the GHGs present in ICEV emissions.

Different sources offer a range of values for these key parameters, and the resulting uncertainty in these values results in uncertainty in any modeling of climate impacts of GHG emissions from ICEVs.

For this report, we use the United Nations Intergovernmental Panel on Climate Change (IPCC) assumption that it “takes only a few years before a CO_2 molecule in the atmosphere is taken up by plants or dissolved in the ocean” but that “the slow exchange of carbon between surface waters and the deep ocean” requires 50-200 years to adjust to the new equilibrium.[8,9] Methane, for its part, remains for 25 years. CO_2e expresses the combination of the GHGs that contribute to climate change adjusted based on each one’s unique GWP. This can also be done manually by summing the mass of the pollutants multiplied by their GWP factors.

Anthropogenic (human-caused) CO_2 enters the atmosphere through the burning of fossil fuels (such as coal, natural gas, and oil), solid waste, trees, and other biological materials, and as a result of certain chemical reactions (e.g., manufacture of cement). According to EPA, “The combustion of fossil fuels such as gasoline and diesel to transport people and goods was the largest anthropogenic source of CO_2 emissions in 2020, accounting for about 33% of total U.S. CO_2e emissions.[10] This category includes

TABLE 2. TRANSPORTATION-RELATED GREENHOUSE GAS CONCENTRATIONS AND GLOBAL WARMING POTENTIAL

GREENHOUSE GAS	CONCENTRATION IN ATMOSPHERE*	ATMOSPHERIC LIFETIME	GLOBAL WARMING POTENTIAL
Carbon Dioxide (CO_2)	416 ppm	Varies	1
Methane (CH_4)	1.895 ppm	100 years	29.8
Nitrous Oxide (N_2O)	0.334 ppm	114 years	273

Sources: Argonne GREET Model (anl.gov) using the IPCC Sixth Assessment Report values and the Global Monitoring Laboratory

** As of November 2022*

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[6] According to EPA: “The Global Warming Potential (GWP) was developed to allow comparisons of the global warming impacts of different gases. Specifically, it is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2). The larger the GWP, the more that a given gas warms the Earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years. GWPs provide a common unit of measure, which allows analysts to add up emissions estimates of different gases (e.g., to compile a national GHG inventory), and allows policymakers to compare emissions reduction opportunities across sectors and gases.” Understanding Global Warming Potentials.

[7] According to EPA: “Atmospheric CO_2 is part of the global carbon cycle, and therefore its fate is a complex function of geochemical and biological processes. Some of the excess carbon dioxide will be absorbed quickly (for example, by the ocean surface), but some will remain in the atmosphere for thousands of years, due in part to the very slow process by which carbon is transferred to ocean sediments.” Overview of Greenhouse Gases.

[8] Intergovernmental Panel on Climate Change (IPCC) / Climate Change: The IPCC Scientific Assessment.

[9] American Chemical Society / On the Atmospheric Residence Time of Anthropogenically Sourced Carbon Dioxide.

[10] EPA / Overview of Greenhouse Gases.

TABLE 3. AIR QUALITY TRENDS RELATED TO TRANSPORTATION CRITERION POLLUTANTS

POLLUTANT	MEAN ATMOSPHERIC CONCENTRATION	PROGRESS TO DATE	NATIONAL STATUS
Carbon Monoxide (CO)	1.2 ppm	87% decrease since 1980	Below National Standard
Ozone	0.067 ppm	29% decrease since 1980	85% of Nation Below National Standard
Lead	0.03 µg/m^3	85% decrease since 1980	Below National Standard
Nitrogen Oxides (NOx)	40.3 ppb	64% decrease since 1980	Below National Standard
Particulate Matter (PM_{10})	59.9 µg/m^3	32% decrease since 1990	Below National Standard
Particulate Matter ($PM_{2.5}$)	8.5 µg/m^3	37% decrease since 2000	Below National Standard
Sulfur Oxides (SOx)	10.8 ppb	94% decrease since 1980	Below National Standard

Source: National Air Quality: Status and Trends of Key Air Pollutants | EPA

domestic transportation sources such as highway and passenger vehicles, air travel, marine transportation, and rail. CO_2 is removed from the atmosphere (or 'sequestered') when it is absorbed by the oceans and plants as part of the biological carbon cycle."

In the U.S., methane accounts for approximately 10% of anthropogenic GHG emissions.[11] Methane is emitted during the production and transport of coal, natural gas, and oil. Methane emissions also result from livestock, other agricultural practices, and land use, and by the decay of organic waste in municipal solid waste landfills. Nitrous oxide is emitted during agricultural, land use, and industrial activities; combustion of fossil fuels and solid waste; and during treatment of wastewater. Methane can be captured from livestock and wastewater and used for pipeline gas, power generation, and automotive fuel.[12] The Biden administration, through the National Climate Task Force, has launched a whole-of-government initiative to significantly redouble efforts to reduce methane emissions.[13]

As CO_2 and methane (particularly for fossil-based natural gas vehicles, NGVs) emissions are the largest share of the mass of GHG emissions from ICEVs, they factor predominantly in the estimation of impacts. Renewable natural gas (RNG) is being pursued as an option to reduce the potential impacts of fossil-based NGVs on GHGs.

1.3 CRITERIA POLLUTANTS

Common air pollutants with known health impacts are defined as "criteria pollutants" under the 1970 Clean Air Act (CAA). The CAA established health-based National Ambient Air Quality Standards (NAAQS) for carbon monoxide, ground-level ozone, lead, nitrogen dioxide, particulate matter, and sulfur dioxide. Air pollution is measured especially in areas of high population and traffic and where pollution problems exist or are expected. Consequently, clean air progress for major cities is well established by EPA or local air districts.[14] Since the implementation of NAAQS, criteria pollutants have decreased significantly, although ozone and $PM_{2.5}$ are remaining challenges for some cities. Criteria pollutants have been mitigated via engine and aftertreatment capture system improvements as well as through fuel chemistry (i.e., ultra-low sulfur diesel, ULSD). Table 3 shows the progress toward criteria pollutant reduction to date.

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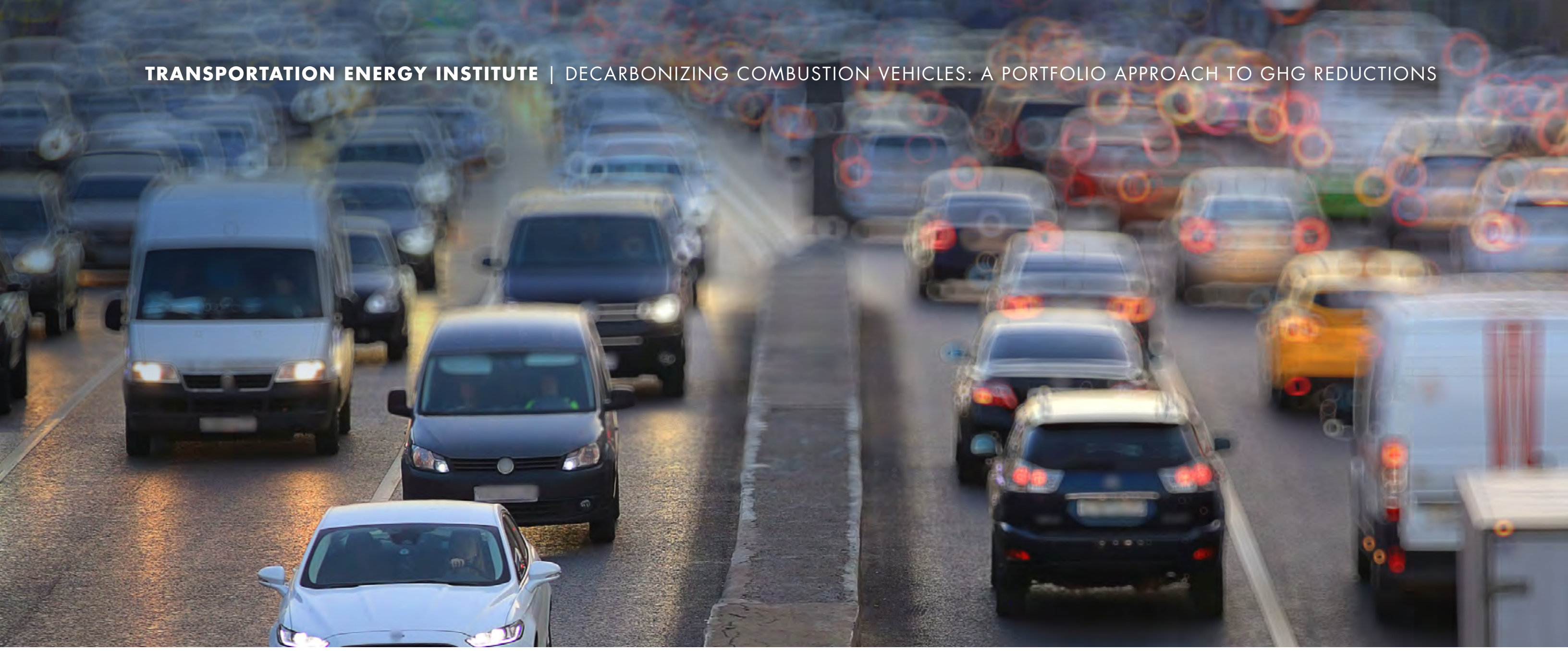
[11] EPA / Inventory of U.S. Greenhouse Gas Emissions and Sinks (1990-2019).

[12] Clarity and Leadership for Environmental Awareness and Research at UC Davis / What is a Dairy Digester and How Does it Affect Methane Emissions?.

[13] The White House Office of Domestic Climate Policy / U.S. Methane Emissions Reduction Action Plan.

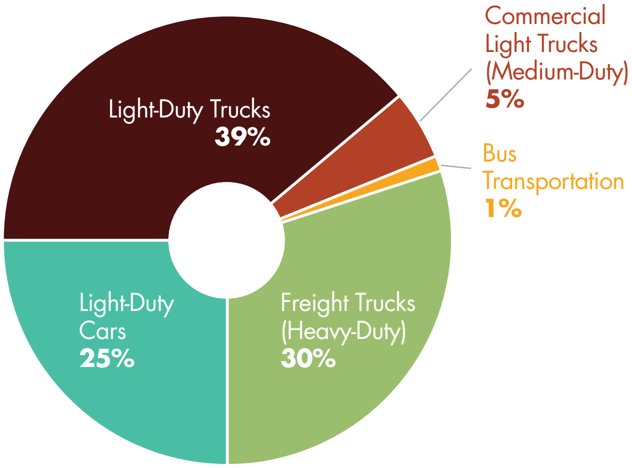
[14] Perfect Pollucon Services / Ambient Air Quality monitoring guidelines.



Current Fleet Composition

As policy makers look towards reducing GHG and criteria pollutants stemming from transportation, a realistic look at fleet turnover rates and other solutions is required. Slow EV adoption rates, coupled with the massive U.S. gasoline and diesel fleet, make apparent that EVs alone will not solve emission issues, especially on a lifecycle basis, within the timeframe demanded.

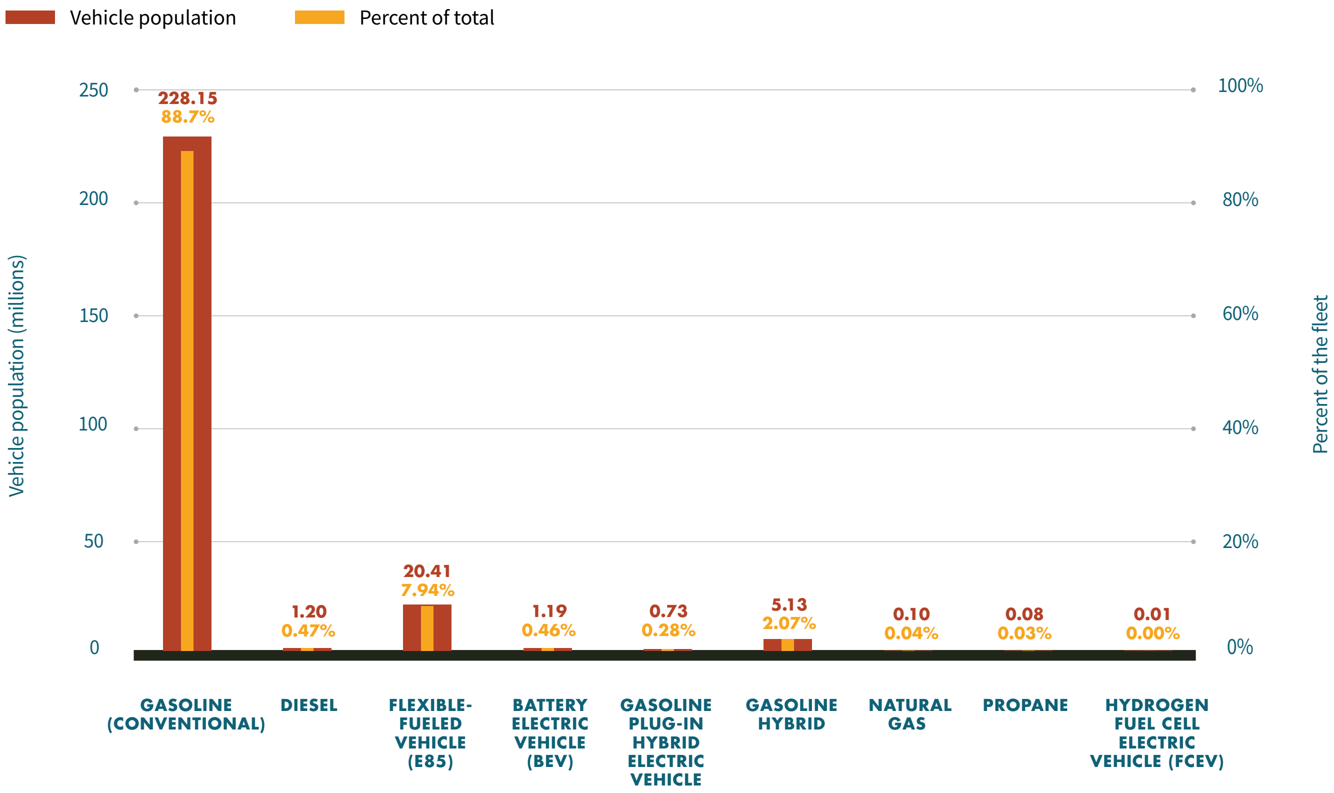
FIGURE 1. ON-ROAD TRANSPORTATION ENERGY USE (2022)



2.1 THE CURRENT FLEET IS DOMINATED BY LIGHT-DUTY VEHICLES

According to the U.S. Energy Information Administration's (EIA) 2022 Annual Energy Outlook (AEO), on-road transportation makes up 80% of total transportation energy used in the U.S. This on-road fuel use is broken down by light-duty cars, light-duty trucks, and heavy-duty vehicles (freight trucks, commercial trucks, and bus transportation) as shown in Figure 1.

FIGURE 2. LIGHT DUTY VEHICLE POPULATION AND PERCENT OF TOTAL FOR FUEL TYPES AND TECHNOLOGIES



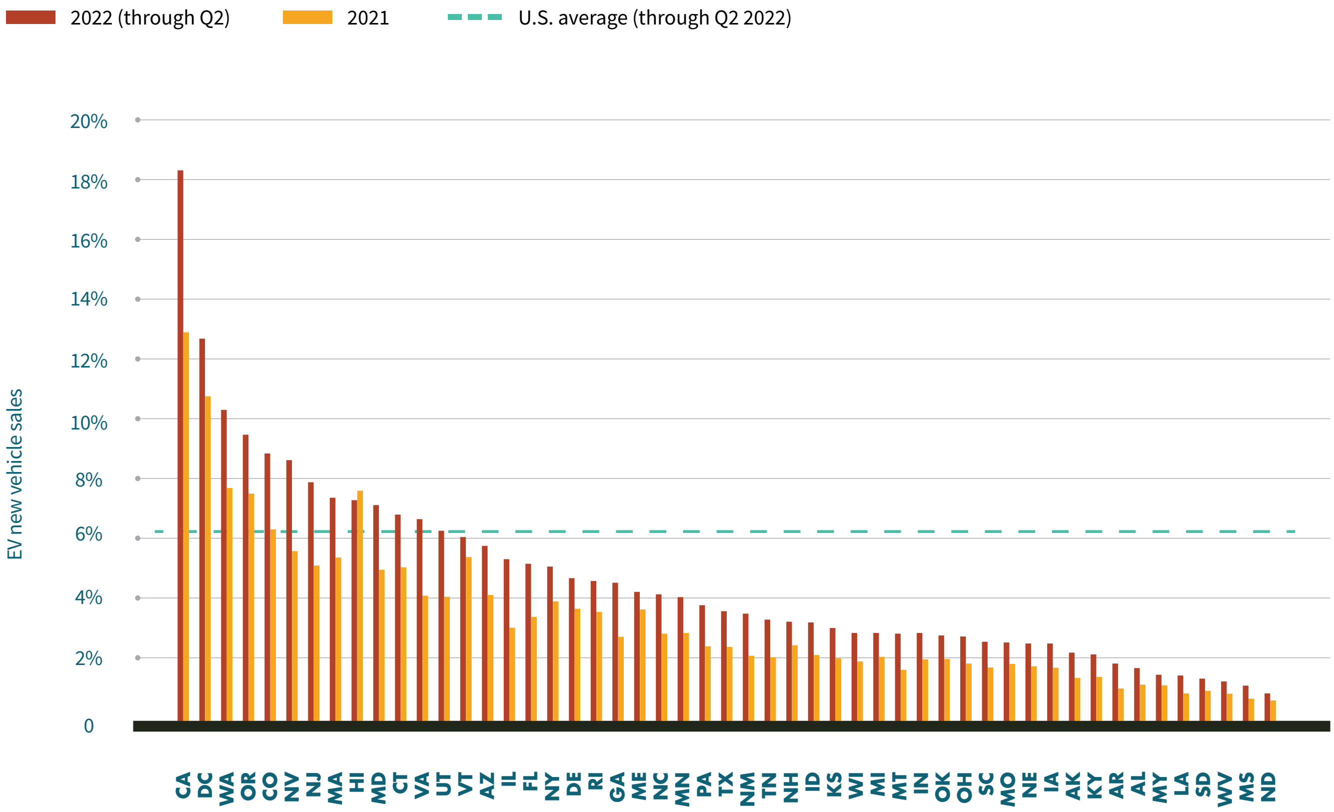
Source: EIA AEO 2022 Vehicle Stock Table 39

Figure 2 shows the distribution of fuel use in the U.S. light-duty fleet. The vast majority (98.7%) of the current U.S. light-duty fleet is powered by gasoline (conventional, gasoline-hybrids, and FFVs), leaving 0.47% diesel powered and 0.75% EV powered (battery electric, PHEVs, and FCEVs).

2.2 THE CURRENT EV MARKET IS CONCENTRATED IN STATES THAT OFFER INCENTIVES

Currently, the EV market varies greatly by state, as shown in Figure 3. State incentives play a large role in the early market share of EVs across the U.S. As can be seen, states and districts like California, Washington, D.C., Washington State, and Oregon—all of which have a history of providing economic incentives for EV ownership—have the largest volume of new EV sales. Additional factors influencing the pace of transition by state include fuel prices, climate laws and regulations, availability of charging infrastructure, and the distribution of population between urban, suburban, and rural areas. As can be seen in Figure 3, California leads the nation with 18% of national new EV sales in the first half of 2022, and according to IHS Markit, California is home to 41% of the nation's registered EV population.[15]

FIGURE 3. EV NEW VEHICLE SALES BY STATE THROUGH 2Q2022



Source: Get Connected: Electric Vehicle Quarterly Report, 2022 (Q2)

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[15] S&P Global Mobility / EV Insights – Part 1.

Passenger cars were the early market entry points for EVs into the light-duty fleet, as shown in Figure 4. With today's enhanced battery developments, EVs are moving into heavier light-duty trucks (mostly as PHEVs) and beginning to enter commercial light-duty trucks (classes 3-6). Transitioning the freight truck fleet (heavy-duty classes 7-8) to EVs is the most challenging due to the size and cost of the required battery packs and cost of required recharging infrastructure.

The total number of new EV models is growing faster than the number of new ICEV models coming to market. According to EIA, "Sales of several existing hybrid, plug-in hybrid, and electric models increased in 2021, but a large portion of the sales increase came from new manufacturer offerings across different market segments. Manufacturers increased the number of non-hybrid ICE vehicle models by 49 in 2021, versus an increase of 126 for hybrid and electric vehicle models."[16]

FIGURE 4. LIGHT-DUTY EV MIGRATION TRENDS

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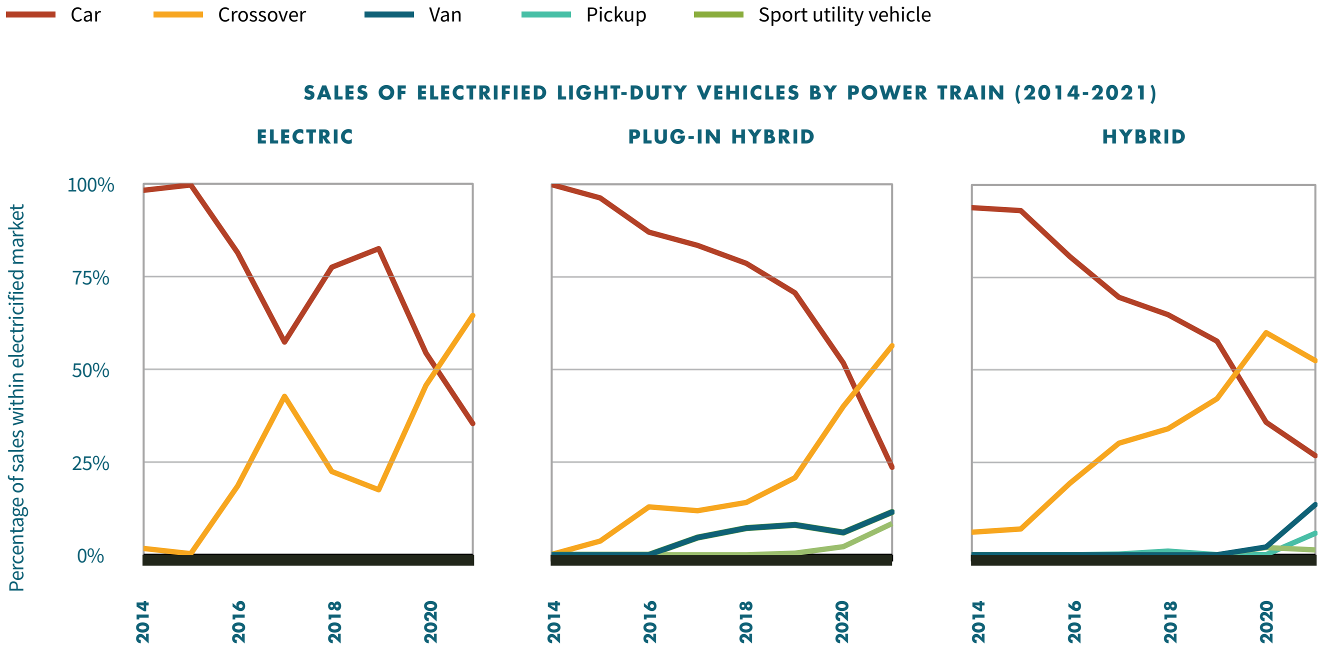

Source: EIA

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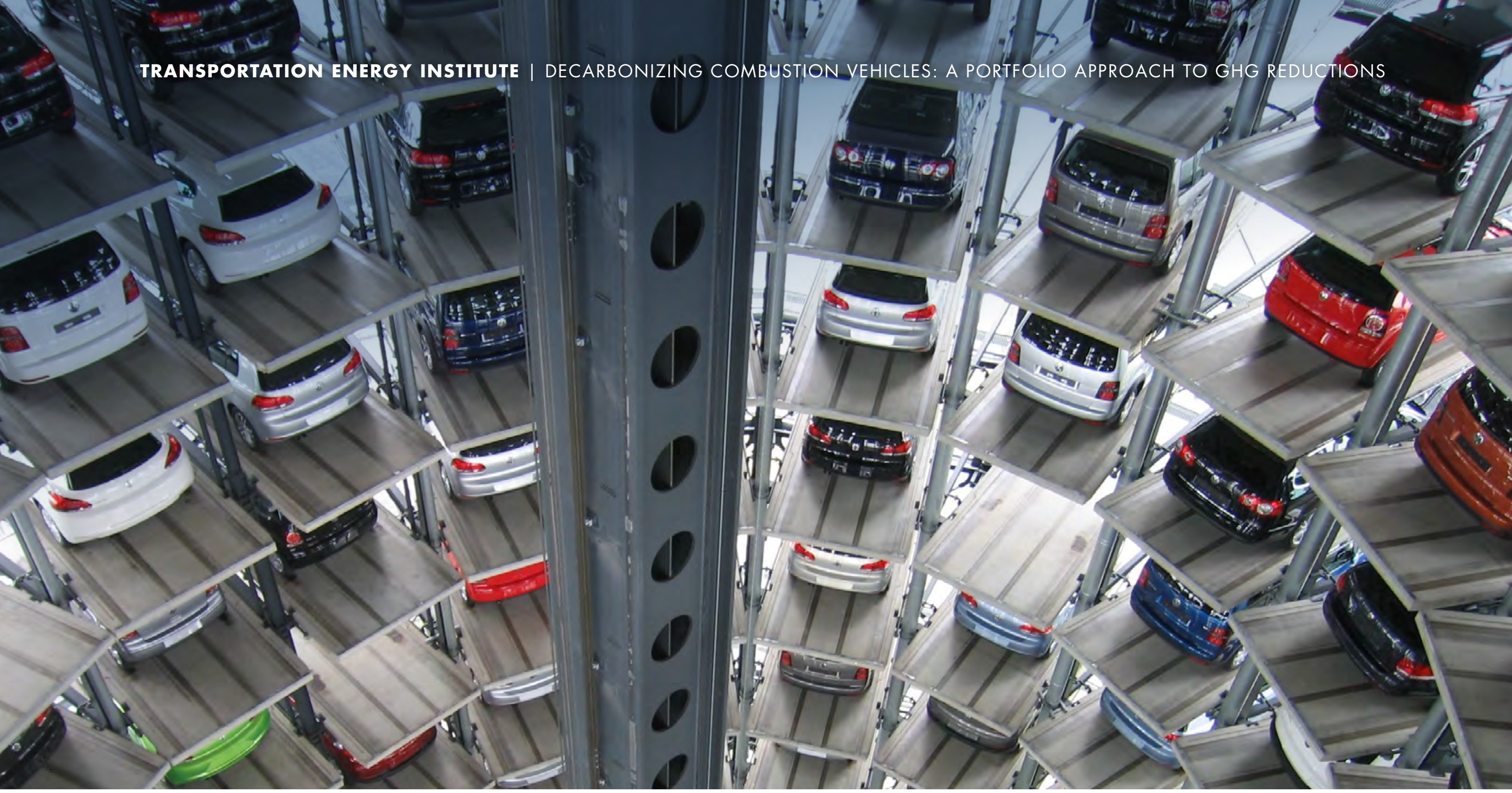
16 U.S. Energy Information Administration / Electric vehicles and hybrids surpass 10% of U.S. light-duty vehicle sales.



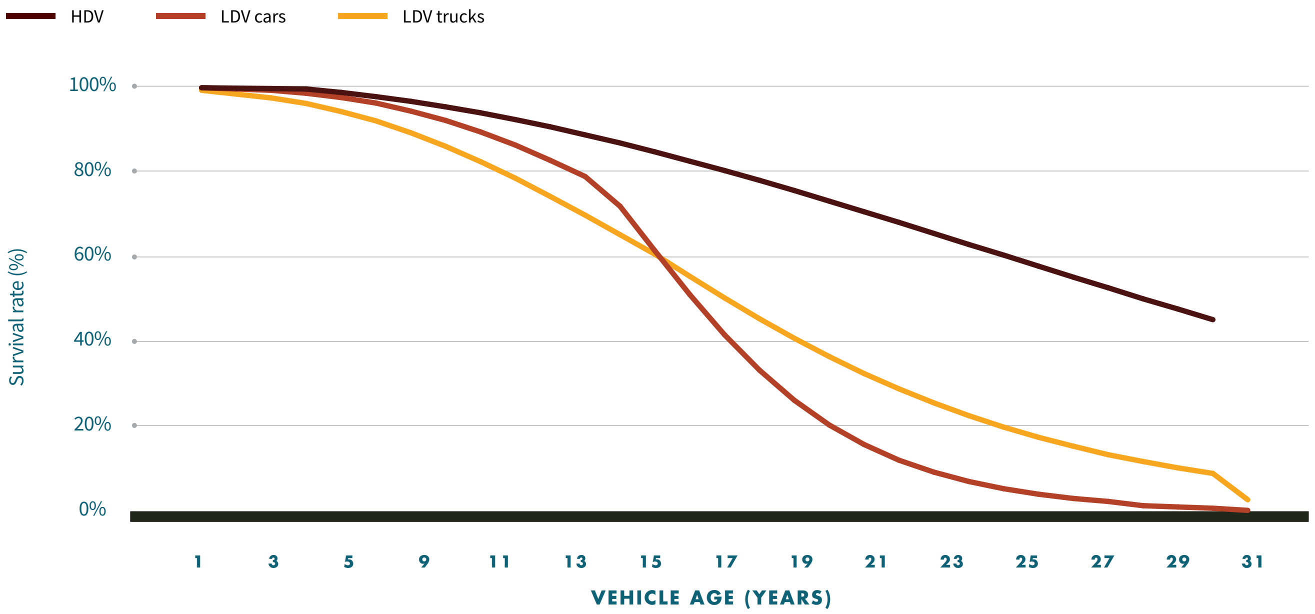
Rate of Fleet Turnover and Displacement

Fleet turnover rate is a measure of the amount of time required for a new vehicle technology to migrate into the total fleet and displace older vehicle technologies. According to AEO data, the maximum pace of fleet turnover is 18.5 years for all new light-duty vehicle sales to match the total fleet population, assuming 100% vehicle survival for all vehicles for all years.

Based on recent data from the Oak Ridge National Laboratory, vehicle survivability varies by several factors, including vehicle class, as shown in Figure 5. As can be seen, across all vehicle classes, 20% of current vehicles will still be on the road in 20 years or more:

1. **20% of cars are on the road after 20 years**
2. **20% of light-duty trucks are on the road after 24 years**
3. **20% of heavy-duty vehicles are on the road after 34 years**

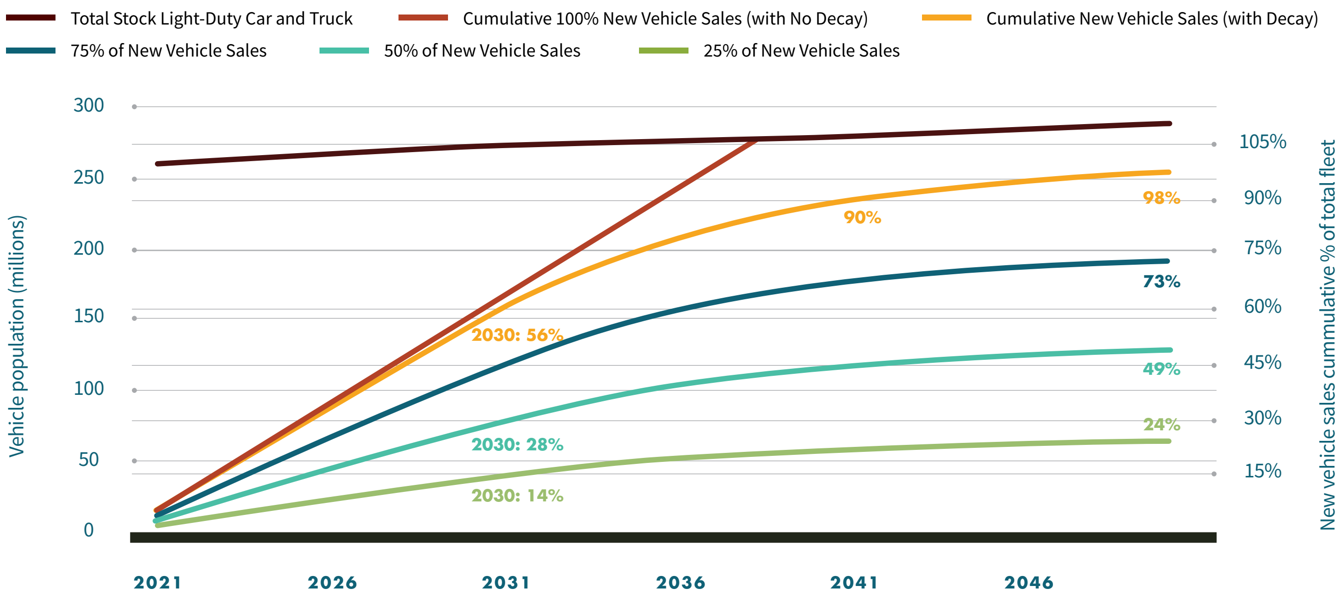
FIGURE 5. VEHICLE SURVIVAL RATE FOR CARS, TRUCKS, AND HEAVY-DUTY TRUCKS



Source: Oak Ridge National Laboratory Transportation Energy Data Book Edition 40, *Tables 3.14, 3.15, 3.16.*

Light-duty fleet turnover is shown below in Figure 6 with a range of new vehicle sales and with and without accounting for vehicle scrappage. After 29 years, new vehicle sales are estimated to replace 98% of the 2021 vehicle population.[17] Various lessor technology migration rates are shown for reference.

FIGURE 6. LIGHT-DUTY FLEET TURNOVER GIVEN A RANGE OF NEW VEHICLE SALES WITH AND WITHOUT POPULATION DECAY



Source: EIA 2022 AEO Reference Case Vehicle Stock Table 39

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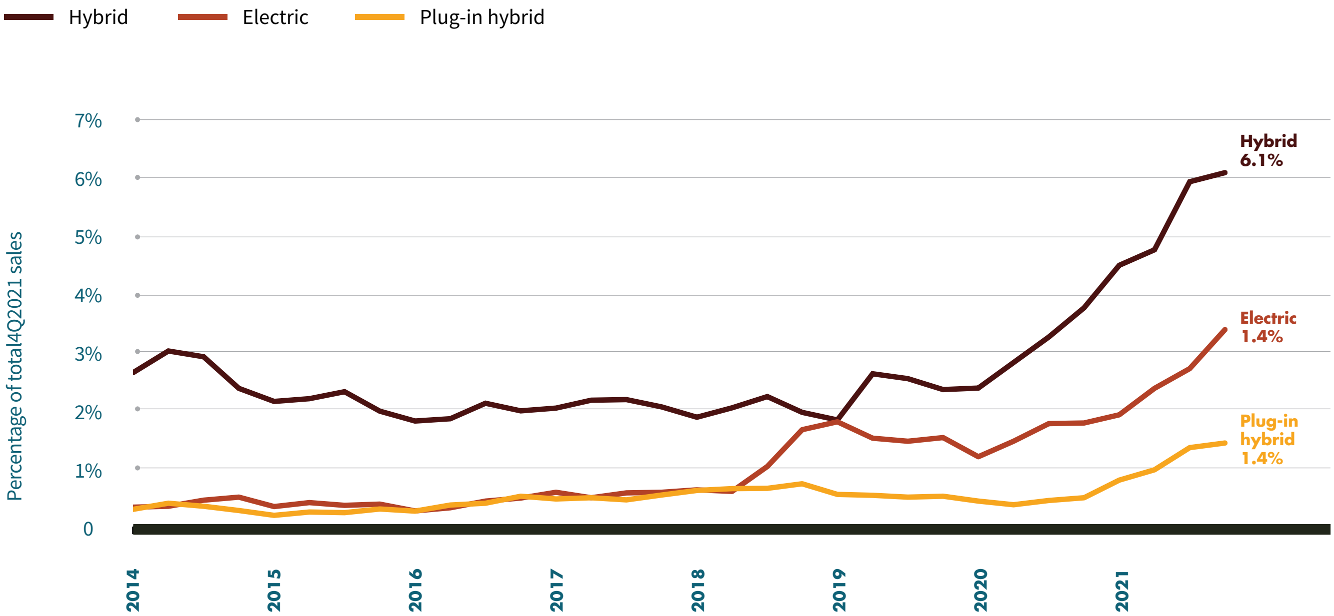
[17] California DMV registrations find 22-24-year light-duty fleet turnover.

3.1 EV ADOPTION RATES ARE INCREASING, BUT EVS ARE NOT EXPECTED TO DOMINATE THE FLEET

Figure 7 shows the EV (electric and PHEV) migration trend into the market reaching 6.6% by the second quarter of 2022. All indications are that EV sales will continue to grow, and we examine various projections in more depth later in this report.

In short, the mix of light-duty EV sales has moved from 80% cars in Q1 2020 to 32% cars in Q2 2022, while the share of utility vehicles in the EV mix grew from 20% to 65%, roughly approximating the current mix of all new light-duty vehicle sales. As this portion of the market shifts from cars to SUVs and trucks, hybrid and PHEV sales will likely strengthen while EV sales soften. The existing trend captures important consumer acceptance rates and product availability as well as the influence of federal and state incentives. Growth in the total number of new EV and hybrid models since 2021 partially explains the recent EV growth shown.

FIGURE 7. LIGHT-DUTY HYBRID AND EV SALES TRENDS (PERCENTAGE OF TOTAL)

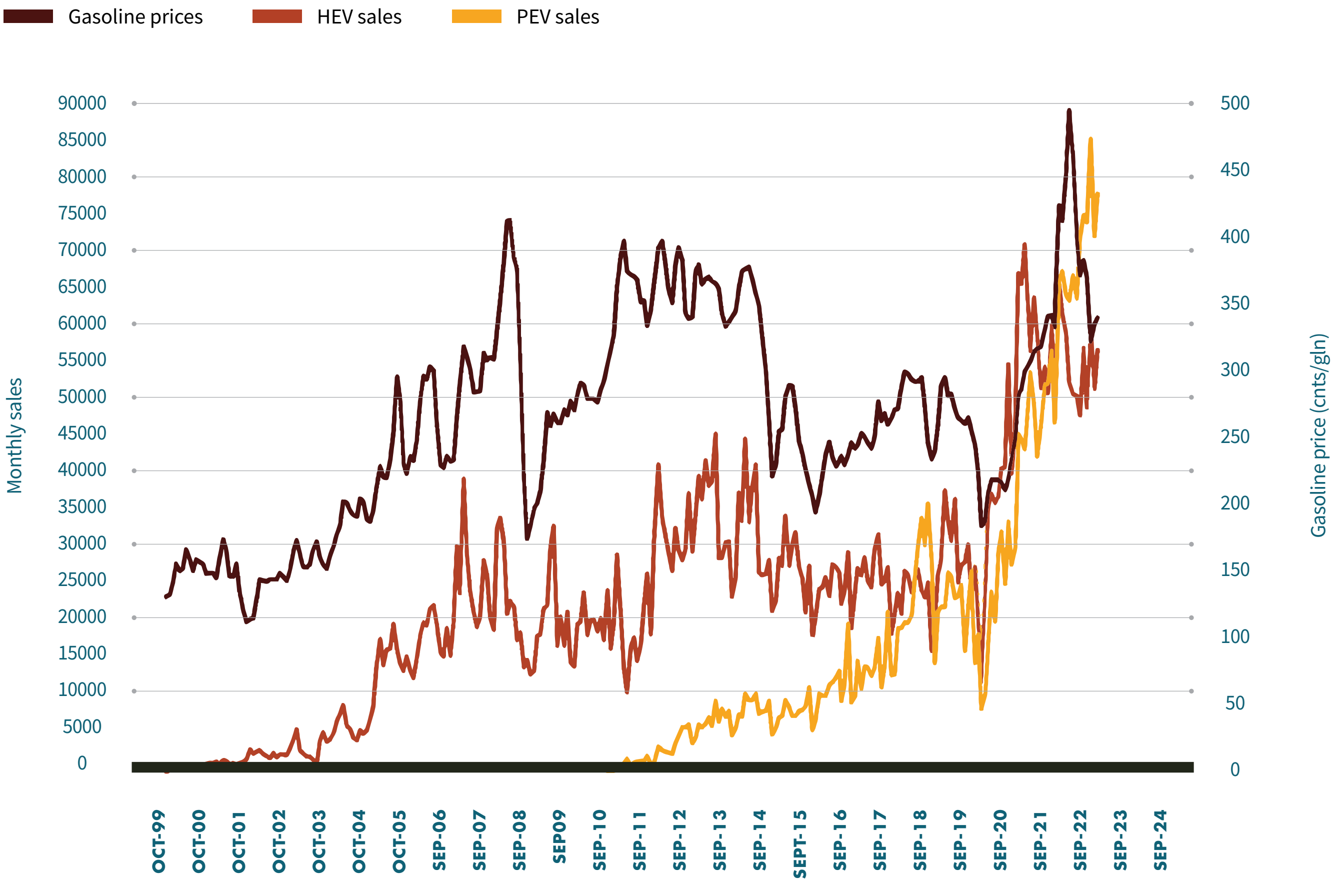


Source: EIA, based on data from Wards Intelligence, February 9, 2022

20% of current vehicles will still be on the road in 20 years or more, across all vehicle classes.

A major influencer for EV sales, and all higher fuel economy vehicles, is prevailing fuel prices. There is a strong correlation between gasoline price increases and increased EV sales. As shown in Figure 8, higher fuel prices have historically led to higher fuel economy, which significantly reduced the nation's energy consumption and GHG emissions. High fuel prices strongly influence the sale and operation of vehicles with lower fuel economies (e.g., SUV and pickup trucks), whereas EV mandates more heavily influence vehicles with higher fuel economies (e.g., cars and crossover vehicles). In addition to fuel prices, the Obama-era corporate average fuel economy (CAFE) regulations, which targeted 54.5 miles per gallon (mpg) by 2025, spurred greater hybrid vehicle availability after 2014, enhancing the consumer hybrid purchasing response to higher fuel prices. Accordingly, EV mandates have less of an impact on fuel-use and GHG emissions reductions than high gasoline prices.

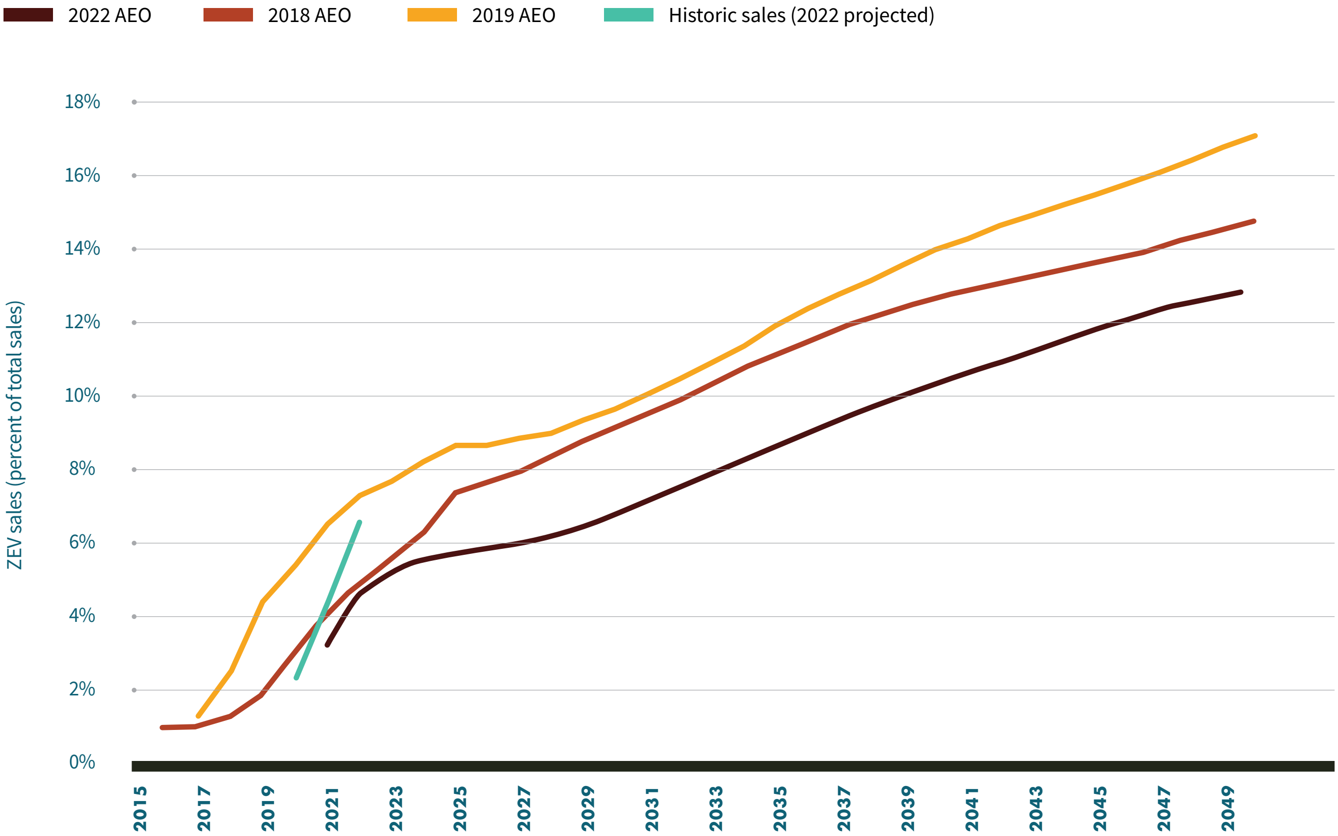
FIGURE 8. MONTHLY NEW GASOLINE HYBRIDS (HEV), EV, AND PHEV (PEV) SALES AND GASOLINE PRICES



Source: Light Duty Electric Drive Vehicles Monthly Sales Updates | Argonne National Laboratory (anl.gov)

Figure 9 provides a national EV sales perspective with three AEO years shown. The AEO reflects existing law and regulation at the time of generation, and changes in CAFE standards between recent administrations have been a major driver of change between the different AEOs. We have chosen to exclude the data from 2020 and 2021 because these years are impacted by the COVID-19 pandemic and the change in CAFE standards between the Trump and Biden administrations. The 2022 AEO closely fits two years of historic trend, and we note that the observed 2022 EV sales as a percent of total new vehicle sales may be artificially elevated due to the current inflationary period (which reduced new vehicle ICEV sales) and continued recovery from COVID-19 (which caused a computer chip shortage that has depressed new car sales).

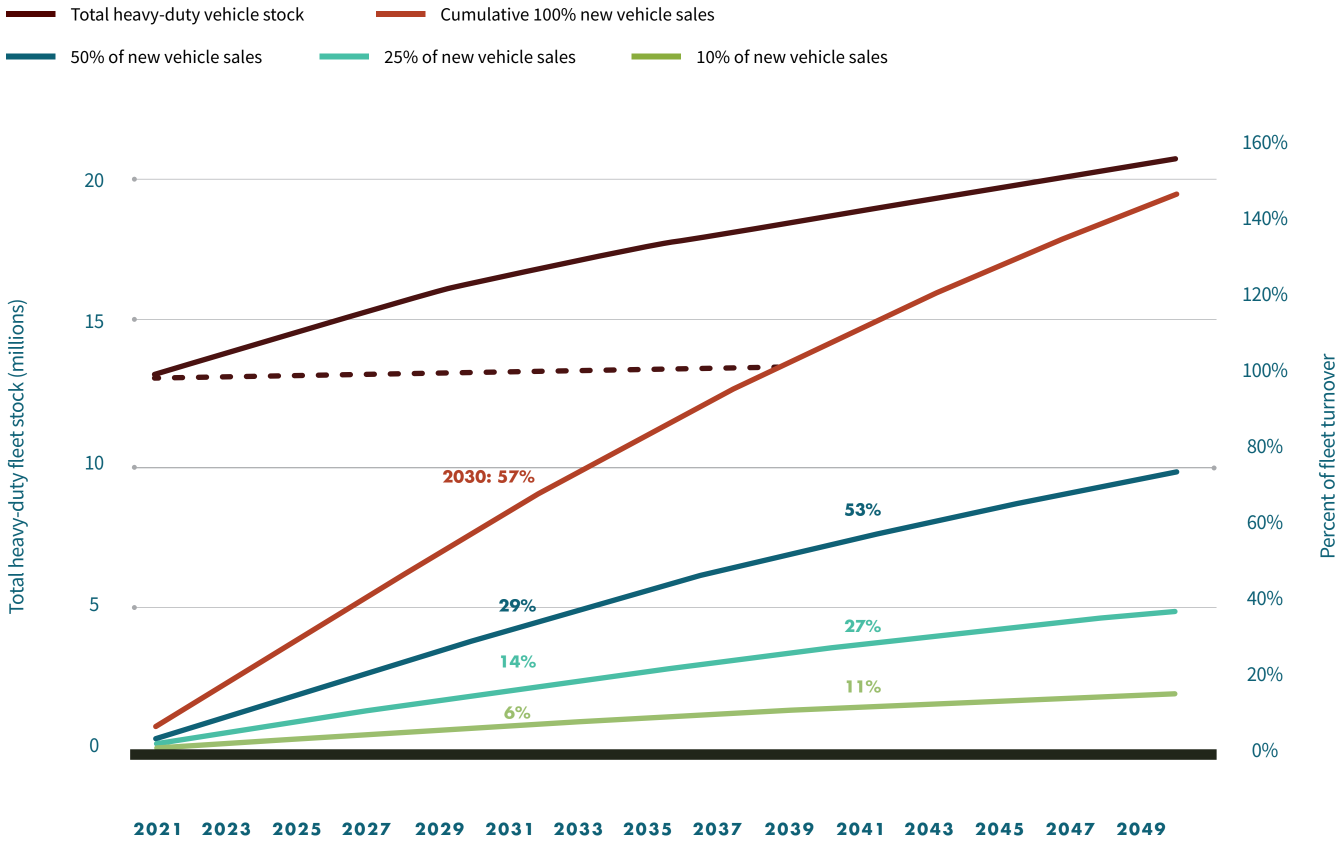
FIGURE 9. NATIONAL ZEV SALES TREND AND PROJECTIONS



Source: Stillwater analysis of EIA AEO Table 38s, Get Connected: Electric Vehicle Quarterly Report 2022 (Q2)

Per the 2022 AEO Reference Case, the turnover rate for llight heavy-duty, medium heavy-duty, and heavy heavy-duty vehicles is currently 19 years based on total projected new heavy-duty vehicle sales and 2021 vehicle population. Figure 10 below shows this 19-year turnover rate, indicating that new vehicle sales will replace the entire 2021 vehicle population in 2039. Also shown is the vehicle turnover rate assuming that a new technology represents 100%, 50%, 25%, and 10% of new vehicle sales. EV migration will most likely happen in the light heavy-duty vehicles (classes 3-4) and medium heavy-duty vehicles (classes 5-6). EVs are currently mandated for California heavy heavy-duty transit buses, and some other states are in trials with heavy-duty transit EV buses. Presently, however, medium- and heavy-duty (M&HD) EVs cost four times more than their diesel counterparts.[18] Hence, M&HD projections are contingent on governmental mandates and subsidies.

FIGURE 10. HEAVY-DUTY VEHICLE FLEET TURNOVER



Note: Shown here are only the heavy-duty classes including light heavy-duty (classes 3-4), medium heavy-duty (classes 5-6), and heavy heavy-duty (classes 7-8). Light-duty vehicles are displayed in Figure 6 *above.*

Source: EIA AEO 2022 Reference Case

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[18] Diesel Technology Forum / Biofuels offer emissions solution for medium, heavy-duty trucks.

Existing Fleet Emissions and Benefits of Incremental Improvement

4.1 GHG EMISSIONS VARY BY FUEL SOURCE AND VEHICLE TECHNOLOGY

According to EPA Fuel Economy Trends Reports, the 2021 weighted population average light-duty cars and trucks have reduced their CO_2 emissions per mile 95% from 1975 levels and 30% from 2000 levels.[19] The existing fleet's GHG emissions are estimated for the 2021 AEO Reference Case shown in Figure 11.

In 2020, cars and trucks represented 74% of the total emissions, M&HD (classes 3-6) trucks were estimated at 6%, and HDV (classes 7-8) trucks were at 20%. The VISION model (developed by Argonne National Laboratory to estimate energy use and carbon emission impacts) offers graphs by decade, masking some of the individual year trends. This model is not as responsive to real-time fuel usage as other models

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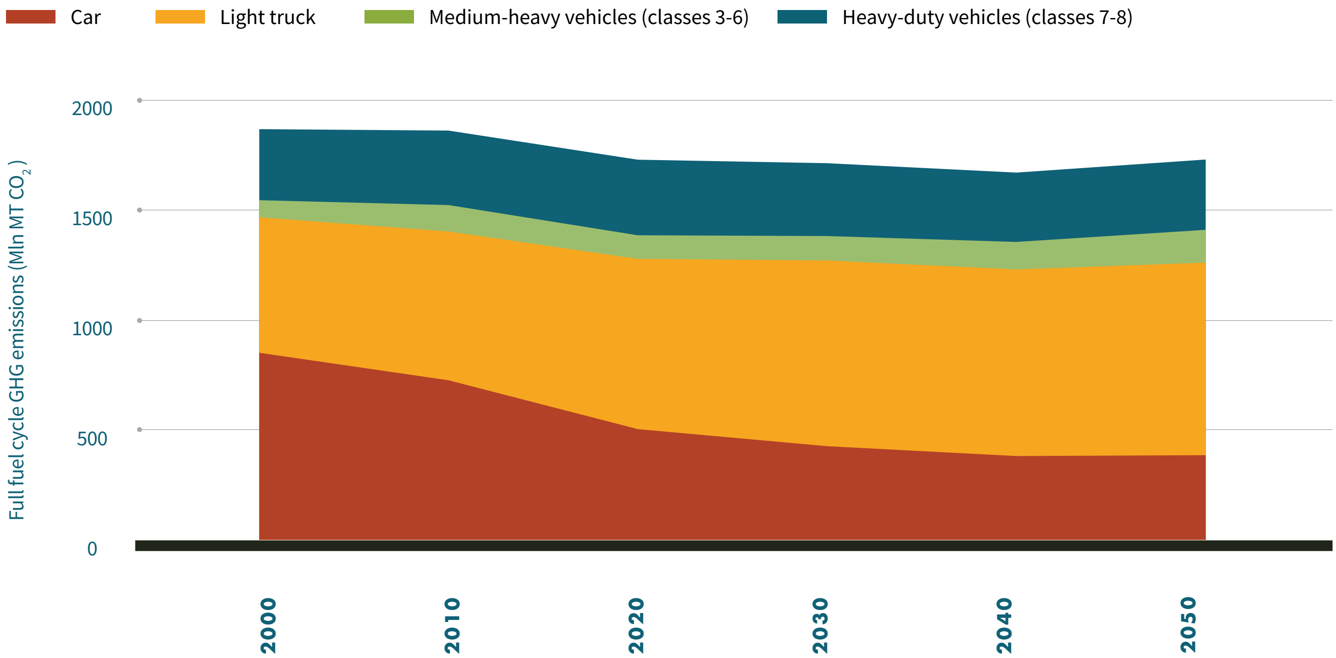
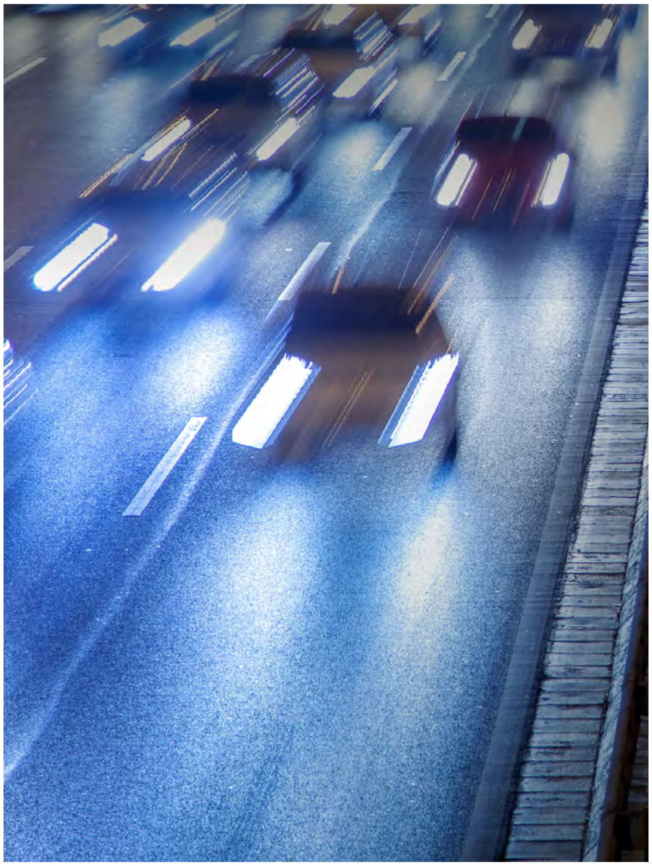
[19] EPA / Explore the Automotive Trends Data.

FIGURE 11. ON-ROAD VEHICLES GHG EMISSIONS



Source: Argonne National Labs VISION 2021 Base Case

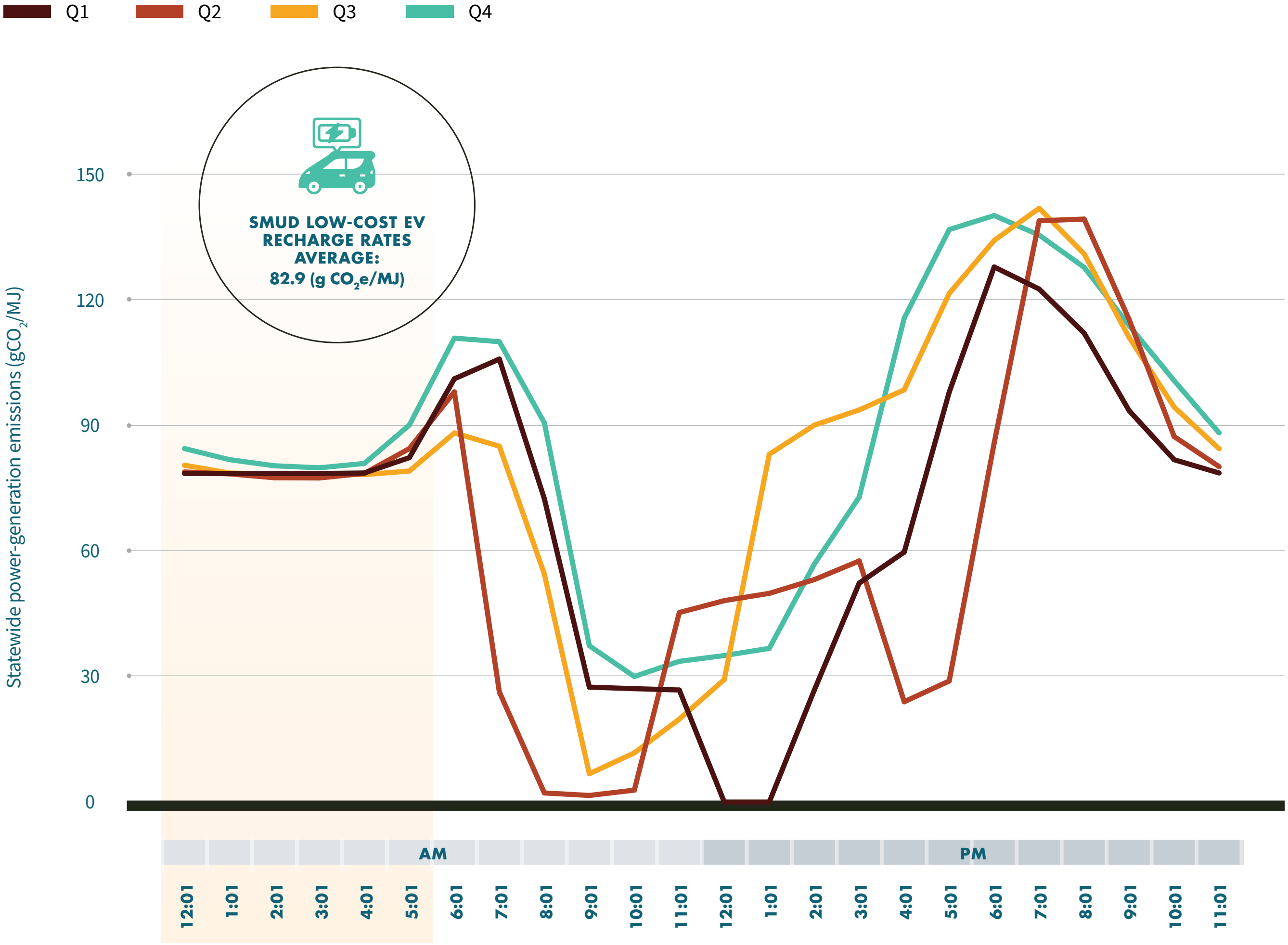
(such as the AEO). Additionally, due to the timing, the effects of the COVID-19 pandemic (declines in vehicle miles traveled and fuel demand) were not modeled. Generally speaking, however, the declines shown in Figure 11 largely can be attributed to higher fuel prices since 2004, combined with higher fuel economy regulations taking full effect by 2016, which contributed to improved fleet fuel economy.



To better focus attention on priority segments of the market, it is important to understand that EVs are currently offered in cars, crossovers, and, starting in 2022, pickup truck models. These vehicles have the lowest energy requirements (and lowest CO_2 emissions), which better fit the current battery profile. PHEVs are expanding into heavier pickups and vans with higher energy requirements. Conventional gasoline hybrids, which do not qualify as ZEVs, are expanding into larger, more energy-consuming vans, SUVs, and pickups. These conventional hybrids are competing with EVs.

GHG emissions reductions are a key justification for policies mandating the switch to EVs. The carbon intensity (CI)—or GHG emissions reduction potential—of the power used to fuel EVs, however, varies widely by source of power generation. Take California as an example, where power plant GHG emissions are varied but typical EV recharge times and associated emissions are narrow. The statewide varied power plant emissions have an annual average CI of 75.93 grams of CO_2e per megajoule of energy (g/MJ). During the early hours of the morning when utilities (like the Sacramento Municipal Utility District, SMUD, exemplified in Figure 12) offer a low-cost 10% discount for EV recharge rates, California's power-generation emissions average 82.96 g/MJ.

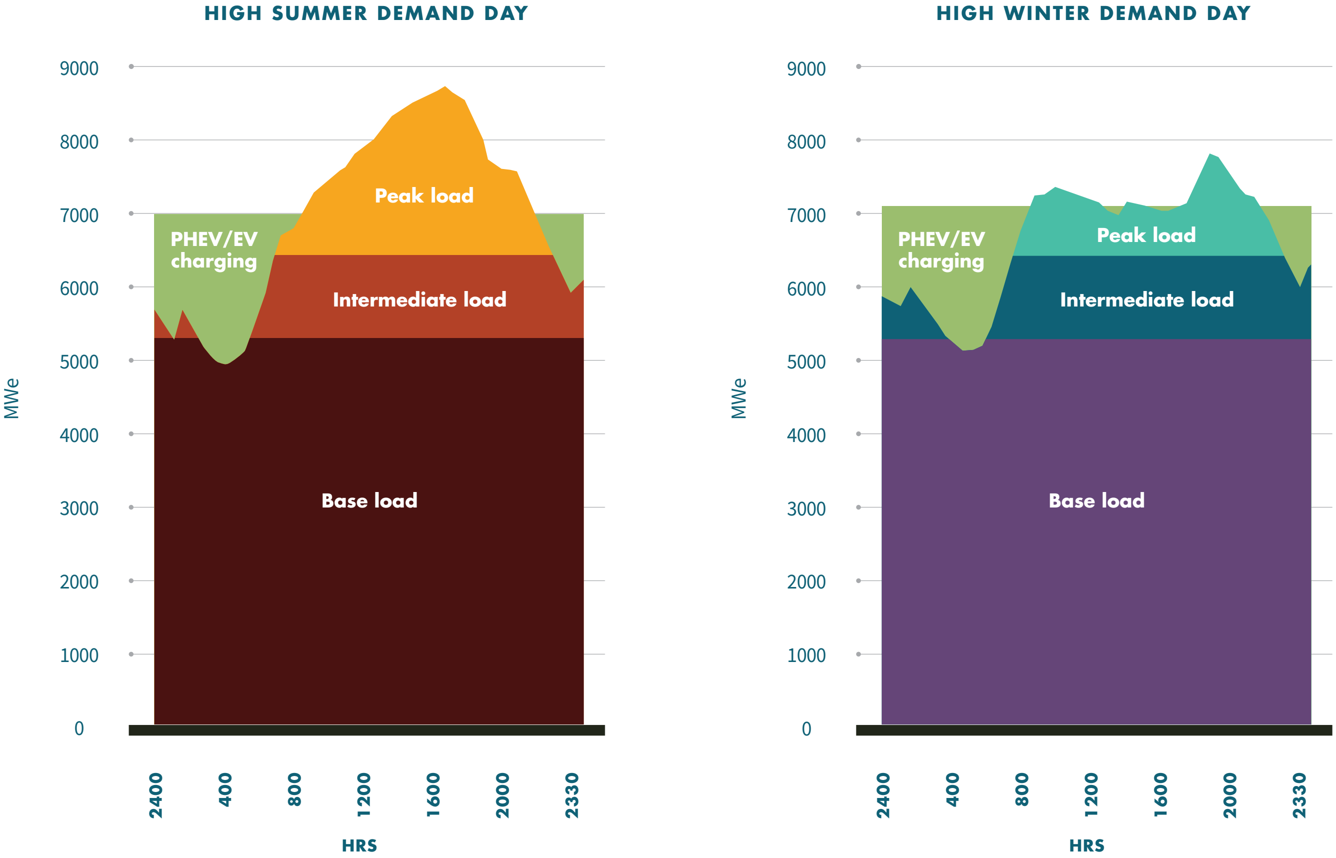
FIGURE 12. CALIFORNIA POWER PLANT GHG EMISSIONS



Source: LCFS Annual Update to Lookup Table Pathways (ca.gov)

Figure 13 provides a generic national perspective on power plants operational throughout the day. The energy demand changes by hour and by season. Utilities will encourage off-peak EV charging and discourage EV charging during the peak demand either through the application of higher rates or through slower charging power. To a large extent, PHEVs and EVs will be able to utilize power at off-peak times (and at lower rates), hence drawing on and increasing demand for baseload grid capacity generated from nuclear, coal, natural gas, and/or imports. Lower carbon EV charging will be a challenge for the eight states that use coal for more than 50% of their electricity today.[20]

FIGURE 13. GENERIC 24-HOUR LOAD CURVE FOR SUMMER AND WINTER POWER GRID



Source: Electric Vehicles - World Nuclear Association (world-nuclear.org)

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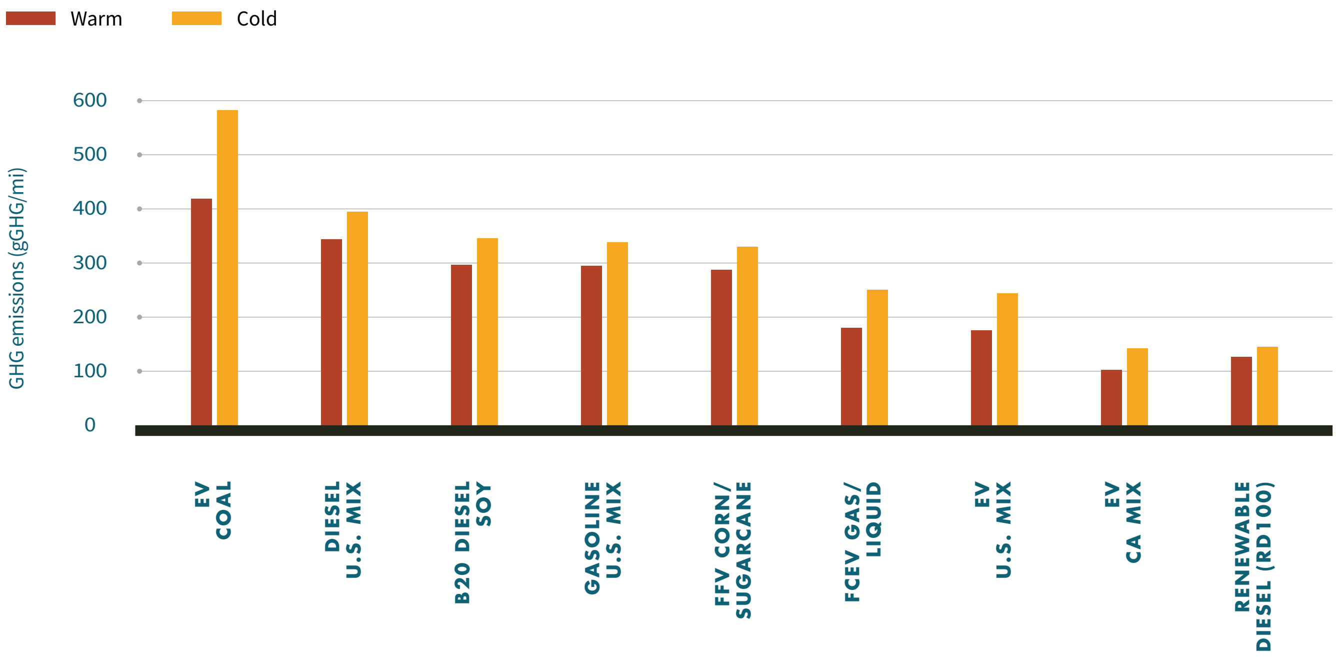
[20] According to the Center for Strategic & International Studies (CSIS), coal represents 50% or more of power generation in West Virginia, Wyoming, Missouri, Kentucky, Utah, North Dakota, Indiana, and Nebraska. Phasing out Coal from U.S. Electricity Increasingly a Regional Challenge.

Nationwide, the range of power-generation emissions is also extremely varied. The variability of power-generation GHG emissions creates an added layer of complexity when seeking to compare GREET life cycle analyses for various biofuel options alongside a single national average CI value for electricity. The outlook for future emissions from ICEVs will depend on the type of feedstocks used to generate renewable fuels. Likewise, the GHG benefits of EVs depend on the CI of the power grid and external factors such as temperature. Figure 14 shows the latest GHG emission comparisons with a range of ICEV versus EV feedstocks. The ICEV baseline is a 36.5 mpg gasoline for comparison with all ZEV-equivalent vehicles.[21] The 87.5 miles per gallon equivalent (mpge) EV has 68% lower GHG emissions than the gasoline-powered ICEV in warm weather and 38% lower emissions in cold weather.[22] FFVs fueled with E85 (fuel containing up to 83% ethanol blended with gasoline) and diesel ICEVs fueled with RD are shown to have similar or greater GHG emissions reductions to EVs powered with U.S. grid electricity. Hydrogen fuel cell electric vehicles' GHG emissions also vary depending on whether they are fueled with compressed or liquified hydrogen.

FIGURE 14. GHG EMISSION DIFFERENCES FROM A LIGHT-DUTY GASOLINE VEHICLE IN WARM AND COLD WEATHER



Source: 2022 GREET and 2021 GREET

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[21] Included is an EV Cold Weather case that captures EVs' 39% reduced fuel economy in cold weather compared to a 15% reduced fuel economy for gasoline powered ICEVs. Sources: AAA / Icy Temperatures Cut Electric Vehicle Range Nearly in Half and U.S. Department of Energy / Fuel Economy in Cold Weather.

[22] Because EVs do not use liquid fuel, their fuel economy is represented as miles per gallon equivalent (mpge), representing the number of miles the vehicle can travel using the same energy content as a gallon of gasoline. One gallon of gasoline has the energy equivalent of 33.7 kWh of electricity. Importantly, the mpge measurement accounts for the energy used from the consumer's wall outlet; it does not account for the 50% power plant and distribution losses.

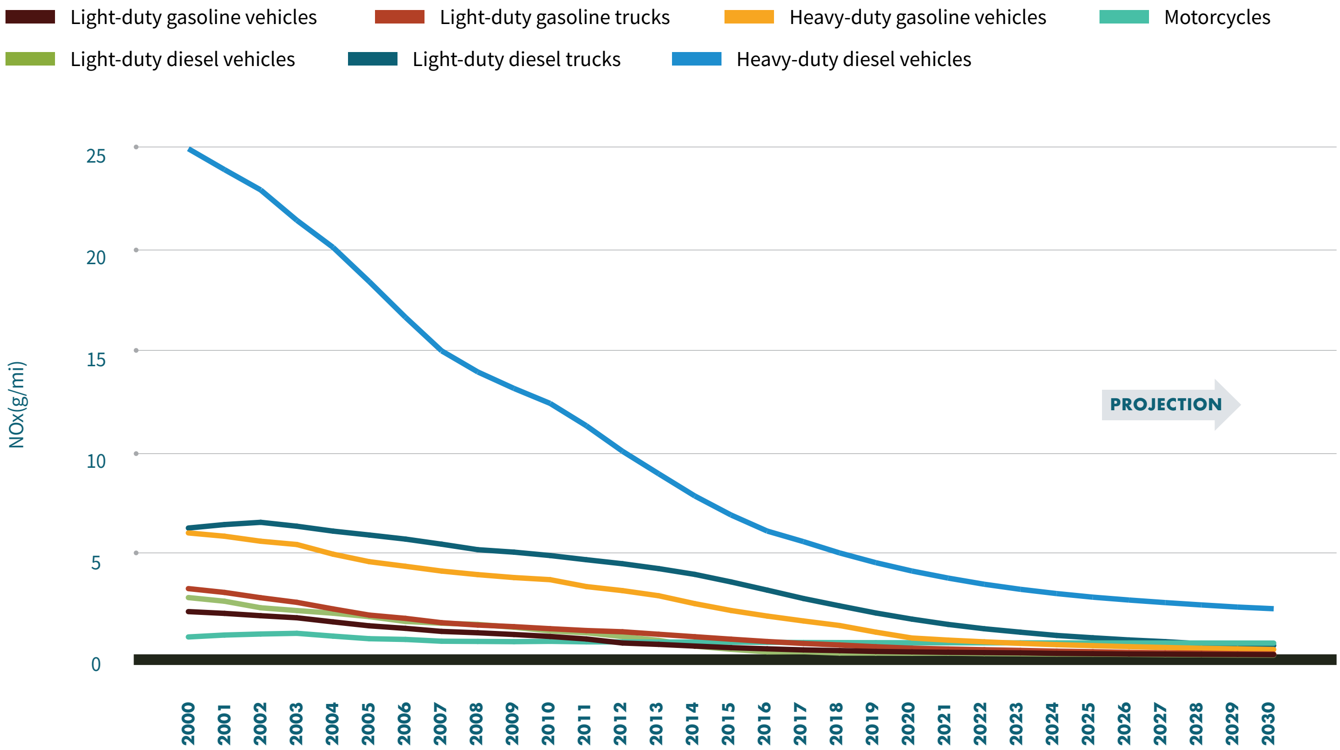
4.2 CRITERIA POLLUTANTS ARE WELL CONTROLLED WITH THE EXISTING FLEET

Criteria pollutant emissions reductions are required to meet federal and state clean air standards.[23] To help focus attention on priority segments of the market for ICEV and EV criteria pollutants, we first examine the national environmental clean air requirements. NO_2, SO_2, and PM_{10} levels nationwide meet ambient air quality standards; except for ozone and $PM_{2.5}$, all cities' criteria pollutants are below the federal standards. Consequently, ICEV and EV criteria pollutant emissions reductions in these areas are not needed as the existing fleet emissions meet or exceed clean air standards and as will be shown later, will continue to improve.

4.2.1 REPLACING "GROSS EMITTERS" FROM THE FLEET WILL FURTHER IMPROVE NOx AND $PM_{2.5}$

Figures 15 and 16 display national average emissions rates for NOx and $PM_{2.5}$, respectively, for the fleet of vehicles per calendar year.[24] Criteria pollutants have been mitigated via engine and aftertreatment capture system improvements as well as through fuel chemistry (such as ultra low sulfur diesel, (ULSD)). All vehicle emissions, except for motorcycles, are reduced 85-90% from 2000-2022 and by 2030 are projected to be reduced by 88-94%. Since 2000, the NOx emission rate from gasoline cars has been reduced by 92%, and by 2030 this rate is projected to be 98% lower than the 2000 baseline. Since 2000, NOx and $PM_{2.5}$ emission rates from the fleet of heavy-duty diesel vehicles have been reduced 85% and 91% respectively.

FIGURE 15. ESTIMATED NATIONAL AVERAGE NOx EMISSIONS RATES PER VEHICLE USING GASOLINE AND DIESEL



Source: EPA, Office of Transportation and Air Quality, pers. comm., Apr. 30, 2021.

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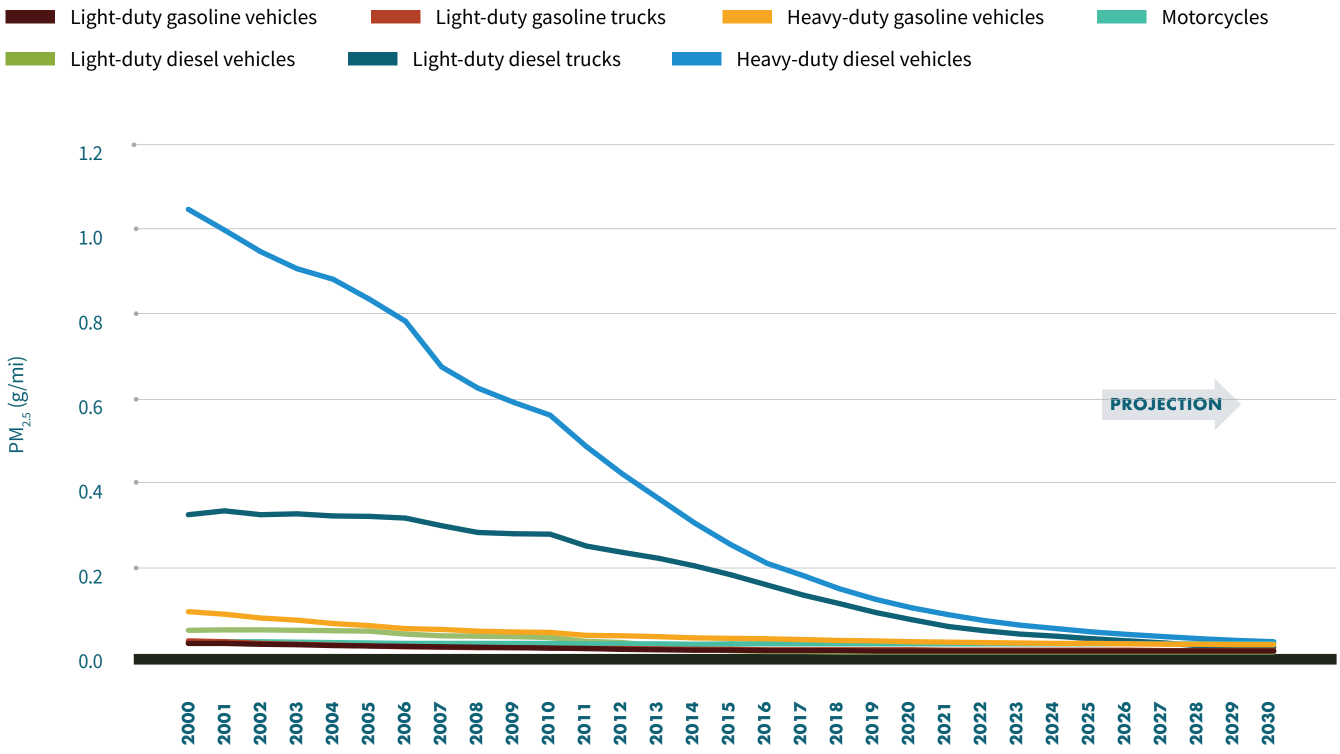
[23] Criteria pollutants include hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and particulate matter (PM).

[24] Shown are averages based on the national average age distributions and vehicle activity including speeds, operating modes, vehicle-miles traveled fractions, starts and idling, temperatures, inspection/maintenance, antitampering programs, and average gasoline fuel properties in that calendar year.

FIGURE 16. ESTIMATED NATIONAL AVERAGE $PM_{2.5}$ EMISSIONS RATES PER VEHICLE USING GASOLINE AND DIESEL



Source: EPA, Office of Transportation and Air Quality, personal communication, Apr. 30, 2021.

BOTTOM LINE: THE FLEET IS CONTINUING TO GET CLEANER. REMOTE VEHICLE EMISSION TESTS FIND 50% OF THE FLEET'S EMISSIONS COME FROM 11% OF THE VEHICLES.[25] REMOVING THESE 11% "GROSS EMITTERS" AND REPLACING THEM WITH CLEANER VEHICLES IS A WELL-KNOWN AND ADVISABLE AIR QUALITY IMPROVEMENT STRATEGY. TODAY'S ICEV FLEET EMISSIONS ARE APPROACHING EV EMISSION RATES, AND ICEV EMISSIONS WILL CONTINUE TO BE REDUCED INTO THE FUTURE AS THE ICEV FLEET GETS CLEANER AND MORE FUEL EFFICIENT.

4.2.2 PARALLELS BETWEEN CRITERIA POLLUTANT REDUCTIONS AND GHG REDUCTIONS

The success of criteria pollutant reduction in ICEVs can offer some insights into reducing GHG emissions in those same vehicles. Criteria pollutant reductions were a result of cleaner fuels and cleaner vehicle technology. Similarly, low-carbon fuels enable lower GHG vehicle emissions from ICEVs. Into the future, capturing refinery emissions and increased use of higher efficiency engines and hybrid powertrains can further lower vehicles' GHG emissions and enhance GHG reductions from existing fuels such as RD and ethanol.

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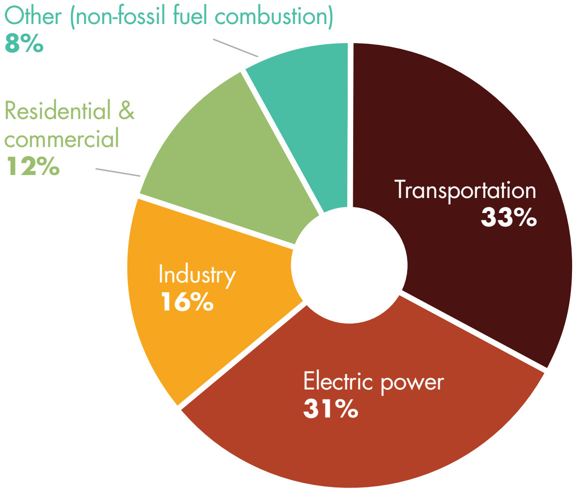
[25] TRUE Initiative / New Report: Real-world emissions of US vehicles increase with age, says 60m dataset - The Real Urban Emissions Initiative.

Technical and Scientific Implications of GHG Emissions

According to the IPCC, anthropogenic CO_2 makes up 5% of the CO_2 inflow into the atmosphere (with natural CO_2 making up the remaining 95%), and U.S. energy use accounts for 13.9% of worldwide anthropogenic CO_2 emissions.[26] In the U.S., transportation contributes 33% and electrical power generation contributes 31% to our national CO_2 emissions.

Figure 17 shows the breakout of estimated U.S. anthropogenic CO_2 sources.

FIGURE 17. U.S. ANTHROPOGENIC CO_2 EMISSIONS BY SOURCE (1990-2020)



Total U.S. emissions in 2020 = 5,981 million metric tons of CO_2 equivalent (excludes land sector). Percentages may not add up to 100% due to independent rounding.
Source: Overview of Greenhouse Gases | EPA

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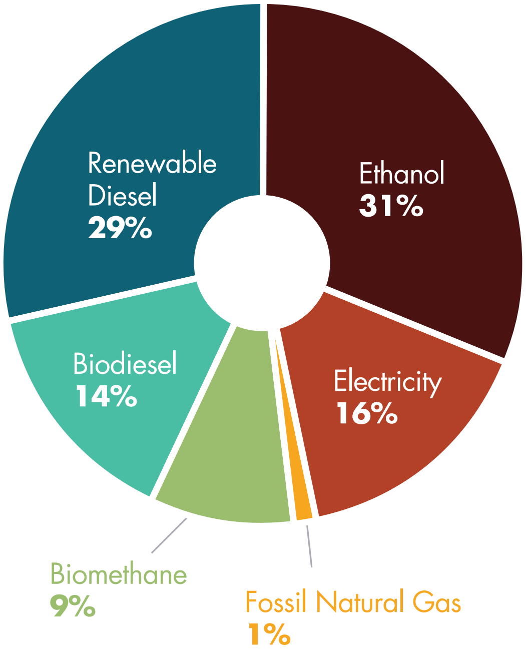
[26] BP / Statistical Review of World Energy.

5.1 BENEFITS OF DECARBONIZING THE EXISTING ICEV FLEET

A key implication of the long atmospheric lifetime of CO_2 and methane is that near-term steps to reduce these emissions play a critical role in limiting the expected increase in average global temperature attributable to these emissions. As light-duty vehicles in the U.S. are typically on the road for 15 to 20 years, capturing the potential emissions reductions from decarbonizing the fuels used in current and future ICEVs in the U.S. fleet is a powerful tool for mitigating the potential impacts of GHG emissions.[27] Decarbonizing the current ICEV fleet can reduce emissions much more rapidly than is possible from the gradual conversion of the fleet to EVs over the timeframe of this study.

One real-world example of biofueled ICEVs' potency to reduce GHG emissions is available through California's Low Carbon Fuel Standard (LCFS). This program quantifies the GHG reductions from alternative-fueled vehicles including ZEVs and from biofuels used to meet the state's transportation fuel GHG reduction goals. As shown in Figure 18, 83% of the program's cumulative GHG reductions to date have come from biofuels and 16% from ZEVs.[28]

FIGURE 18. MOBILE SOURCE CUMULATIVE GHG REDUCTIONS TO DATE



Source: Low Carbon Fuel Standard Reporting Tool Quarterly Summaries | California Air Resources Board

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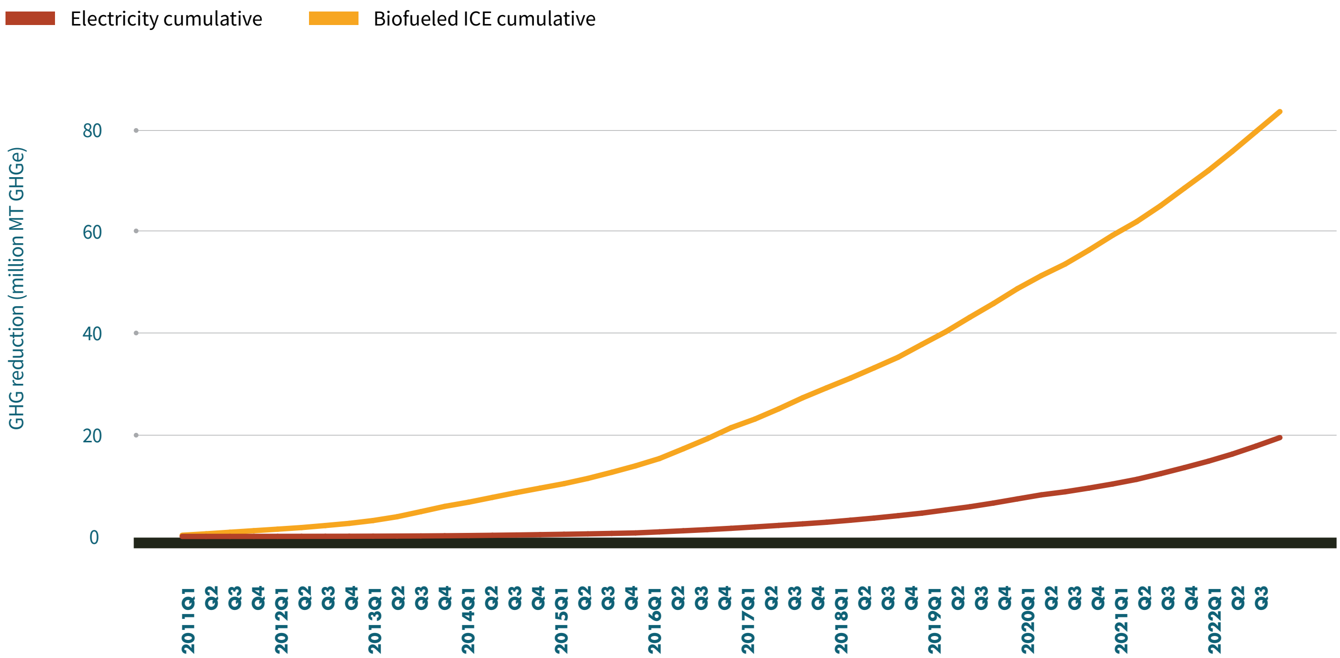
[27] EPA / Draft Technical Assessment Report: Midterm Evaluation of Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards for Model Year 2022-2025.

[28] CARB uses a modified version of the widely used GREET model adjusted to better reflect California power plants and refining emissions.

In the absence of a large EV fleet, biofueled ICEVs are reducing GHG emissions now. Figure 19 shows that, cumulatively through 3Q2022, biofueled ICEVs have contributed four times more GHG emissions reductions than EV technologies under California's LCFS program. Biofueled ICEVs will continue to dominate GHG reductions and complement EVs' GHG reductions due to biofuels' competitive CI values relative to U.S. average grid power. The real-world example of California's LCFS program demonstrates how biofuels can be employed over broad and more energy intensive transportation applications while reducing GHG emissions.

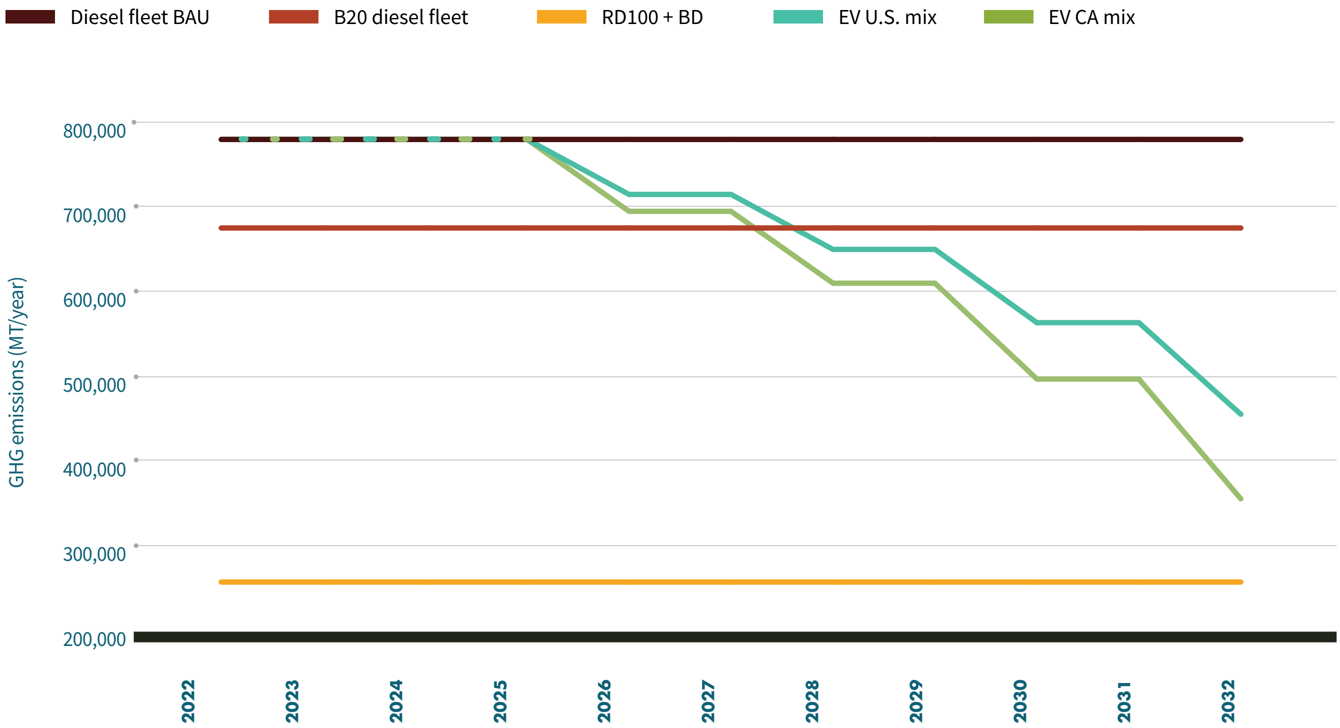
FIGURE 19. CUMULATIVE GHG REDUCTIONS FROM BIOFUELED ICEVs VS. EVs



Source: Low Carbon Fuel Standard Reporting Tool Quarterly Summaries | California Air Resources Board

Stillwater completed a study evaluating 10,000 medium- and heavy-duty vehicles' GHG reductions available now via ICEVs fueled with biofuels versus the slower introduction of M&HD EVs. Figure 20 shows the assumed biofuels and EV technology migration rates. Given these assumptions, by 2032, ICEVs fueled with 100% renewable diesel (RD100) would achieve cumulative GHG reductions four times greater than those achieved by EVs, and ICEVs fueled with 20% BD blended with 80% petroleum diesel (B20) would match the M&HD EVs' cumulative GHG reductions. The seven-year projection represented in Figure 20 uses fixed GREET 2021 CI values for both liquid fuels and power plants.[29] The green lines representing EV fleet emissions decline because of increasing EV penetration into the medium- and heavy-duty fleet.

FIGURE 20. MEDIUM- AND HEAVY-DUTY VEHICLE ANNUAL GHG EMISSION SCENARIO (2022-2032)



Source: Stillwater assessment using 2021 GREET and EPA MOVES3 assumptions

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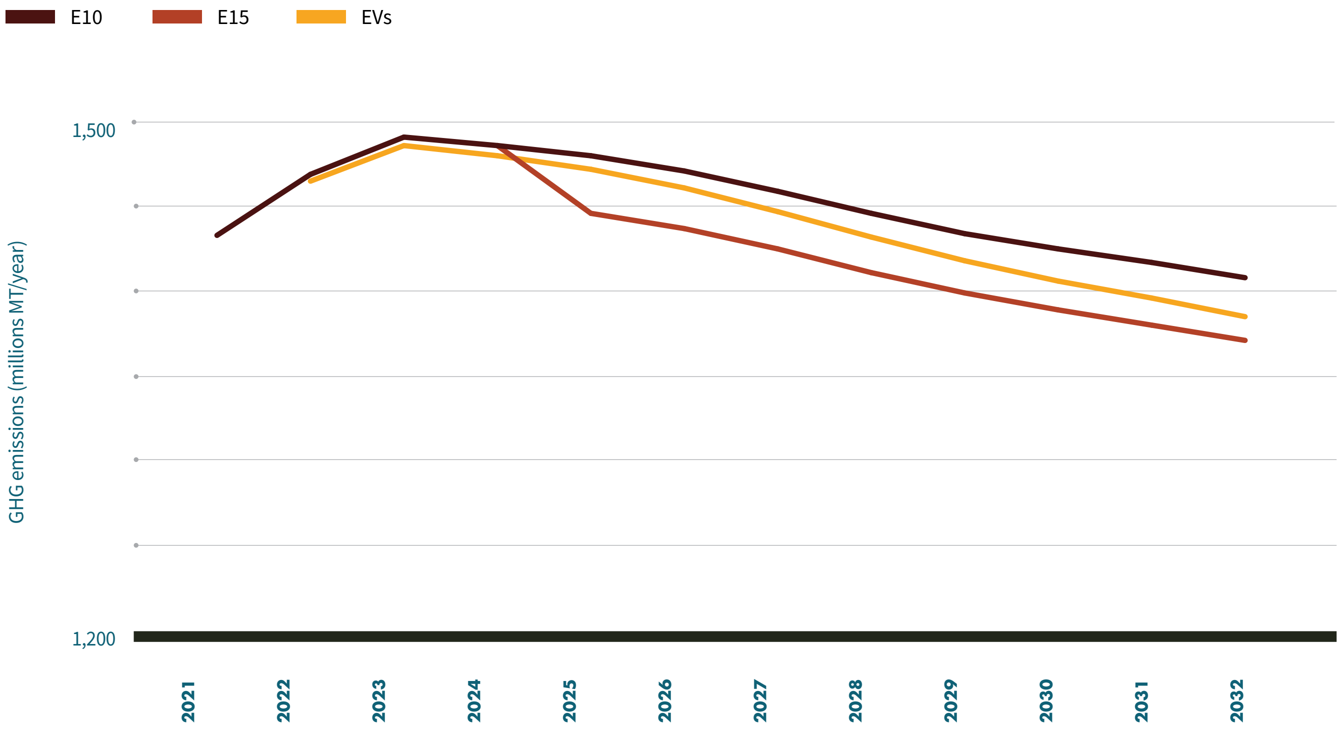
[29] The 2021 GREET CI values used were 122 U.S. mix, 33 for RD100, and 30 for BD100 (all values in gCO_2e/MJ).

Broadening our view from the small heavy-duty fleet example presented in Figure 20, Stillwater examined the larger light- and medium-duty vehicle fleet. The AEO projects the gasoline-fueled fleet declining over future years with increasing EVs. Figure 21 shows the assumed biofuels and EV technology migration rates for the light- and medium-duty fleet in EIA's AEO 2022 Reference Case. Given these assumptions, if gasoline with 15% ethanol (E15) replaced gasoline with 10% ethanol (E10) in light- and medium-duty vehicles starting in 2024, by 2032 ethanol would provide twice the cumulative GHG reductions as EVs over the decade. Importantly, the heavy-duty fleet scenario represented in Figure 20 remains fixed at 10,000 vehicles. Conversely, based on AEO projections, the light- and medium-duty fleet scenario represented in Figure 21 shows a decline in ICEV population and fuel usage over the next decade as EVs displace ICEVs over time. This is reflected in the downward trend line for all three fuels shown in Figure 21.

FIGURE 21. LIGHT- AND MEDIUM DUTY VEHICLE ANNUAL GHG EMISSIONS REDUCTION SCENARIO (2022-2032)



Source: Stillwater assessment using 2022 GREET and EIA AEO 2022 Reference Case

Lifecycle Analysis of Options

Evaluation and Comparison of Life Cycle Emissions of ICEV Fuel Options

This section will evaluate and compare the life cycle carbon emissions of various ICE fuel options as well as pending developments that could reduce their carbon intensity over time. We will focus our evaluation on ICEV fueling options including petroleum-based fuels (gasoline and diesel), biofuels, natural gas (including renewable natural gas), hydrogen, e-fuels, and propane (including renewable propane).

TABLE 4. FEEDSTOCKS USED TO PRODUCE GASOLINE AND DIESEL

FEEDSTOCK	COMPOSITION
Petroleum	85%
Natural Gas	14%
Coal	1%

Sources: 2022 GREET and Choose Energy, Electricity Generation by State, October 2022

6.1 DEFINITION OF TRANSPORTATION FUELS

The mix of transportation fuels currently available to fuel ICEVs are made from several fossil and renewable sources. As a baseline, conventional gasoline and diesel are created using the feedstock portions shown in Table 4. In the sections that follow, we explore GHG-reducing ICEV fuel options displacing petroleum gasoline and diesel use today as well as GHG-reducing options under development.

6.1.1 ICEV FUELING ALTERNATIVES

Alternative (nonpetroleum) fuels which may be used in ICEVs include ethanol, biodiesel (BD), and renewable diesel (RD). Ethanol and BD are blended with gasoline and petroleum diesel, respectively, before being used as a transportation fuel. RD, however, is a drop-in renewable fuel which is molecularly identical with petroleum-derived diesel and is therefore compatible with existing ICEVs without blending or engine modifications. BD and ethanol fuels are generally limited to low blends: 20% for BD (B20) and 10% for ethanol (E10). In 2011 EPA approved E15 use in light-duty conventional vehicles of model year 2001 and newer.[30]

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[30] U.S. Department of Energy (DOE) Alternative Fuels Data Center (AFDC) / E15.

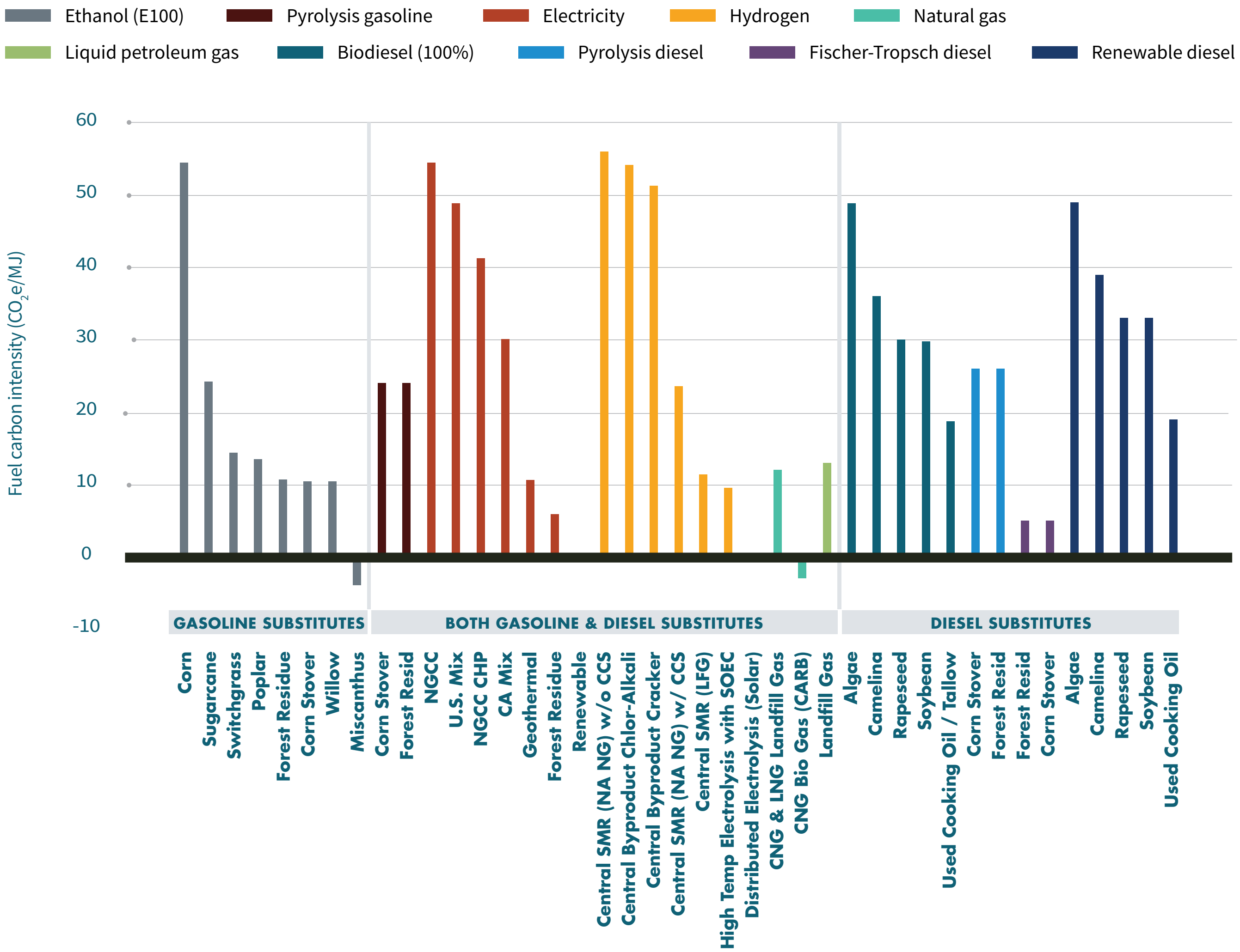
6.1.2 ALTERNATIVE-FUELED VEHICLE FUELING OPTIONS

Alternative-fueled vehicles (AFVs) have varying levels of modifications to the engine, vehicle fuel tank, and/or retail fuel distribution system which differentiate them from traditional ICEVs. EVs, hydrogen fuel cell electric vehicles (FCEVs), propane- and natural gas-powered ICEVs are today's dedicated AFVs. Flexible-fueled vehicles (FFVs) are unique alternative-fueled vehicles that have engines and fuel tanks designed to run on any blend of gasoline up to E85 fuels. However, E85 does require a dedicated retail fuel station dispenser.

6.2 EXAMINING ALL LOW-CARBON OPTIONS

Stillwater examined the 66 transportation fuel sources evaluated in GREET and grouped them under 10 major fuels from 41 fuel sources shown below. Figure 22 shows the GHG reductions potential from these existing transportation fuel options relative to gasoline at 90 grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ or simply g/MJ). We restricted the list of fuel options to those that provide GHG reductions similar to or greater than EVs fueled with U.S. mix electricity (excluding coal). GHG-reducing options currently

FIGURE 22. LOW-CARBON FUEL OPTIONS AVAILABLE FOR TRANSPORTATION FUELS



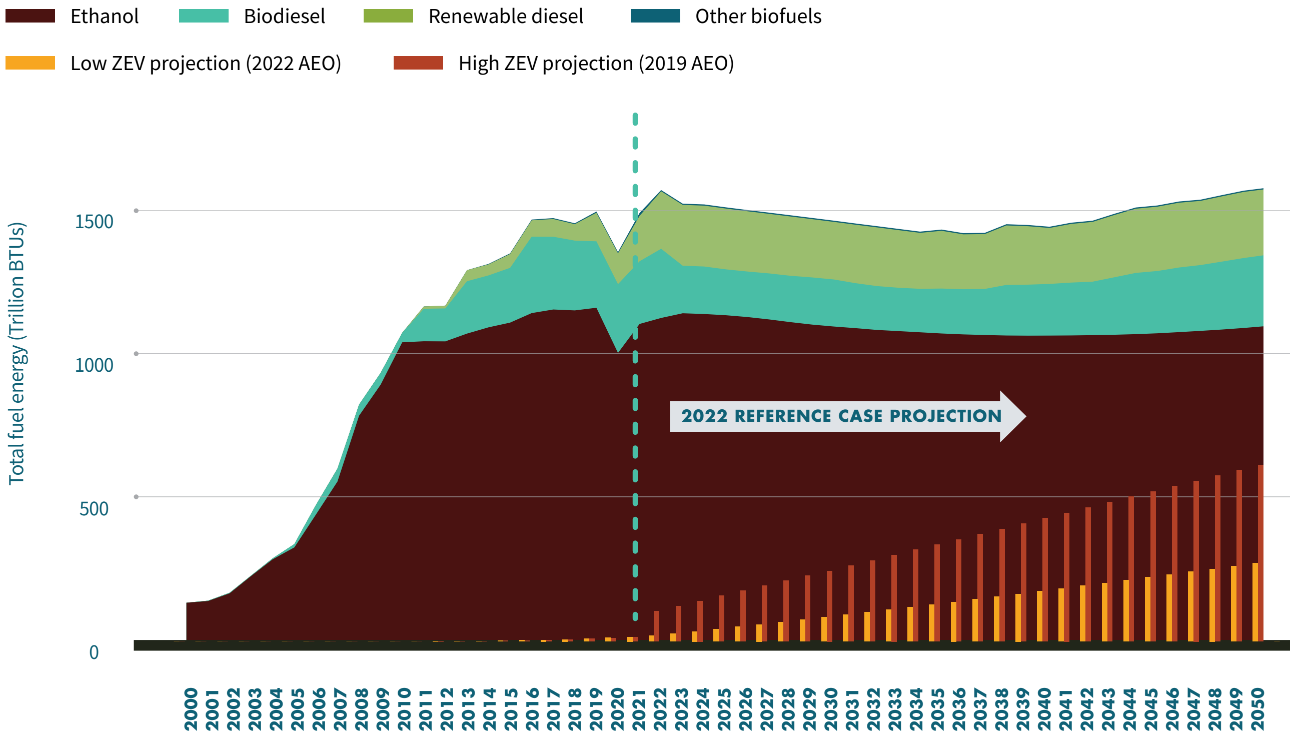
Source: GREET 2021 & 2022. Assumes EV EER of 2.4 and FCEV 1.7.

available include fuels like BD, ethanol, and RD from at least 24 biofuel sources that can be supplied and consumed with existing infrastructure and vehicles today. Note: The fuels listed in Figure 22 are unblended; blend restrictions exist for BD and ethanol.

Figure 23 shows the three most prevalent biofuels in use since 2000. The 2022-2050 projection uses the EIA AEO 2022 Reference Case as a baseline; Stillwater estimated the historic (2011-2021) EV energy use to augment the 2022-2050 projection by using new vehicle sales provided by Oak Ridge National Laboratory.[31]

The two ZEV projections (which include BEV, PHEV and FCEVs) use the 2021 and 2019 AEO Reference Cases. The ZEV projections show ZEV energy use increasing significantly by 2050 but remaining below current levels of biofuel energy use. This is due in part to biofuel use in larger vehicles (i.e., medium- and heavy-duty renewable diesel- and biodiesel-fueled vehicles) compared with EV penetration in predominantly smaller vehicles, which use less energy per vehicle. It is important to note that the 2022-2050 biofuels projection is not significantly different from the current numbers for U.S. feedstock use and biofuel production. However, demand may be expanded into new sustainable aviation fuels markets.

FIGURE 23. HISTORICAL AND PROJECTED LIGHT-DUTY VEHICLE BIOFUEL AND EV ELECTRICITY USE



Source: EIA AEO 2022, Table 10.2c; *Oak Ridge National Laboratory,* Transportation Energy Data Book Edition 40, Table 6.02*;* EIA AEO 2022, Table 17

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[31] Bureau of Transportation Statistics / Hybrid-Electric, Plug-in Hybrid-Electric and Electric Vehicle Sales.

From this data, we can begin to determine the cumulative national vehicle GHG reductions from 2000 onward. But we must draw on a few additional key variables. Each fuel's carbon intensity (CI) value is of utmost importance. We determine the CI of each fuel based on the 2022 GREET values, as shown in Table 5. Note that energy economy ratios (EERs) are used in combination with the U.S. average utility CI to determine the CI for EVs.[32]

TABLE 5. FUEL CARBON INTENSITY ASSUMPTIONS

FUEL TYPE	CARBON INTENSITY (gCO_2e/MJ)	EER-ADJUSTED CARBON INTENSITY (gCO_2e/MJ)
Gasoline (E0, E10, E15)	93, 91, 89	
Diesel	91	
Natural Gas (CNG / LNG)	75 / 77	
Ethanol (100%)	57	
Ethanol (E85)	64	
Biodiesel (B20)	80	
Biodiesel (100%)	36	
Renewable Diesel (100%)	34	
Electricity (U.S. mix)	130	Light Duty, 33; Heavy Duty, 33
Hydrogen (gas / liquid)	93 / 134	Light Duty, 48 / 69; Heavy Duty, 44 / 64
Propane	79	

Note: Uses a 2021 sales-weight average technology share to GREET fuel economy estimates, to determine LD EV EER of 3.9 and 1.9 FCV. The simple average of GREET 2022 LM&H duty vehicle EERs is 3.9 and 2.1 for EVs and FCEVs, respectively.

Source: 2022 GREET model

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[32] Electricity is sold as kWh and is divided by 3.6 to convert kWh into MJ. It is then divided by the higher energy efficiency of EVs versus gasoline (2.5 EER) to yield the GREET values shown in Table 5.

TABLE 6. LIGHT-DUTY VEHICLE FUEL ECONOMIES

	2021 MPG (GREET)	2021 MPG (2022 AEO)	2035 MPG (2022 AEO)
FCEV (mpge)[32]	61.48	52.95	51.62
BEV (mpge)	87.42	95.75	100.04
Gasoline	30.08	35.29	37.03
Gasoline Hybrid	36.47	50.64	52.70

Source: 2022 GREET, 2022 AEO Reference Case Fuel Economy

TABLE 7. CUMULATIVE NATIONAL VEHICLE GHG REDUCTIONS STARTING FROM 2000

YEAR	BIOFUELED ICEVs (INCLUDING AFVs)	AFVs PROPANE & CNG	ELECTRIC VEHICLES & H_2
2021	99%	1%	0.94%
2035	88-81%	0.9-0.8%	11.9-20%
2050	76-68%	0.9-0.7%	24-32%

Note: Values may not total 100% due to rounding errors.

Source: Stillwater Associates analysis of EIA AEO 2022, Table 10.2c*, GREET 2022 CI values used*

It is also important to incorporate fuel economy when calculating emissions reductions. Table 6 shows the current range of vehicle fuel economy estimates used to compare vehicle fuel economy and GHG emissions through 2035. According to EPA's fuel economy trends report in 2021, the median gasoline car sold had a fuel economy of 30.91 mpg.[33] By 2025, the median gasoline car mpg is projected to reach the same fuel economy value as the current gasoline hybrid. In addition, the 2022 AEO uses higher fuel economy estimates for all vehicles compared to GREET; the 2022 AEO estimates are closer to GREET's hybrid vehicle fuel economy.[34]

We then converted this historical and projected biofuel and electricity usage, fuel CIs, and vehicle fuel economy into displaced gasoline or diesel gallons as appropriate, with a nominal CI value applied to each fuel to estimate the carbon dioxide equivalent CO_2e[35] emissions and reductions for biofueled ICEVs and alternative-fueled vehicles shown in Table 7.

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[33] EPA / The EPA Automotive Trends Report.

[34] Because EVs do not use fuel, their fuel economy is represented as miles per gallon equivalent (mpge). This is similar to mpg, but it represents the number of miles the vehicle can go using a quantity of fuel with the same energy content as a gallon of gasoline. One gallon of gasoline has the energy equivalent of 33.7 kWh of electricity.

[35] Carbon dioxide equivalent, or CO_2e, is a measurement used to compare the emissions from various greenhouse gases (GHGs) on the basis of their global warming potential (GWP) by converting amounts of other gases to the equivalent amount of carbon dioxide with the same GWP.

Pending Developments Which May Influence the Life Cycle Emissions of ICEV Fuel Options

7.1 PETROLEUM GASOLINE AND DIESEL PRODUCTION

As highlighted in our overview of the time required to turn over the on-road fleet, it is expected that petroleum-derived fuels will comprise a substantial share of transportation fuel demand for the next few decades. Accordingly, opportunities to reduce the GHG emissions associated with these fuels will be key in reducing the overall GHG footprint associated with transportation.

Here we focus on potential developments which could reduce the carbon intensity associated with the production and distribution of hydrocarbon gasoline and diesel (well-to-pump, or WTP). Potential developments which may impact the carbon emissions downstream of the pump, primarily those associated with the combustion of these fuels, alone or in blends with renewable fuels, will be discussed later in this report.

The current value of the components of carbon emissions through this portion of the value chain are estimated in the GREET model[36] as follows:

- **Crude oil production and transport to refineries –** 8,329 grams of CO_2 equivalence per million BTU (gCO_2e/mmBTU) or 7.90 grams of CO_2 equivalence per megajoule[37] (gCO_2e/MJ), based on the current U.S. average crude oil mix transported to U.S. refineries.
- **Energy consumed in the refining process (thermal and mechanical) plus transport of refined gasoline and diesel from the refinery to the distribution terminal –** 16,760 gCO_2e/mmBTU or 15.89 gCO_2e/MJ for gasoline blendstock (the Before Oxygenate Blending used for production of E10 gasoline blends) and 8,293 gCO_2e/mmBTU or 7.86 gCO_2e/MJ for ultra-low sulfur diesel (ULSD), both produced at U.S. refineries to meet U.S. specifications.

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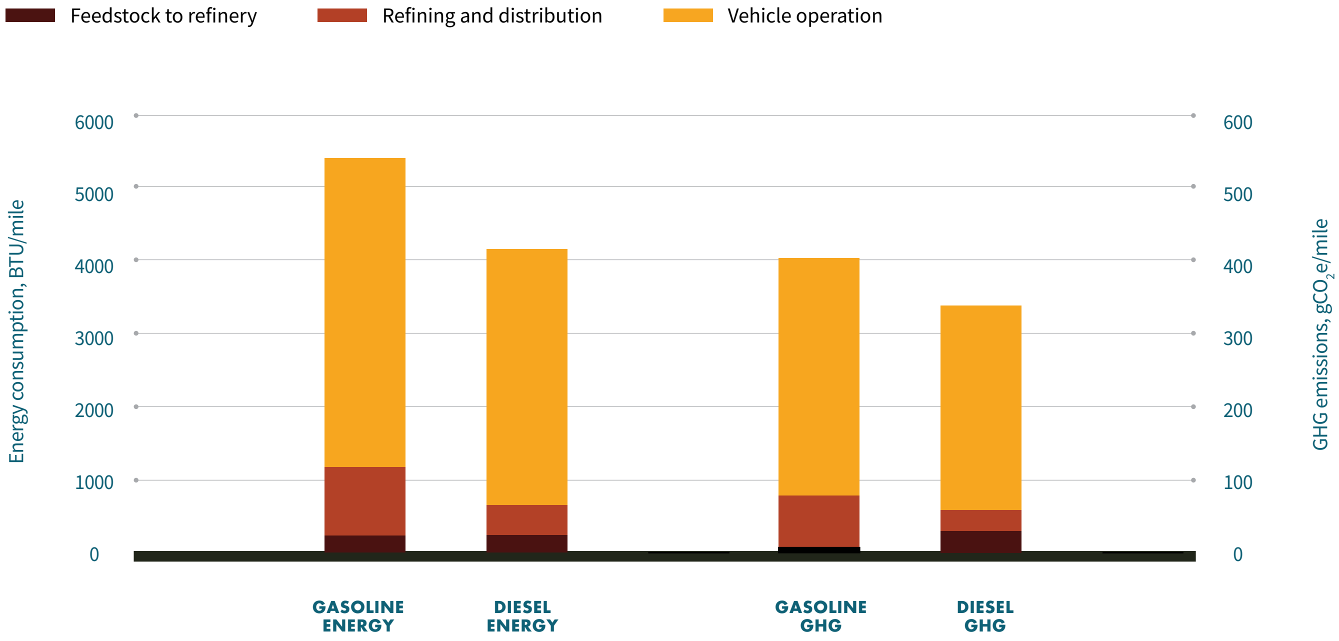
[36] Argonne National Laboratory / GREET 2022.

[37] 1 mmBTU = 1,054.5 MJ.

FIGURE 24. ENERGY CONSUMPTION AND GHG EMISSIONS FROM PRODUCTION AND USE OF GASOLINE AND DIESEL



Source: GREET model, Stillwater analysis

A comparison of the energy consumption and GHG emissions associated with the production and use of petroleum gasoline and diesel is presented in Figure 24. As can be seen in this figure, energy consumption and GHG emissions for both gasoline and diesel primarily occur with their end use. Further, gasoline refining consumes more energy and emits more GHGs than diesel refining, while diesel engines are more efficient at converting fuel energy into miles traveled.

7.1.1 CRUDE PRODUCTION AND TRANSPORT

The primary sources of emissions associated with this portion of the value chain are the energy (thermal and mechanical) utilized in producing the crude and transporting it to market, those from the flaring of associated gas, and fugitive losses of volatile hydrocarbons.

Currently, the energy requirements in the crude field are largely met through combustion of natural gas and distillates to generate steam and electricity required at the wellhead. Increasing regulation of carbon emissions, however, is driving the industry toward increasing utilization of renewable energy such as solar thermal for steam production and solar photovoltaic and wind for power generation.[38]

Flaring and fugitive emissions associated with crude production are estimated in the GREET model as contributing 1,083 gCO_2e/mmBTU out of the 8,329 gCO_2e/mmBTU of GHG emissions associated with crude oil production and transport. Economically, these emissions are controlled by the market value of any product consumed in flaring or lost through evaporation; increasing global market values for these commodities, particularly natural gas, provide incentive to minimize these emissions.

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[38] Some crude producers in California currently take advantage of these energy sources to earn LCFS credits.

Additionally, regulations in the U.S. and other crude-producing countries can be expected to mandate reductions in these losses going forward.

In summary, increasing commercial value of crude oil and natural gas as well as more stringent environmental regulations can be expected to maintain or reduce carbon emissions associated with crude oil production and transport even as production shifts to more energy-intensive crude production.

7.1.2 REFINING AND DISTRIBUTION

GHG emissions associated with the conversion of crude oil to petroleum gasoline and diesel at refineries are primarily due to the combustion of fossil fuels to generate heat required by refining processes and to produce high-pressure steam to drive large pumps and compressors. Additionally, CO_2 is produced in some refining processes, primarily the combustion of coke to regenerate the catalyst and provide the necessary heat of reaction in fluid catalytic crackers (FCCs) and in the conversion of natural gas and other light hydrocarbons to hydrogen in steam methane reformers (SMRs). A smaller quantity of emissions is attributable to electricity consumed by pumps, compressors, and process control devices. Additionally, distribution of gasoline and diesel to market requires electricity to operate pipelines and diesel fuel consumed by tank trucks and trains used to transport products to market.

Key boundary conditions around refinery GHG emissions are set by the need to consume all the refinery gas production, ideally in value-generating processes with a minimum of flaring, and the need to combust all the coke generated in the FCC unit. Within these boundary conditions, there are a number of steps which refineries can take to reduce their CO_2 emissions. Historically, energy is one of the largest costs in operating a refinery; thus, refineries regularly invest in energy-saving technologies.

Potential areas for GHG reductions from refinery operations include:

1. **Energy Efficiency –** This includes process optimization, thermal integration, increased insulation, and elimination of steam leaks. These are steps refineries routinely take and can be expected to continue, resulting in slow but continuous GHG reductions.
2. **Renewable Energy –** For energy requirements beyond those provided from combustion of refinery gas and FCC coke, refineries can readily contract for renewable electricity and renewable natural gas (RNG). In some cases, they may be able to claim environmental credits for this substitution, including the use of book-and-claim accounting where these renewable energy sources cannot be directly supplied to the refinery.
3. **Carbon Capture –** The use of carbon capture and storage (CCS) at a refinery can most readily be implemented at the FCC units and hydrogen plants as they produce high-concentration CO_2 streams, generally in excess of any that can be sold to industrial gas suppliers. According to the GREET model, GHG emissions associated with the production of gasoline at U.S. refineries totals 16,760 gCO_2e/mmBTU while GHG emissions from production of ULSD totals 8,293 gCO_2e/mmBTU. Of these totals, GREET finds that FCC emissions amount to 2,083 gCO_2e/mmBTU, and those from hydrogen plants (SMRs) amount to an additional 75 gCO_2e/mmBTU. Accordingly, the implementation of CCS at FCCs and hydrogen plants would roughly offset almost 15% of GHG emissions associated with gasoline refining and nearly 30% of GHG emissions associated with diesel refining. The balance of refinery CO_2 emissions is primarily produced by fuel combustion in heaters located in different process units at the plant. The CO_2 present in the exhaust from these heaters is diluted with

nitrogen and other gases and, thus, requires a more complex cleanup process before it can be sent to a CO_2 pipeline and sequestered. Implementation of CCS also requires that the refinery be connected to a CO_2 pipeline for transport to an approved storage well.

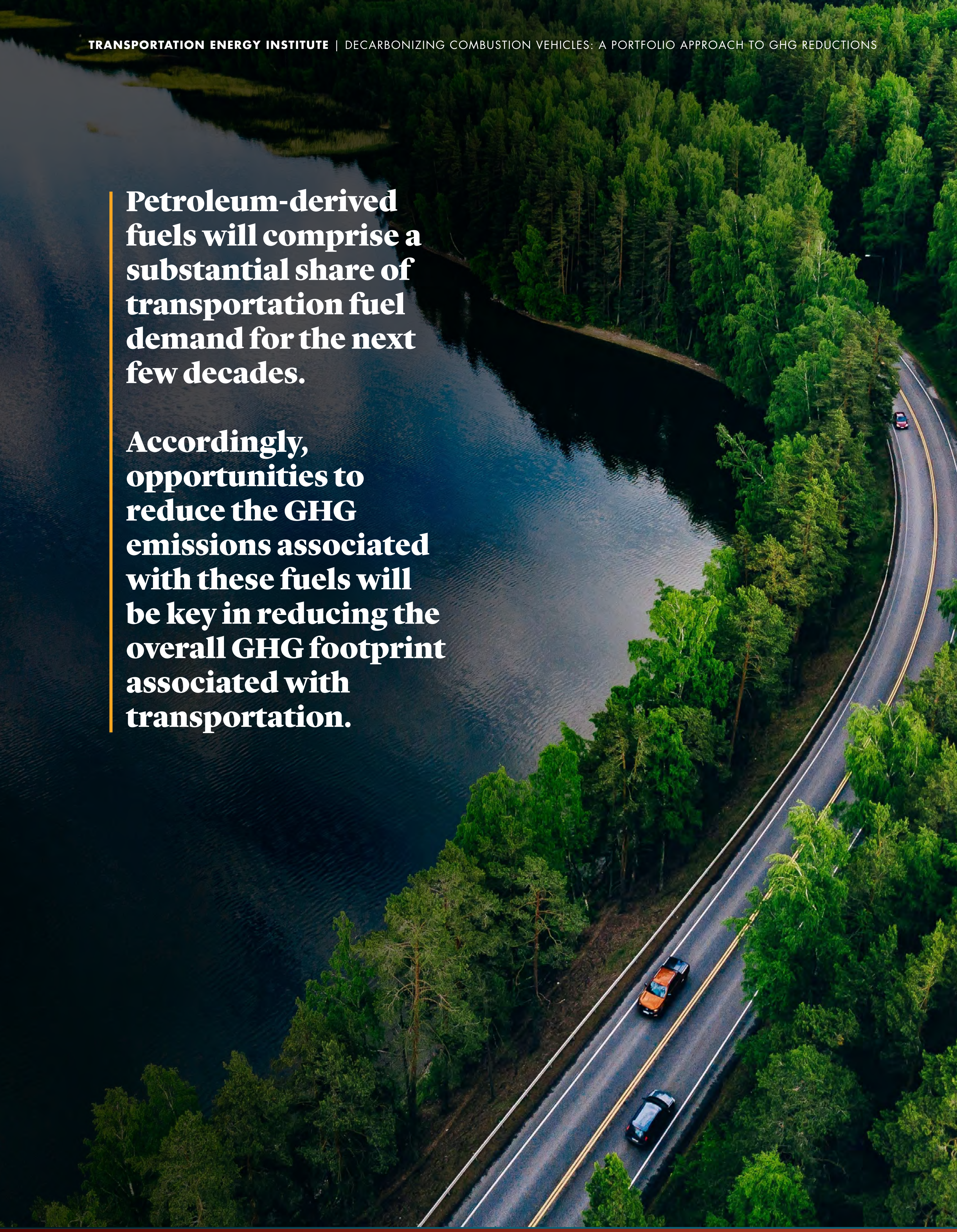
4. **Electrification –** Many of the larger pumps and compressors in refineries are powered by steam turbines and, thus, require the generation of steam in a furnace with associated CO_2 emissions. Historically, this has been done for capital cost and reliability considerations. For additional capital, many refineries have replaced steam turbine drivers in these services with electric motors to secure lower operating costs. The extent of the GHG reductions achievable through this investment is most pronounced if the refinery is also able to procure renewable electricity to drive these motors.

5. **Renewable/Low-Carbon Hydrogen –** Refineries can reduce the carbon intensity of the hydrogen they consume in their operations by replacing the use of fossil natural gas in their SMRs with RNG, implementing CCS at the SMR, or by sourcing green hydrogen. Given the very large volumes of hydrogen required by most refineries, substantial growth in production of green hydrogen and steep cost reductions would be required for this to be a material option.

6. **Renewable Feedstocks –** Even relatively small petroleum refineries have much larger capacity than the available renewable feedstocks such as vegetable oils, pyrolysis oils, and Fischer-Tropsch (FT) syncrudes, and these feedstocks are not direct substitutes for crude oil. Thus, plants seeking to process renewable feedstocks typically need to make significant investments or reduce output in order to accommodate them on a material scale. Over time, if demand for petroleum fuels declines due to growing electrification of the vehicle fleet, renewable feedstocks may become a better fit for supplying a declining market for liquid fuels.

In summary, there are a number of options for refineries to incrementally decrease the carbon intensity of their gasoline and diesel products. Additionally, implementation of CCS and transition to renewable feedstocks can enable deeper GHG reductions but will be difficult to implement at the full scale of most refineries. Given the large demand for gasoline and diesel in the transportation market for the foreseeable future, any achievable reduction will result in material reductions of annual GHG emissions.

The implementation of any of these options could be significantly accelerated if governments adopted policies which would incentivize both capital and operational decarbonization measures. Such policies, however, come at a cost which would likely be borne by fuel consumers.



Petroleum-derived fuels will comprise a substantial share of transportation fuel demand for the next few decades.

Accordingly, opportunities to reduce the GHG emissions associated with these fuels will be key in reducing the overall GHG footprint associated with transportation.

7.2 ETHANOL PRODUCTION

GHG emissions associated with ethanol production are primarily derived from growing the feedstock and the consumption of thermal energy in the ethanol production process. For corn ethanol produced at a U.S. dry mill with natural gas to fuel the process (the predominant source of supply to the U.S. market), these two factors are roughly equal in magnitude.

7.2.1 ETHANOL FEEDSTOCK PRODUCTION

Nearly all the fuel-grade ethanol currently being produced in the U.S. is produced from corn. The carbon in corn and other biomass comes from CO_2 already in the atmosphere, rather than from carbon sequestered deep in the earth in the form of petroleum. Accordingly, the use of ethanol and other biofuels instead of petroleum-derived fuels serves to eliminate new carbon in the biosphere. Consistent with that, the CO_2 emissions associated with the combustion of biofuels (often referred to as biogenic carbon) is ignored in the life cycle analysis for these fuels.[39]

The major contributors to the carbon intensity of corn production are the diesel fuel used to power farm equipment and the production of nitrogen fertilizers used to enhance corn yields.

The steady growth of per-acre yields of corn in the U.S. over the past century has meant that the amount of diesel fuel consumed in planting and harvesting each bushel has decreased. The growing commercial availability of BD and RD provides corn growers the option to significantly reduce the GHG emissions associated with the operation of their diesel-powered equipment. Additionally, the increase in per-acre yields means that any impacts of indirect land use change associated with land required for corn production has steadily decreased on a per-bushel basis.

As fertilizer usage is one of the costliest inputs to corn production, U.S. farmers work to improve their agronomic practices to reduce fertilizer requirements. Further, seed developers regularly develop new corn varieties which offer improved efficiency, further reducing fertilizer requirements. Growers in the U.S. are increasingly paying attention to adoption of more sustainable agronomic practices due to demand from key customers. Corn and ethanol industry groups are advocating with regulators to recognize documented use of sustainable agricultural practices in renewable fuel regulations; if that were to occur, it would provide substantial additional incentives to growers of corn and other biofuel feedstock producers to modify their practices to take advantage of those incentives.

In addition to corn, a smaller share of U.S. ethanol production comes from grain sorghum (milo), wheat, and other grains. While these alternative feedstocks have lower per-acre yields than corn, they are also less fertilizer-intensive.

A small but growing share of U.S. ethanol comes from corn kernel fiber, which is otherwise a by-product of corn ethanol production. By allowing increased ethanol production from each bushel of corn, corn kernel fiber ethanol effectively reduces the GHG emissions of ethanol production. Growth in corn kernel fiber ethanol production has been hampered by EPA being slow to grant Renewable Fuel Standard (RFS) pathway approval. A recent announcement from EPA suggests that they are preparing to approve additional production pathways.[40]

In summary, GHG emissions associated with the production of corn and other ethanol feedstocks is expected to decrease over the timeframe of this study.

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[39] Combustion of fossil fuels in the process of growing biomass feedstocks and converting them to fuel is, however, included in the LCA.

[40] EPA / Guidance on Qualifying an Analytical Method for Determining the Cellulosic Converted Fraction of Corn Kernel Fiber.

7.2.2 ETHANOL PLANT OPERATIONS

Other than feedstock production, the next largest source of GHG emissions associated with ethanol production comes from energy use in the ethanol plant. Most of this energy comes from natural gas used to produce heat and steam required by the process and from electricity used to power mechanical equipment such as mills, centrifuges, and pumps.

The major demands for thermal energy in ethanol plants are to drive distillation, regenerate the molecular sieve dryers, and dry the distillers grains coproduct. As energy use is a major cost for ethanol producers, they routinely invest in plant upgrades to incrementally lower their energy consumption when the economics are favorable. Increasingly, lowering operational energy demands can reduce the ultimate CI of the ethanol, thereby increasing the value of the ethanol under fuel performance/low-carbon fuel standards.

1. **Drying of Distillers Grains –**The drying of the distillers grains with solubles (DGS) typically represents around two-thirds of natural gas usage at dry mill ethanol plants. Drying of the DGS to dried distillers grains and solubles (DDGS), a high-protein livestock feed, is typically required to ensure storage stability required for shipping long distances to market. Plants located close to feedlots can eliminate the drying process and ship the product as wet distillers grains and solubles (WDGS). Production of ethanol with WDGS instead of DDGS reduces the CI of the ethanol by about 17 gCO_2e/MJ.[41]
2. **Replace Fossil Natural Gas with RNG[42] –** As production of RNG grows, particularly in the Midwest, it is likely that more ethanol producers will take advantage of this to produce lower-carbon ethanol.
3. **Invest in More Efficient Technologies –** Energy-saving technologies, such as membrane dryers, are regularly being introduced and are continuously adopted by producers as they have funds available. This trend is expected to continue, resulting in continuing incremental reductions in plant emissions.
4. **Carbon Capture and Storage –** About half of the CO_2 produced at ethanol plants comes in the form of a highly concentrated CO_2 stream produced in the fermenter.[43] The chemistry of the fermentation process produces about 2.8 kg of CO_2 for every gallon of fuel-grade ethanol. Due to its high concentration, this CO_2 can be readily captured and processed for CCS. The implementation of CCS on the fermenter effluent at a typical dry mill ethanol plant can reduce the CI of the ethanol by about 27 gCO_2e/MJ, approximately equal to the carbon emissions associated with growing and harvesting the corn for that ethanol production and about 40% of the typical 68 gCO2e/MJ CI for U.S. dry mill corn ethanol. The enhanced CCS provisions of the Inflation Reduction Act of 2022 (IRA) and the growing role of programs such as California's LCFS provide substantial economic incentives for plants to make these investments.
5. **Renewable Power –** Plants can obtain additional GHG reductions through contracting for supply of renewable electricity instead of using the local grid mix to power the plant.

Brazilian sugarcane ethanol is the second largest source of fuel-grade ethanol globally and its production results in somewhat lower GHG emissions than U.S. corn ethanol due to high per-acre yields of sugarcane and substantial coproduction of renewable power (from combustion

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[41] Estimated based on a savings of 250,000 BTU of natural gas per mmBTU of ethanol production and fossil natural gas combustion emissions of 73,365 gCO_2e/mmBTU.

[42] The LCFS regulation requires plants to receive any RNG directly from the producer (“behind the meter”) in order to take credit for its use in their pathway CI. This puts ethanol plants at a disadvantage relative to vehicle fleets, which can take credit for RNG sourcing via book-and-claim accounting.

[43] The CO_2 produced in the fermenter is biogenic and, hence, does not count in the calculation of a plant’s CI. Capturing that CO_2, however, does enable the plant to take credit for the reduced CO_2 emissions.

of the sugarcane bagasse). Use in the U.S., however, has generally been limited due to demand in Brazil and the extended logistics required to transport it to the U.S. market. Currently, the sugarcane ethanol reaching the U.S. market is primarily directed to California to take advantage of the LCFS credits available. U.S. imports of sugarcane ethanol are not expected to materially increase over the timeframe of this study.

In summary, the GHG emissions of fuel-grade ethanol can be expected to gradually decrease due to continuing optimization of both agricultural operations and ethanol production. A much more substantial reduction may be achieved if use of CCS at U.S. ethanol plants becomes widespread.

7.3 TANK-TO-WHEEL TRENDS FOR GASOLINE-ETHANOL BLENDS

As detailed earlier in this report, gasoline-ethanol blends will be the primary fuel for most light-duty ICEVs in the U.S. for many years to come. This includes passenger cars and light-duty trucks with conventional, hybrid, and PHEV drive trains. The previous sections cover expected trends in the well-to-tank (WTT) portion of the life cycle for these fuels. This section focuses on the tank-to-wheels portion of the life cycle. The TTW portion of the life cycle will primarily be influenced by commercial deployment of incremental improvements and major evolution of ICEVs.

7.3.1 E10 AND E15

E10 is likely to remain the largest portion of the light-duty fuel mix in the coming years as it represents the primary fuel for all existing gasoline ICEVs in the U.S. The volume share of light-duty vehicle fuel going to E10 can be expected to decline gradually over time due to increasing federal fuel efficiency corporate average fuel economy (CAFE) standards and potential growth in the use of E15 and higher blends of ethanol with gasoline. New ICEVs are expected to see slight improvements in TTW emissions due to incremental improvements in the efficiency of gasoline engines and a growing share of conventional hybrids. During this periods, PHEV and BEV deployments are expected to increase. However, slower than anticipated development of battery technologies costs could reduce the deployment of expected PHEV and BEV and may force OEMs to increase ICEV technology improvements.

As nearly all new ICEVs are now designed to accept E15,[44] the pace of transitioning the regular gasoline market from E10 to E15 will depend on removing existing regulatory restrictions on E15 in conventional gasoline markets during the summer, increasing retail availability, and driving consumer acceptance. As recently reported by the Renewable Fuels Association, the emergency approval of E15 during the summer of 2022 appears to have significantly advanced consumer acceptance of the fuel.[45]

Provisions in the IRA also provide new funding which can be used to help grow retail availability of E15.[46] However, a permanent solution to the regulatory limitation on summertime E15 in conventional gasoline markets has yet to be reached. If the political and regulatory process to unlock this restriction on E15 can be found, there is strong reason to believe that the consumer cost benefits of E15 will result in it ultimately seeing rapid growth in market share and additional reductions in GHG emissions from gasoline ICEVs. If all U.S. gasoline demand were to transition from E10 to E15, this would result in a 22,000 metric tons per year reduction in U.S. GHG emissions.[47]

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[44] The one category of ICEVs which do not currently receive OEM approval of E15 are premium-required vehicles. E15 in the U.S. market is primarily offered at 88 R+M/2, below the 91 R+M/2 minimum for which these vehicles are typically designed. Significant retail availability of higher octane E15 is unlikely to occur until after 88 R+M/2 achieves a substantial share of the market.

[45] Renewable Fuels Association / E15 Extended Gasoline Supplies at a Critical Time This Summer and Saved Americans Millions at the Pump.

[46] 117th Congress / Public Law 117-169.

[47] Assumes a gasoline CI of 91 g/MJ, an ethanol CI of 55 g/MJ, and U.S. gasoline demand of 14,538 trillion BTU per year based on the estimate for U.S. light-duty gasoline demand. U.S. Energy Information Administration (EIA) / Annual Energy Outlook 2022 (AEO 2022).

7.3.2 E85 AND OTHER HIGHER ETHANOL BLENDS USED WITH FFVs AND POTENTIAL NEW VEHICLES

The use of blends containing greater than 15% ethanol would offer significant GHG reductions from ICEVs, based on ethanol offering substantial GHG benefits relative to gasoline. However, blends containing greater than 15% by volume of ethanol with gasoline are currently restricted to use in FFVs. Historically, production of FFVs by original equipment manufacturers (OEMs) was primarily motivated by CAFE credits offered for manufacture of those vehicles rather than consumer demand. Most owners of FFVs are unaware of the fact that their vehicles can consume E85, and E85 sales data collected by EIA suggest that very few FFVs are actually fueled with E85. According to the Alternative Fuels Data Center (AFDC), there were an estimated 21 million FFVs on the road in the U.S. in 2018.[48] As reported in EIA's AEO for 2020,[49] U.S. E85 demand in 2018 was 453 million gallons, or about 21.6 gallons per FFV on the road in 2018.[50] With limited consumer interest in E85 and FFVs, OEMs have been decreasing their FFV model offerings as CAFE incentives phase out.

Reasons cited for limited consumer interest in E85 and FFVs include limited awareness on the part of owners of FFVs, limited retail availability of E85 (the AFDC currently lists 4,204 public E85 fueling sites in the U.S. compared to an estimated 140,000 retail gasoline stations), and inconsistent retail price incentives to offset to poorer fuel economy realized when operating on E85. E85 retail availability varies markedly between U.S. regions, with high concentrations in the Midwest and growing interest in California (stimulated by the value of LCFS credits to lower the effective cost). Thus, while there is a substantial opportunity to grow E85 sales to existing FFV owners, limited retail availability remains an obstacle in much of the U.S., and the lack of new FFV models places a downward limit on potential demand as existing FFVs are retired and replaced with non-FFVs. Reversing this trend would likely require reinstating incentives for OEMs to produce new FFVs while creating additional incentives and increased fuel visibility and availability to encourage FFV owners to regularly fuel with E85.

The use of E85 with FFVs is primarily a strategy to displace petroleum-fueled vehicles where possible with vehicles which can use either gasoline or E85. This strategy, however, fails to take advantage of ethanol's high octane value. An alternative ethanol strategy is to use mid-level ethanol blends (e.g., E25, E30, or E40) to facilitate production of fuels with higher octane (e.g., an AntiKnock Index octane rating of 88 compared to the 87 of typical U.S. regular gasoline) than what can be economically achieved with petroleum gasoline and using that fuel in engines designed to take advantage of that higher octane to achieve greater fuel economy. This approach, however, requires coordinated deployment of both the vehicles and their required fuel and, likely, designing the vehicles to operate on standard E10 when the higher octane fuel is not available. Additionally, in order for the OEM to gain CAFE credit for the higher fuel economy when using the higher octane fuel, EPA would require measures to assure that the higher octane fuel is actually being used by vehicle owners. Thus, achieving the theoretical benefits which could be achieved with a

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[48] Alternative Fuels Data Center / Flexible Fuel Vehicles.

[49] U.S. Energy Information Administration / Annual Energy Outlook 2022 - Reference Case, Table 37.

[50] Reported as 43 trillion BTU based on 3.987 million BTU per barrel of E85.

higher octane mid-level ethanol blend would require close coordination between multiple OEMs, EPA, fuel producers, and fuel retailers. Solving this complex coordination problem when many stakeholders are focused on transitioning the market to EVs as rapidly as possible adds to the challenge. Accordingly, mid-level higher octane blends and vehicles are only likely to emerge if the transition to EVs hits a very difficult roadblock.

7.4 CNG/LNG VEHICLES FUELED WITH RNG

According to EIA, U.S. use of natural gas as a vehicle fuel in 2021 amounted to 54.5 billion standard cubic feet (BSCF, or 52,300 billion BTU,[51] or 381 million diesel gallon equivalent [DGE]) out of total U.S. natural gas demand of 30,665 BSCF (29,400,000 billion BTU).[52] This usage can be in the form of compressed natural gas (CNG, natural gas compressed to, typically, 3,600 psi) or liquified natural gas (LNG, natural gas cooled until it turns into a liquid). Both CNG and LNG can be produced from either fossil natural gas or renewable natural gas (RNG, natural gas produced from decomposition of biomass at landfills, wastewater treatment plants, manure from dairy and swine production, etc.).

RNG used as transportation fuel is eligible to earn RFS renewable identification numbers (RINs); in 2021, EPA reports 43,793 billion BTU of RNG (319 million DGE) was used to produce CNG or LNG for transportation fuel.[53] Thus, RNG currently accounts for about 84% of CNG and LNG used for transportation in the U.S. In California and Oregon, where the LCFS and the Clean Fuels Program (CFP) provide additional incentives for use of RNG, the RNG share of CNG and LNG use is currently over 95%. The GHG benefits associated with the use of RNG in natural gas vehicles (NGVs) compared to both fossil natural gas and ULSD vary significantly with the feedstock used to produce the RNG and can be estimated based on the CIs assigned by the California LCFS[54] as shown in Table 8.[55]

TABLE 8. GHG REDUCTIONS WITH RENEWABLE NATURAL GAS

FEEDSTOCK	AVERAGE CI (gCO_2e/MJ)	% GHG REDUCTION VS. FOSSIL NATURAL GAS	% GHG REDUCTION VS. PETROLEUM DIESEL
Dairy Manure	-309	490	407
Food Scraps/Waste	-80	201	180
Landfill Gas	55	30	45
Other Organic Waste	0	100	100
Swine Manure	-338	527	437
Urban Landscaping Waste	3	97	98
Wastewater Sludge	47	40	53
Fossil Natural Gas	79	n/a	n/a
Petroleum Diesel (ULSD)	100	n/a	n/a

Source: CARB, Stillwater analysis

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[51] 1 cubic foot = 0.960 thousand BTU of CNG or LNG. EIA / AEO 2022 Table 68.

[52] EIA / Natural Gas Summary.

[53] EPA / RINs Generated Transactions.

[54] CARB / LCFS Pathway Certified Carbon Intensities.

[55] The negative CIs associated with RNG from manure and food scraps/waste are attributable to the avoidance of fugitive methane emissions when these feedstocks are converted to RNG rather than allowed to biodegrade.

In the near term, U.S. production of RNG from a variety of feedstocks, most notably dairy and swine manure, is growing rapidly. This increased supply is expected to be used first to displace much of the remaining use of fossil natural gas in NGVs with additional volumes of RNG from dairy and swine manure being directed to displace use of higher CI sources of RNG in California and Oregon NGVs.[56] Further, the size of the NGV fleet is growing in a number of heavy-duty sectors driven by economics, corporate environmental goals,[57] and, potentially, an increase in state LCFS-type programs.[58]

EPA's recently proposed eRIN program under the RFS[59] offers a new path to the transportation market for biogas[60] and RNG. Under this proposal, electricity derived from biogas or RNG would qualify to earn RINs (referred to eRINs) under certain conditions. Specifically, the power would need to be generated in the 48 contiguous states of the U.S. or portions of Canada and Mexico which are connected to the U.S. power grid. Such eRINs could only be separated from the electricity (and, thus, used for RFS compliance purposes) if they are contracted to a producer of light-duty EVs or PHEVs. The producer would be eligible each quarter to separate a number of eRINs corresponding to the estimated power used to charge their qualifying vehicles (new or existing) operating in the 48 contiguous states. As converting biogas is generally less costly than upgrading the biogas to RNG and injecting it into a common-carrier natural gas pipeline system, this provides a new incentive to grow biogas production and biogas-fired power generation.[61]

7.5 FISCHER-TROPSCH DIESEL

FT diesel (also known as biomass to liquid, or BTL, diesel) offers the potential to greatly expand the available supply of high-quality RD by utilizing abundant biomass feedstocks such as agricultural residues, wood waste, and municipal solid waste (MSW). These difficult-to-process feedstocks represent nearly all the potential growth in U.S. biomass feedstocks identified in the U.S. Department of Energy's 2016 update to their Billion-Ton Report.[62]

The challenge with commercializing this technology has been to achieve reliable, scalable operation at an acceptable capital cost. This is especially challenging for MSW as a feedstock due to the wide range of potential contaminants and its inherent variability. The firm which has achieved the greatest progress to date toward commercial operation is Fulcrum Bioenergy; they recently claimed achieving commercial operation of the gasifier unit at their Sierra BioFuels Plant in Reno, Nevada, utilizing MSW feedstocks.[63] While this is an essential milestone, this is only the first step in the process as they will also need to achieve commercial operation on their FT process unit (which converts syngas from the gasifier to FT syncrude) and upgrading units (which convert the FT syncrude to saleable products) in order to produce diesel fuel.

If Fulcrum or other firms developing this technology are successful at achieving reliable commercial operations at an acceptable cost, this will enable production of RD and sustainable aviation fuel to grow well beyond the feedstock supply constraints

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[56] Higher CI sources of RNG displaced by dairy and swine manure-based RNG are assumed to displace fossil natural gas in non-transportation uses such as power generation and industrial heating.

[57] Example: Transportation firms such as UPS and Amazon are using RNG as a cost-effective route to reduce their carbon footprint using readily available vehicles.

[58] The Clean Fuel Standard in Washington State takes effect in 2023, and several other states are considering adoption of similar programs.

[59] EPA / Renewable Fuel Standard (RFS) Program: Standards for 2023-2025 and Other Changes.

[60] The terms biogas and RNG are sometimes, incorrectly, used interchangeably. Biogas is the product of degradation of biomass to a mixture of approximately 50% methane and 50% CO_2. Biogas becomes RNG only after it is purified to pipeline-quality natural gas specifications by removing the bulk of the CO_2 and other impurities.

[61] In their proposed rule, EPA assumes that, in the near term, much of the eRIN generation would come from existing biogas-fired power generation; the incentive for new biogas-fired generating capacity is expected to take a few years to develop and will ultimately be limited by the rate of growth of the light-duty EV and PHEV population in the 48 states.

[62] U.S. Department of Energy (DOE) Office of Energy Efficiency & Renewable Energy / 2016 Billion-Ton Report.

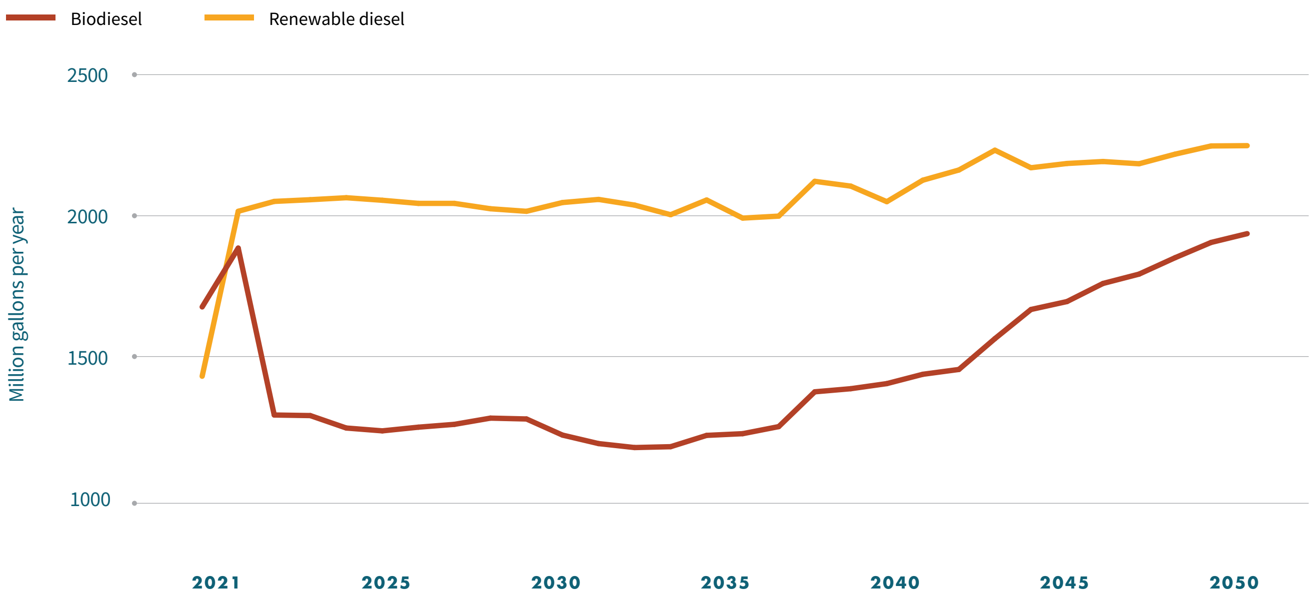
[63] Fulcrum BioEnergy / Fulcrum BioEnergy Successfully Starts Operations of its Sierra BioFuels Plant, May 24, 2022.

which are expected to limit growth of BD and RD produced from fats, oils, and greases. Incentives provided by the RFS, Blenders' Tax Credit , IRA, and LCFS programs will play a significant role in bridging the cost spread between FT diesel and petroleum diesel. As FT diesel has the potential to be a drop-in fuel which can be used in blends of up to 100%, it will be possible to displace a very large fraction of petroleum diesel demand over the time required to grow feedstock collection operations and develop process facilities.

7.6 BIODIESEL BLENDS UP TO B20

BD blends have become a well-established portion of the U.S. diesel fuel market, with nearly all diesel vehicles currently on the road compatible with blends up to B5 and a growing share compatible with blends up to B20. BD blenders are available at a growing share of U.S. fuel terminals, and most diesel infrastructure is compatible with B20. This would appear to open the opportunity to grow the use of B20, both in blends with petroleum diesel and in blends with RD. The challenge for further growth in BD usage, however, comes from increasing competition with RD for feedstocks. The rapid growth in U.S. RD production capacity represents a challenge to BD producers as both technologies utilize the same feedstocks (fats, oils, and greases) and RD plants generally have greater economies of scale; are owned by larger, better-financed firms; and offer a product which can be utilized in blends of up to 100% in existing diesel equipment and infrastructure. This feedstock competition is a major limiting factor in EIA's outlook[64] for future U.S. demand for BD and RD, as illustrated in Figure 25 below. It may be observed that U.S. BD demand is forecast to drop sharply in 2023 following the rapid growth of RD production in 2022; demand is not forecast to exceed 2022 levels until 2049. Changing this assessment would require either an unexpected issue which reverses growth in RD production and demand or a breakthrough which would unlock additional feedstock types for BD production.

FIGURE 25. PROJECTED U.S. BIODIESEL AND RENEWABLE DIESEL DEMAND



Source: EIA, Stillwater analysis

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[64] EIA / AEO 2022, Table 11.

The impact of BD on GHG emissions varies not only with its percentage contribution to the diesel fuel pool, but also with the CI of the product. The largest contributor to the CI of BD is the choice of feedstock, with nonfood feedstocks such as used cooking oil (UCO), inedible tallow, and distillers corn oil (DCO, a nonedible by-product of corn ethanol production at dry mill plants) having much lower CIs than vegetable oils (such as soybean oil and canola oil) due to the lack of direct and indirect land use change considerations. In the future, inedible oils derived from cover crops, such as camelina, carinata, and pennycress, may begin to make a growing contribution to the BD feedstock mix, growing the potential supply of BD while offering low CIs.[65] As the California LCFS, Oregon CFP, and other similar programs place high value on low CI feedstocks, their use is currently being maximized. Accordingly, we expect that feedstock growth in the near term will lean toward greater use of higher CI feedstocks such as soybean oil and canola oil, raising the overall CI of available BD. This trend may slow or reverse in the longer term if production of oils from cover crops becomes a material contributor to the BD and RD feedstock pool. As the RD production process tends to be less sensitive to feedstock quality, we further expect that RD producers will differentially attract the more variable low CI feedstocks such as UCO and inedible tallow.

The coming transition from the current biomass-based diesel blenders' tax credit (BTC) to the clean fuels production credit (CFPC) will create additional incentive for all domestic BD and RD producers to compete for the lowest CI feedstocks.[66] This transition, which is a component of the recently adopted IRA,[67] takes effect January 1, 2025, and establishes a variable tax credit for fuels meeting a maximum CI of 50 kilograms of CO_2e per million BTU (47.39 gCO_2e/MJ) as determined by a process to be established by the Internal Revenue Service.

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[65] An assessment of the potential contribution of cover crops is included in the Feedstock Options section of this report.

[66] Imported product will not be eligible.

[67] 117th Congress / Public Law 117-169.

7.7 RENEWABLE DIESEL BLENDS UP TO RD100

RD, as a term, is sometimes used generically for all renewably derived substitutes for petroleum diesel. For the purposes of this study, we use the term specifically to refer to the hydrocarbon-based mixture produced from the hydrodeoxygenation of fats, vegetable oils, and greases (sometimes referred to as FOG) and suitable for use as diesel fuel. RD using this pathway is currently being produced by Neste, Diamond Green Diesel, Chevron-REG, and a growing list of additional producers. RD can be combined with petroleum diesel at any blending level, up to 100% substitution. Not only is this theoretically possible, R99 (pure RD blended with at least 0.1% volume percent petroleum diesel in order to separate RINs and capture the BTC) is sold at many retail sites in California and directly to a number of centrally fueled fleets. A blend of 80% RD with 20% BD is also offered commercially and used neat by a number of fleets. During the second quarter of 2022, the California diesel pool averaged 37% RD and 7% BD content.

As discussed earlier, RD producers compete with BD producers for the same feedstocks. The current, rapid growth in RD production capacity means that the supply of both fuels will soon become feedstock limited. Figure 25 shows EIA's forecast of U.S. demand for RD and BD out to 2050. The contribution of RD to the U.S. diesel pool, particularly in California, is growing rapidly as U.S. production of RD is rapidly increasing.

As is the case with BD, the impact of RD on GHG emissions varies not only with its percentage contribution to the diesel fuel pool, but also with the CI of the product. The largest contributor to the CI of RD is the choice of feedstock, with nonfood feedstocks such as UCO, inedible tallow, and DCO having much lower CIs than vegetable oils due to the lack of direct and indirect land use change considerations. In the future, inedible oils derived from cover crops, such as camelina, carinata, and pennycress, may begin to make a growing contribution to the RD feedstock mix, growing the potential supply of RD while offering low CIs.[68] As the California LCFS, Oregon CFP, and other similar programs place high value on low CI feedstocks, their use is currently being maximized; accordingly, we expect that feedstock growth in the near term will lean toward greater use of higher CI feedstocks such as soybean oil and canola oil, raising the overall CI of available RD. This trend may slow or reverse in the longer term if production of oils from cover crops becomes a material contributor to the BD and RD feedstock pool. As the RD production process tends to be less sensitive to feedstock quality, we further expect that RD producers will differentially attract the more variable low CI feedstocks such as UCO and inedible tallow, enabling RD, on average, to be lower in CI than BD.

The coming transition from the current BTC to the CFPC will create additional incentive for all domestic BD and RD producers to compete for the lowest CI feedstocks.[69]

7.8 E-FUELS

Electrofuels, often shortened to e-fuels, refers to liquid fuels synthesized from carbon dioxide and water with the use of electricity. These are created by utilizing a concentrated source of carbon dioxide, such as that captured from a process stream or via direct air capture, producing green hydrogen via electrolysis of water, and reacting that hydrogen with the carbon dioxide over one or more stages of catalysis to produce liquid fuels. These fuels can include gasoline, jet fuel, and diesel along with coproduct chemicals. Effecting this series of reactions requires substantial quantities of electricity to capture the concentrated carbon

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[68] An assessment of the potential contribution of cover crops is included in the Feedstock Options section of this report.

[69] Imported product will not be eligible.

dioxide, electrolyze the water to hydrogen, and drive the ultimate conversion to liquid fuels. Due to the large quantity of electricity required, the CI of these fuels is highly dependent upon the CI of the electricity consumed; typically, this requires the e-fuel process to have a captive source of renewable power to assure a favorable CI relative to petroleum-derived fuels. Building an e-fuels plant is capital intensive; thus, return on investment is very sensitive to utilization (i.e., the number of hours per year of operation). Accordingly, the hourly variability of wind and solar power make it challenging to develop an economic project using these sources of renewable energy; plants coupled with geothermal or nuclear power production may offer more robust economics.

Research on each component of the e-fuel process (carbon capture, electrolysis, and conversion to liquid fuels) is ongoing. It is likely that current research projects will steadily reduce the amount of electricity required to produce each gallon of e-fuel. There are a number of commercial projects currently in development with the earliest commercial-scale production expected in the 2025 or 2026 timeframe.

Even with expected improvements in the efficiency of e-fuel technology, it will still be less efficient than using the same amount of renewable electricity to displace fossil electricity, charge EVs, or produce green hydrogen to fuel FCEVs. Even with those limitations, there are circumstances where e-fuels may be an important contributor to the decarbonization of ICEVs:

1. **Even with an accelerating transition of the ICEV fleet to EVs, the pace of fleet turnover (as discussed earlier) means that there will be substantial demand for liquid fuels out to 2050 and beyond.**
2. **While FCEVs may ultimately form a significant share of the vehicle fleet, commercial deployment of this technology significantly lags EVs, thus market demand for green hydrogen may be slow to develop.**
3. **Due to their high energy density, liquid fuels are easier to transport and are more readily stored than either electricity or hydrogen. These factors facilitate long-term storage and distribution from point of manufacture to point of demand.**
4. **Neither electricity nor hydrogen have been demonstrated as feasible alternatives to liquid fuels for commercial aviation or oceangoing marine fuel applications.**
5. **Petroleum refining inherently produces a mix of products which can only be varied within certain limits, and the transition away from petroleum fuels makes it cost-prohibitive to make substantial capital investments in retooling refining capacity. Accordingly, differences in the pace at which different transport modes shift away from petroleum can result in a shrinking petroleum refinery fleet which is not configured to meet transitioning market demands; e-fuels may provide an essential pathway to closing the resulting gaps.**

As the pace of the energy transition varies between different transportation modes and different parts of the globe, e-fuels may play a key role in balancing market supply and demand. The extent to which that will impact U.S. and global GHG emissions will be highly dependent upon the pace at which this technology can be optimized to decrease its carbon intensity.

Shortcomings of Existing Models in Calculating Criteria Pollutants

Existing vehicle energy and emission models simplify the nation's nearly 300-million-vehicle fleet generally to single values to allow comparisons between fuel and vehicle types. This simplification is necessary to handle the complexities of vehicle emissions. However, important realities can be lost to oversimplification. This section will examine the PM and NOx complexities that are not represented well in existing life cycle analysis models.

There are several models used today to characterize vehicle technology emissions. These models reflect governmental agencies' latest understanding of statewide and regional vehicle activities and emissions, and they are used to assess recently adopted regulations' potential to reduce future emissions. The three main models used, and therefore the models discussed herein, are:

1. **The GREET model**
2. **The MOtor Vehicle Emission Simulator (MOVES3) model**
3. **The EMission FACtor (EMFAC) model**

These three models are summarized in Table 9.

TABLE 9. KEY VEHICLE MODELS USED TO QUANTIFY VEHICLE TECHNOLOGY EMISSION DIFFERENCES

MODEL	DEVELOPER	SCOPE
GREET Well-to-Wheels	Argonne National Laboratory	Extraction, transportation, refining, refueling, vehicle and road emissions
MOVES3	U.S. Environmental Protection Agency (EPA)	National criteria pollutant emissions. Vehicle emissions only.
EMFAC	California Air Resources Board (CARB)	California criteria pollutant emissions. Vehicle emissions only.

All three models use unadjusted laboratory vehicle emission test results which are designed for regulatory purposes. Laboratory tests accurately measure tailpipe emissions for regulatory standards enforcement, but they are significantly errored when they are used to estimate the on-road vehicle emissions. Two technical flaws obscure ICEV criteria pollutant emission analysis as compared to EVs. Laboratory testing protocols exclude the facts that 1) ICEV engines consume air[70] and 2) ICEVs therefore consume air pollution. To accurately compare EVs and ICEVs on criteria pollutant emissions requires including the ICEV engine's air consumption of on-road air pollution. When laboratory test results are adjusted to include these two factors, today's cleanest ICEVs are shown to reduce existing air pollution during air violation days.[71] The population of cleanest ICEVs is currently a small portion of the total ICEV fleet but outnumbers today's EV population and the anticipated EV population by 2050.[72] Still, CARB and EPA do not yet include the fact that ICEVs consume and clean up air pollution on the road. We will quantify the magnitude of this error with the GREET estimated emissions.

8.1 PARTICULATE MATTER (PM)

PM pollution poses significant health threats, especially to children and the elderly.[73] EPA estimates that mobile sources (i.e., vehicles) represent less than 5%[74] of PM emissions; the vast majority of PM emissions (73%) result from fires, dust, and agriculture.[75]

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[70] Per Cummins vehicle emission tracking, heavy-duty diesel vehicles in service consume 81+/- 11 m3 of air per diesel gallon consumed.

[71] Emission models use the median vehicle emission test values. "Today's cleanest ICEVs" refers to the portion of vehicles that are cleaner than that median value. A significant portion of the cleanest half of the fleet can be shown to have negative emissions when operated in polluted environments.

[72] Stillwater Associates' analysis of 2019 model year certification emission values and CARB heavy-duty vehicle emission surveillance program. CARB / EMFAC2021 Volume III Technical Document.

[73] Particulate matter contains microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems. Some particles less than 10 micrometers in diameter can penetrate deep into the lungs, and some may enter the bloodstream. Of these, particles less than 2.5 micrometers in diameter ($PM_{2.5}$) pose the greatest health risk.

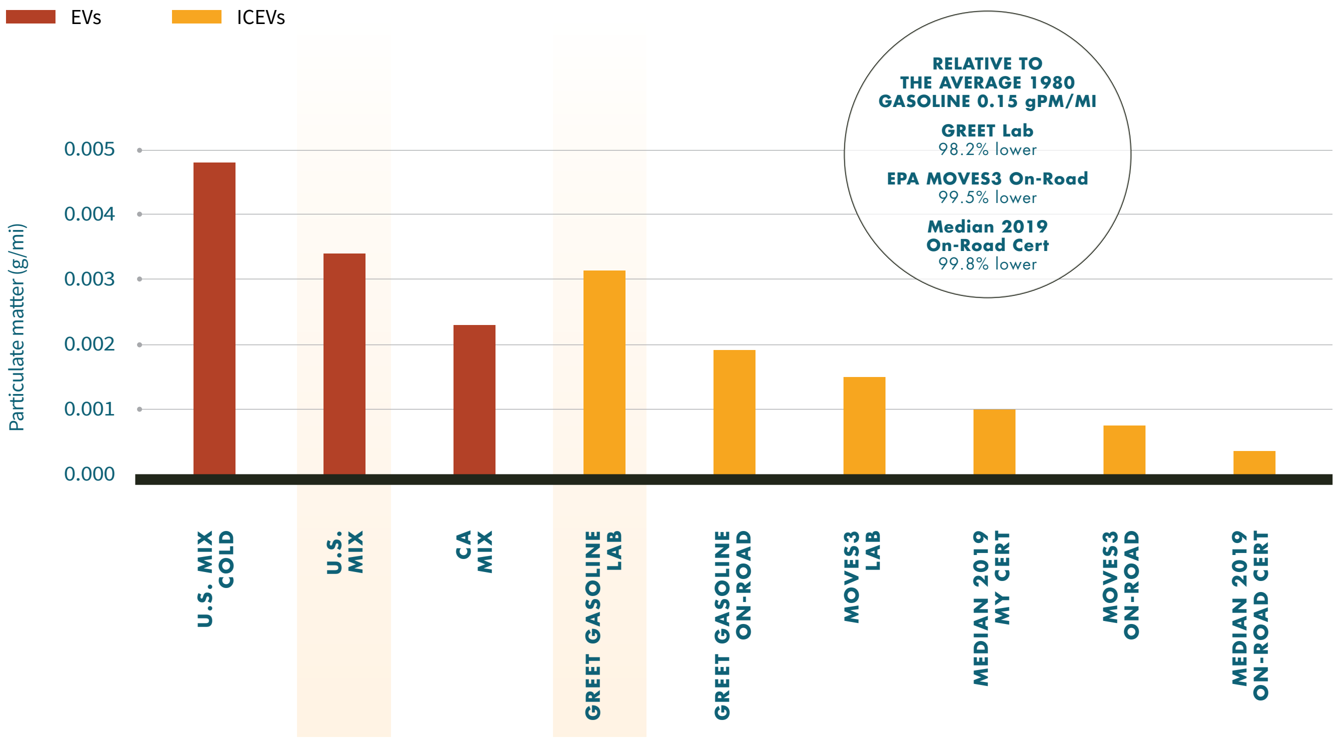
[74] If EPA revised their vehicle emission assessments to include the fact that ICEVs consume PM pollutants, the present estimate would be reduced by half.

[75] EPA / Draft Policy Assessment for the Reconsideration of the National Ambient Air Quality Standards for Particulate Matter.

According to GREET well-to-wheel (WTW) emission values, today's gasoline and diesel vehicles' tailpipe PM emissions are 98.3-100.3% lower than the average 1980 gasoline car, and 97.3-99.4% lower on a WTW basis.[76] Comparing EVs charged using the average U.S. mix electricity to the range of modern gasoline and diesel PM emissions, there is less than a 3% difference between any light-duty vehicle options.

Figure 26 shows the GREET PM emission comparisons alongside other emission estimates for various vehicles and fuels. The most commonly used fuels are highlighted. The emissions analysis shows that when including power plant emissions, EVs have slightly higher PM emissions than estimates for gasoline and diesel PM vehicle levels used by EPA MOVES3 emission inventory and EPA 2019 model-year vehicle certification laboratory (Median 2019 MY Cert bar in the figure) and on-road (Median On-Road Cert bar in the figure) emission values. The EPA MOVES3 emission inventory estimates the gasoline vehicles' PM value using laboratory clean air; this value is 55% lower than EVs charged by U.S. mix.[77] Adjusting EPA data for on-road air pollution, the EPA MOVES3 value becomes 79% lower than EVs charged using U.S. mix electricity. As can be seen in Figure 26, the full range of credible vehicle emission estimates shows that ICEV PM emissions are equivalent to or below that of EVs, and all are near zero.

FIGURE 26. VEHICLE PM EMISSION ESTIMATES FOR LIGHT-DUTY ICEVs AND EVs (EXCLUDING COAL POWER)



Sources: Stillwater Associates analysis of 2022 GREET, EPA MOVES3, EPA 2019 Model Year Raw Certification Emission Values, 1998 SwRI In-Use Characterization of Light-Duty Vehicle Particulate Matter Exhaust Emissions, and 2022 GREET

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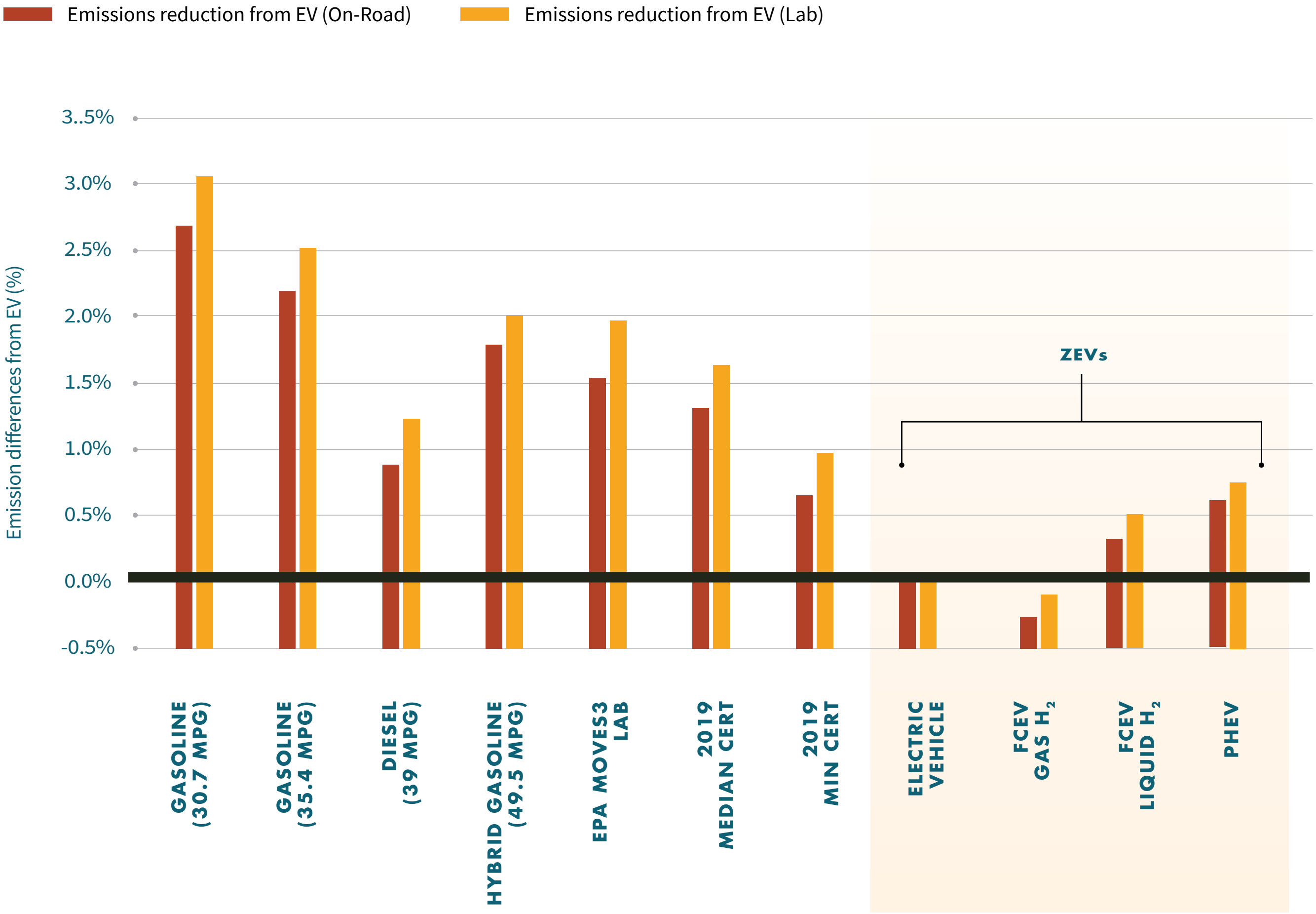
[76] The average 1980 gasoline powered vehicle's PM emissions level was 0.15 g PM$_{10}$/mile while the average smoking gasoline vehicle emissions level was 0.40 gPM$_{10}$/mile. Whitney, K.A. / Characterization of Particulate Exhaust Emissions from In-Use Light-Duty Vehicles.

[77] EPA / MOVES Onroad Technical Reports.

According to EPA MOVES3 data, today's vehicles have 98.5% lower PM emissions than their 1980 gasoline counterparts. Figure 27 shows the remaining PM reduction (relative to a 1980 gasoline vehicle) versus an EV charged by U.S. mix. All options today reduce PM to within 3% of the EV charged by U.S. mix power. As can be seen, FCEVs show potential for below-zero PM emissions on road. Bottom line: PM emissions are 99.7% lower than 1980 models, and the remaining PM emissions variation between existing vehicle types is negligible.

FIGURE 27. WELL-TO-WHEEL PM EMISSIONS REDUCTION DIFFERENCES RELATIVE TO EV U.S. MIX



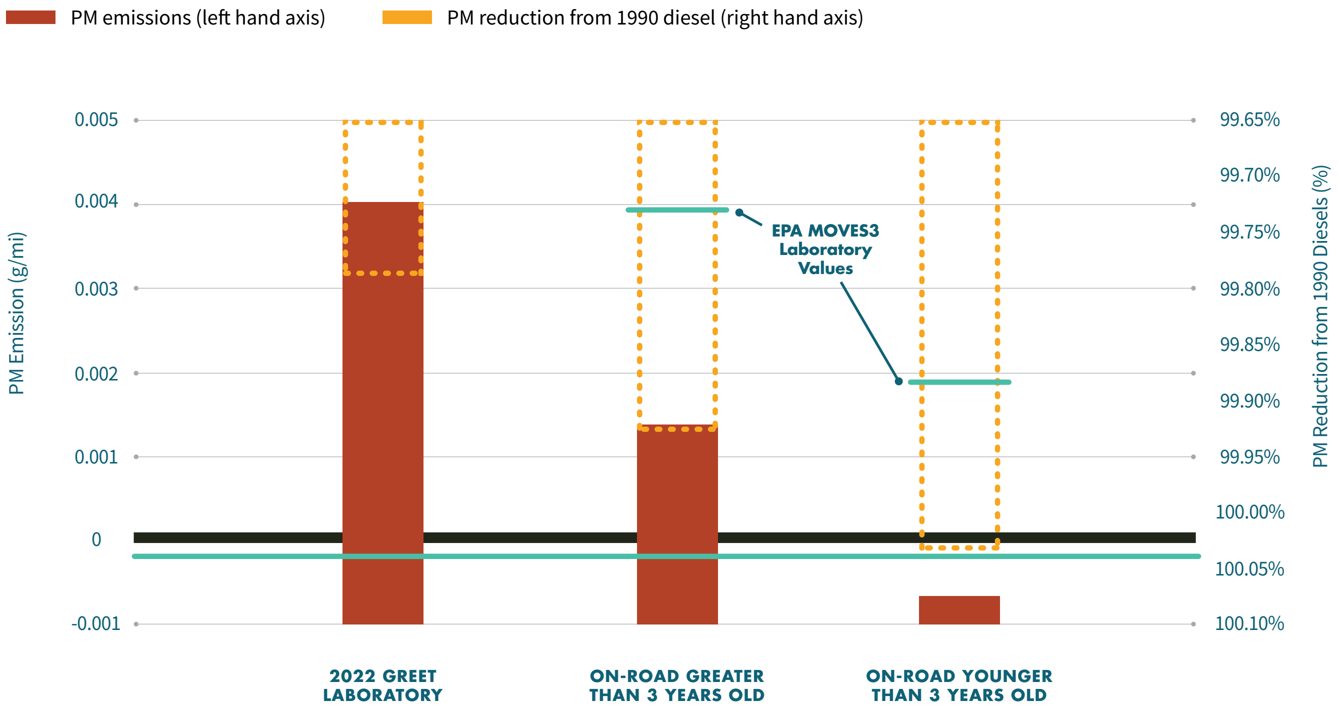
Note: Excludes EVs Coal Plant Charged which has 47% Higher PM Emission Rates than U.S. Mix

Source: Stillwater Associates analysis of GREET 2021 & 2022

8.1.1 HEAVY-DUTY DIESEL PM EMISSIONS

Heavy-duty diesel tailpipe exhaust PM emissions have declined 99.8% versus 1990 models according to laboratory tests reported in EPA MOVES3 and CARB EMFAC emission inventories. Figure 28 shows the diesel tailpipe emissions using GREET WTW and EPA MOVES3 laboratory emission rates with adjustment for on-road air pollution consumption.[78] The graph shows newer diesel vehicles with emissions below zero due to the diesel engine's air pollution consumption and cleanup by its emission controls. With on-road air pollution consumption and cleanup, diesel PM emissions are 99.93% and 100.03% lower than 1990 diesel levels.

FIGURE 28. HEAVY-DUTY DIESEL VEHICLE TAILPIPE PARTICULATE MATTER EMISSIONS



Source: Stillwater Associates analysis of 2022 GREET and EPA MOVES3 Emission Rates

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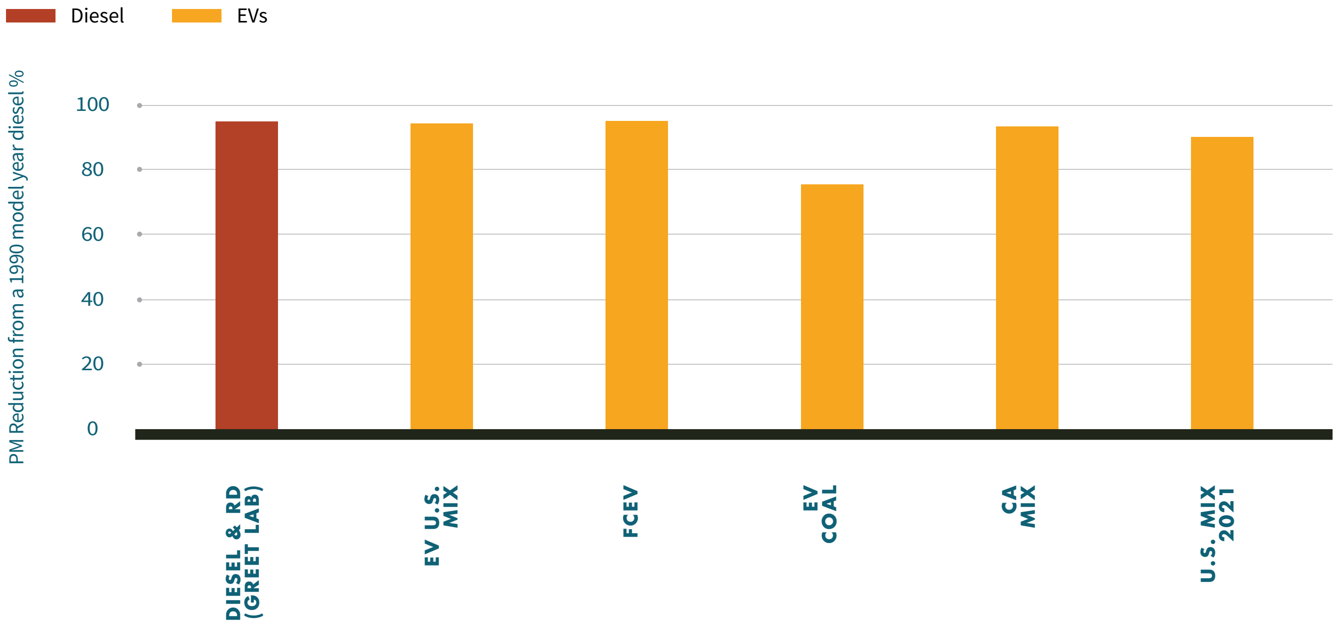
[78] EPA MOVES3 tailpipe emission rates are 0.004 and 0.002 g PM_{10}/mi for vehicles older than three years and younger than three years, respectively. Per Cummins, diesel engines consume $81^{+/-11}$ m^3 of air/diesel gallon. On-road PM_{10} pollution is assumed at 200 µg/m^3.

FIGURE 29. WELL-TO-WHEELS PM EMISSIONS REDUCTIONS FROM A 1990 MODEL YEAR DIESEL



Note: Heavy-duty PM emission rates versus EPA and CARB estimates adjusted for on-road conditions
Source: Stillwater Associates analysis of engine air consumption and GREET 2022

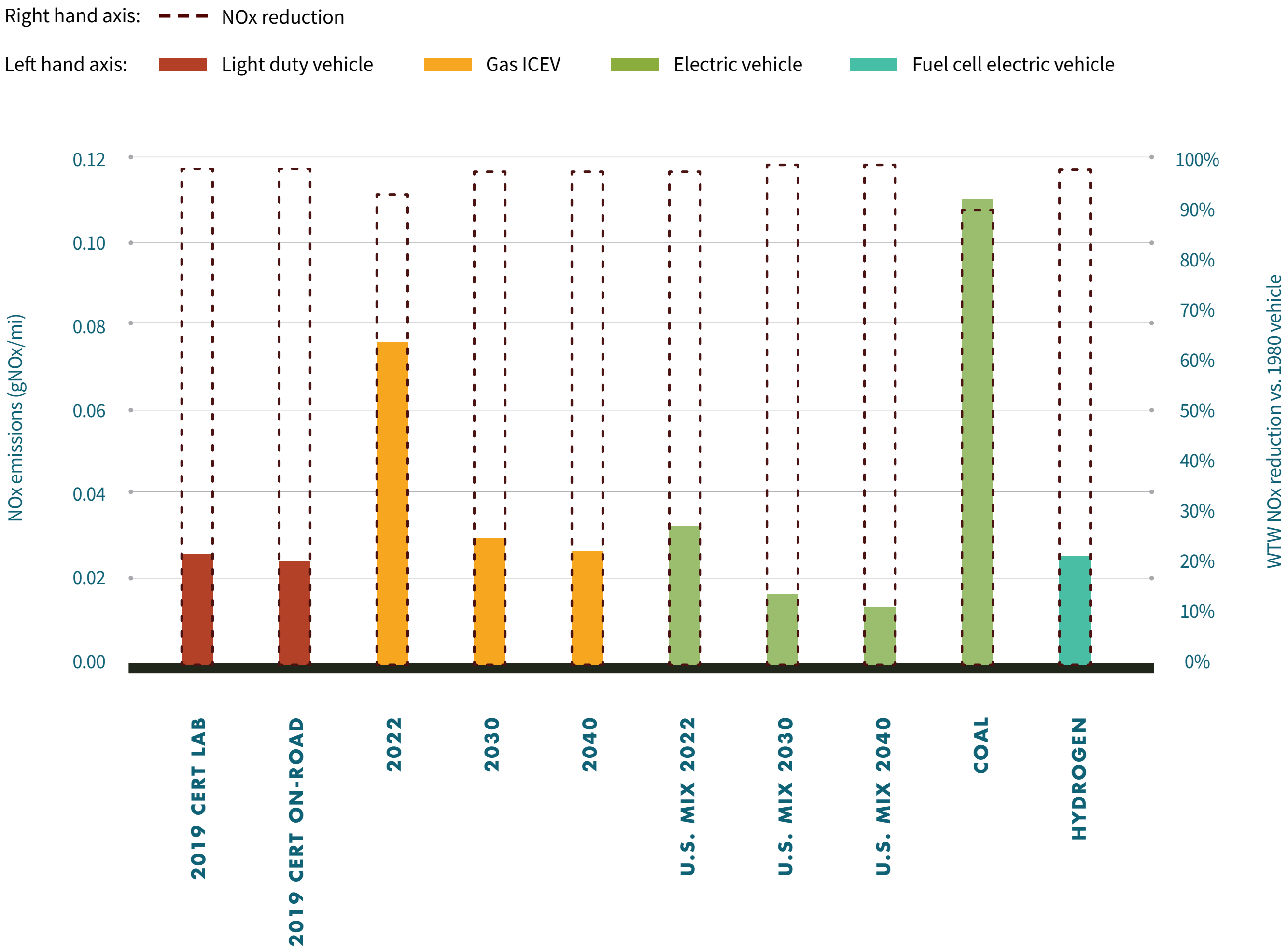
Figure 29 expands the view of emissions from tailpipe only (as displayed in Figure 28) to show the WTW emissions reductions from a 1990 model year diesel for several options. A WTW analysis evaluates the PM emissions from fuel extraction, refining or electrical production, and vehicle use emissions. Vehicle PM emissions reductions are nearly equal between EVs and diesels—all are 99.97% or higher. On a WTW basis, diesel-fueled ICEVs reduce PM emissions 94.9-100% and EVs reduce PM emissions 90-94% from a 1990 diesel PM level on a WTW basis, biofueled and petroleum-fueled diesel ICEVs provide greater PM reductions than their battery EV counterparts charged using the U.S. grid mix, and the diesel ICEVs match FCEVs on PM emissions reductions.

BOTTOM LINE: ALL PROPERLY OPERATING (AND NON-COAL-CHARGED) HD EVs AND HD DIESEL ICEVs PROVIDE ZERO AND NEAR-ZERO PM EMISSIONS AND ESSENTIALLY EQUIVALENT PM REDUCTIONS FROM A 1990 BASELINE ON A WTW OR VEHICLE BASIS.

8.2 NOx EMISSIONS VARIANCES

In 1988, California implemented the Low Emission Vehicle program, seeking to reduce criteria pollutants (and especially NOx) by at least 97% so that California might attain the federal ozone standard. At that time, only EVs could provide the 97-98% lower NOx than ICEVs. Today, with the transition to ultra-low sulfur gasoline and diesel enabling higher efficiency catalytic converters on gasoline vehicles and the introduction of selective catalytic reactors to control diesel NOx emissions, ICEVs have reduced criteria emissions 97-99%. In fact, GREET WTW estimates show that, on average, most of today's vehicle options provide at least 97% reduced NOx from a 1980 model year vehicle emission level. Using current GREET values and EPA certification data, we compared the NOx emission levels of various vehicles and fuels. The results are displayed in Figure 30.

FIGURE 30. WELL-TO-WHEELS NOx EMISSIONS AND REDUCTION VS. 1980 MODEL YEAR VEHICLE

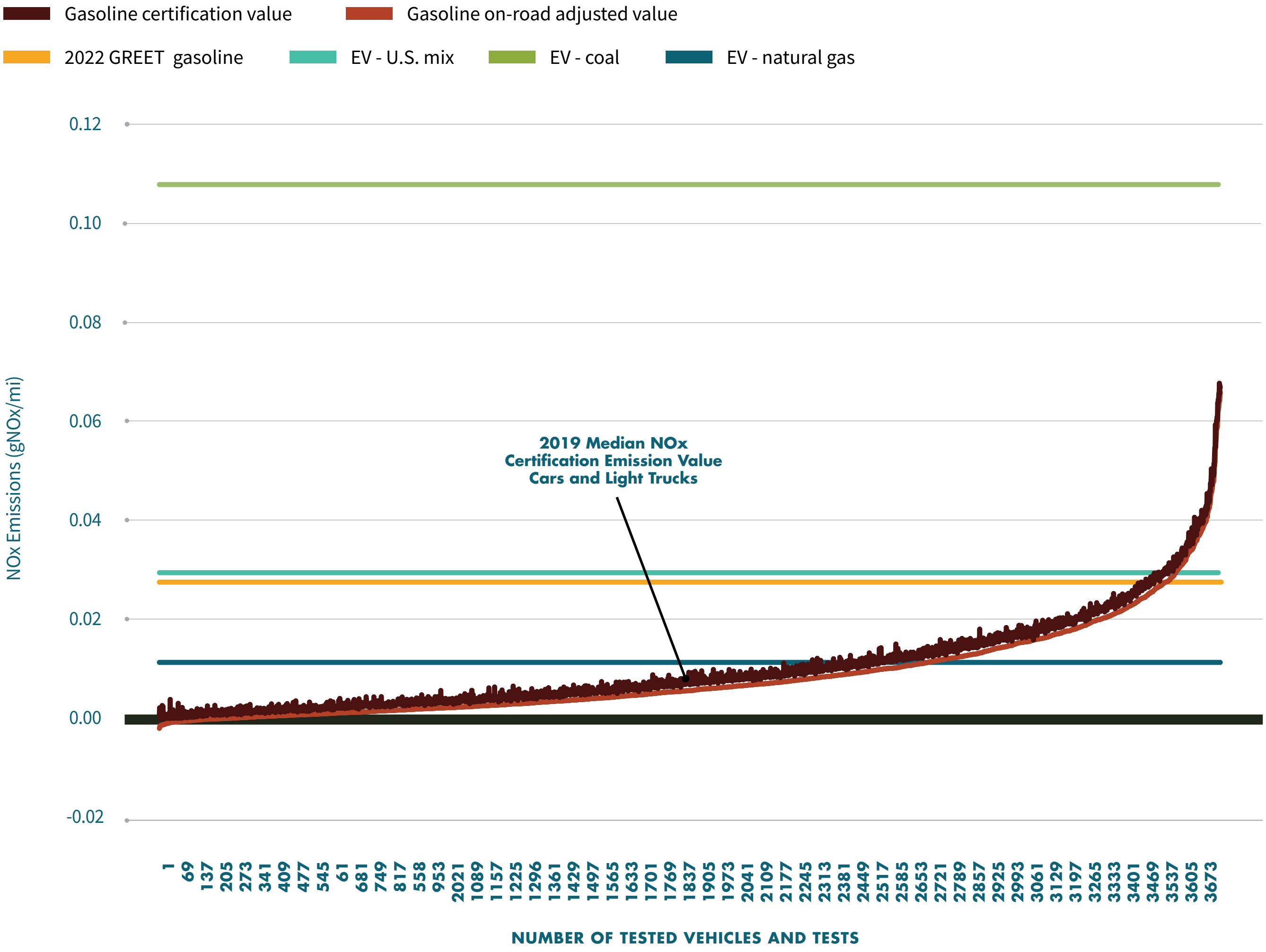


Source: Stillwater Associates analysis of 2020 & 2022 GREET, and EPA certification emission values for the 2019 model year light-duty vehicles. A 1980 model-year vehicle emits 1.0 g NOx/mi. We use 1980 model-year vehicles as the baseline because this exemplifies the period of time before regulatory agencies began tightening restrictions on NOx emissions.

Note: LDV data is EPA certification data, all others are GREET.

Comparing EPA NOx emission certification values for all 2019 vehicle models,[79] GREET results indicate that both gasoline-fueled ICEVs' and EVs' NOx emissions will continue to decrease in the future, and all vehicle technology options' NOx reductions from a 1980 NOx level are within 1% of each other. These results are displayed in Figure 31 below.

FIGURE 31. 2019 MODEL-YEAR CERTIFICATION EMISSION VALUES VS. EV AND GASOLINE VEHICLES



Source: Stillwater Associates analysis of EPA 2019 certification emission values and GREET 2022 & 2020

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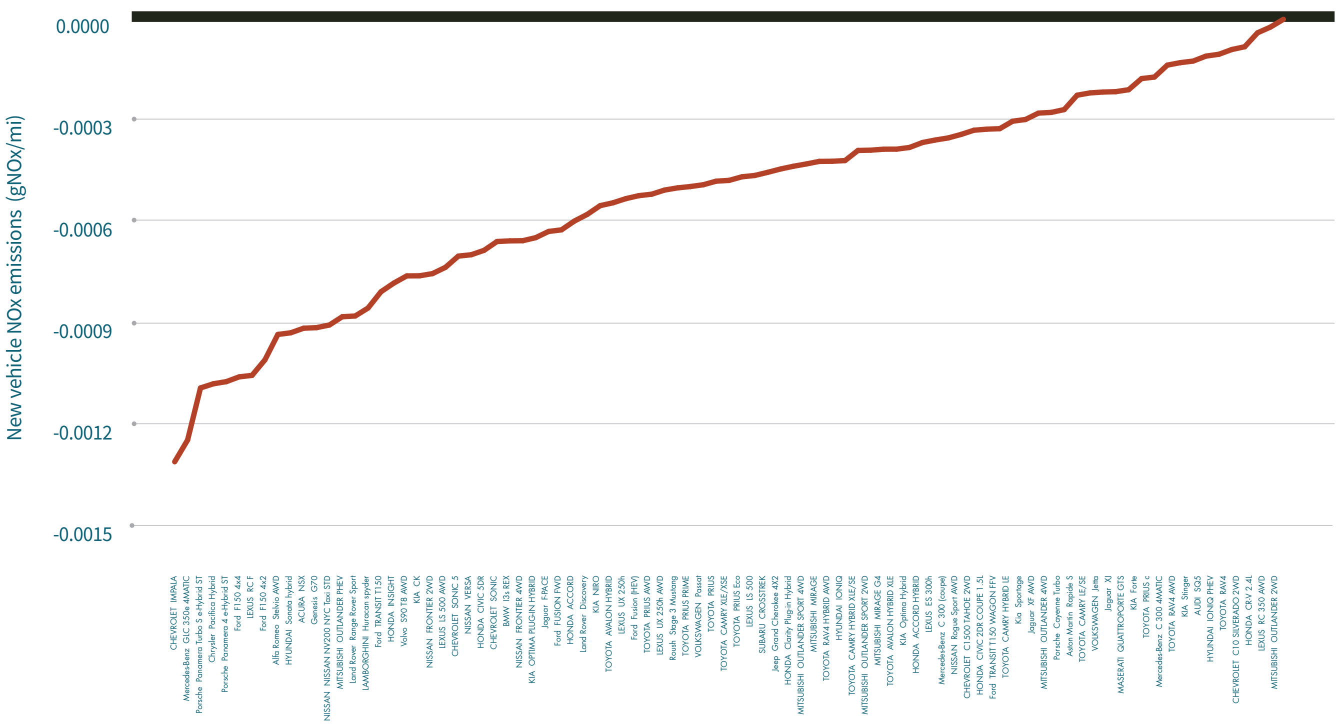
[79] All vehicle models are required to be certified to meet federal or California state exhaust emission standards for the useful life of 120,000-150,000 miles. All manufacturers are required to operate a vehicle for each engine type for the useful life of and test at intervals to verify that the vehicle exhaust meets emission standards.

FIGURE 32. LIST OF VEHICLES WITH POTENTIALLY NEGATIVE NOx EMISSIONS ON-ROAD



Source: Stillwater Associates analysis of U.S. EPA 2019 model year certification emission values, adjusted for the engine's consuming 79-81 m³ air per gallon of fuel consumed and driven on roadway with 526 µg NOx/m³.

Additionally, we adjusted the certification emission value from the laboratory to account for on-road NOx pollution. Figure 32 shows 87 models with net negative NOx emission levels when they are driven in on-road air pollution of 526 µg NOx/m³.[80] Most of these vehicles are net negative NOx emitters when driven on the highway drive cycle, which is also where there is higher NOx pollution due to older car and truck emissions. This real-world potential net negative NOx emission is not presently reflected in GREET or recognized by EPA. Current criteria pollutant analysis omitting this potential penalizes ICEV NOx emissions and overstates ZEV NOx benefits. It is also important to note that the list shows several high-volume sales models that significantly outnumber EV sales models.

One of the main reasons for concern about NOx emissions is the role NOx plays in contributing to ozone pollution. As discussed earlier, there are 25 cities that do not meet the ozone clean air standard. Unlike other pollutant reductions (e.g., PM and CO) that directly lead to clean air, NOx reductions do not. NOx both contributes to the formation of ozone and acts as a scavenger to reduce ozone levels, depending on the atmospheric conditions present.

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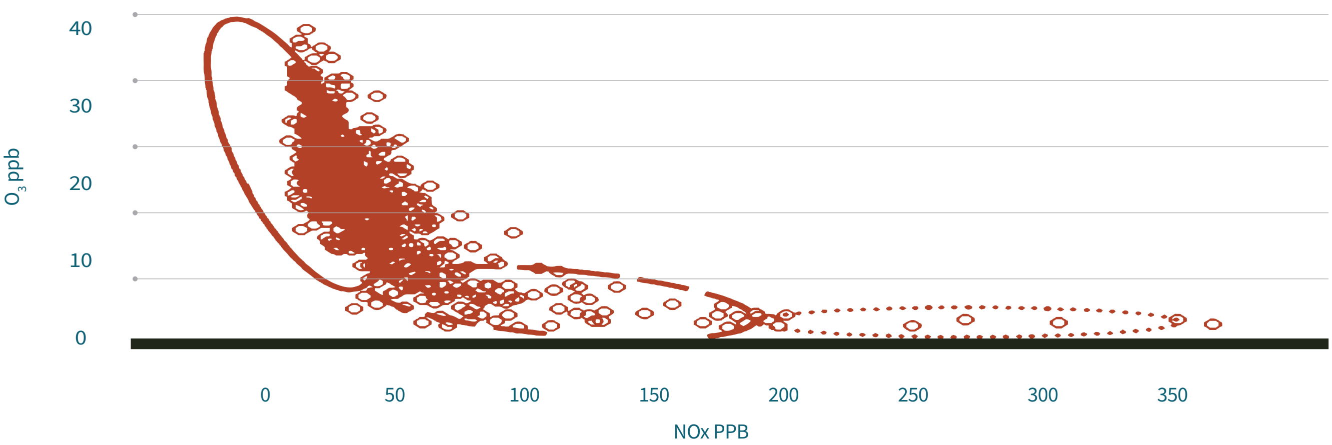
[80] Health Effects Institute / Concentrations of Air Toxics in Motor Vehicle–Dominated Environments, Table 9 NOx levels.

FIGURE 33. SCATTER PLOT OF OZONE AND NOx POLLUTANTS



Source: Non-parametric nature of ground-level ozone and its dependence on nitrogen oxides (NOx): A view point of vehicular emissions

This has been demonstrated in several weekday vesus weekend studies in California. Neither EPA MOVES3 nor CARB EMFAC fully represent this phenomenon. Today 85% of the nation's cities have clean air meeting federal ozone levels. These cities' ozone progress can be viewed as air basins where NOx reduction helps lower ozone pollution. The remaining 15% of cities have atmospheres that are stubbornly resisting mobile source NOx reductions, and some of these cities' ozone levels are increasing as more lower NOx vehicles are used. The remaining cities not meeting clean ozone standards tend to be hydrocarbon emission-limited (HC-limited) air basins. Only in HC-limited air basins does reducing HC emissions lower ozone.

Cities with air basins which are HC-limited have atmospheric conditions which create more ozone when NOx is reduced (e.g., when low-NOx vehicles are introduced). Los Angeles, Riverside, and San Diego, California, are locations where ozone levels are increasing as lower NOx vehicles are concurrently introduced. Vehicles with NOx emissions reduce peak ozone levels in HC-limited air basins. EVs' lower NOx tailpipe emissions and negative ICEV emission levels are not envisioned to generate any ozone reductions in these areas. Evidence from a United Kingdom report suggests they may actually increase ozone levels.[81] As shown in Figure 33, there is a negative correlation between NOx and ozone as NOx levels are reduced below 50 parts per billion.

With ozone formation and ozone scavenging conditions changing from hour to hour and seasonally in each unique geographic area with ozone standard exceedances, it is difficult to determine the relative benefits or disbenefits from reducing NOx emissions.

BOTTOM LINE: AFTER 35 YEARS OF REDUCED NOX VEHICLE EMISSIONS FOR OZONE ATTAINMENT, EVIDENCE SUGGESTS THAT LOW-NOX VEHICLES ARE PART OF THE SOLUTION BUT DO NOT CONTRIBUTE TO A REDUCTION IN OZONE IN ALL MARKETS BECAUSE OF PREVAILING REGIONAL ATMOSPHERIC CONDITIONS. CONSEQUENTLY, VEHICLES CANNOT BE EXPECTED TO REMEDIATE CONDITIONS THAT ARE BEYOND THEIR INFLUENCE.

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[81] S. Munir, H. Chen & K. Ropkins / Non-parametric nature of ground-level ozone and its dependence on nitrogen oxides (NOx): A viewpoint of vehicular emissions.

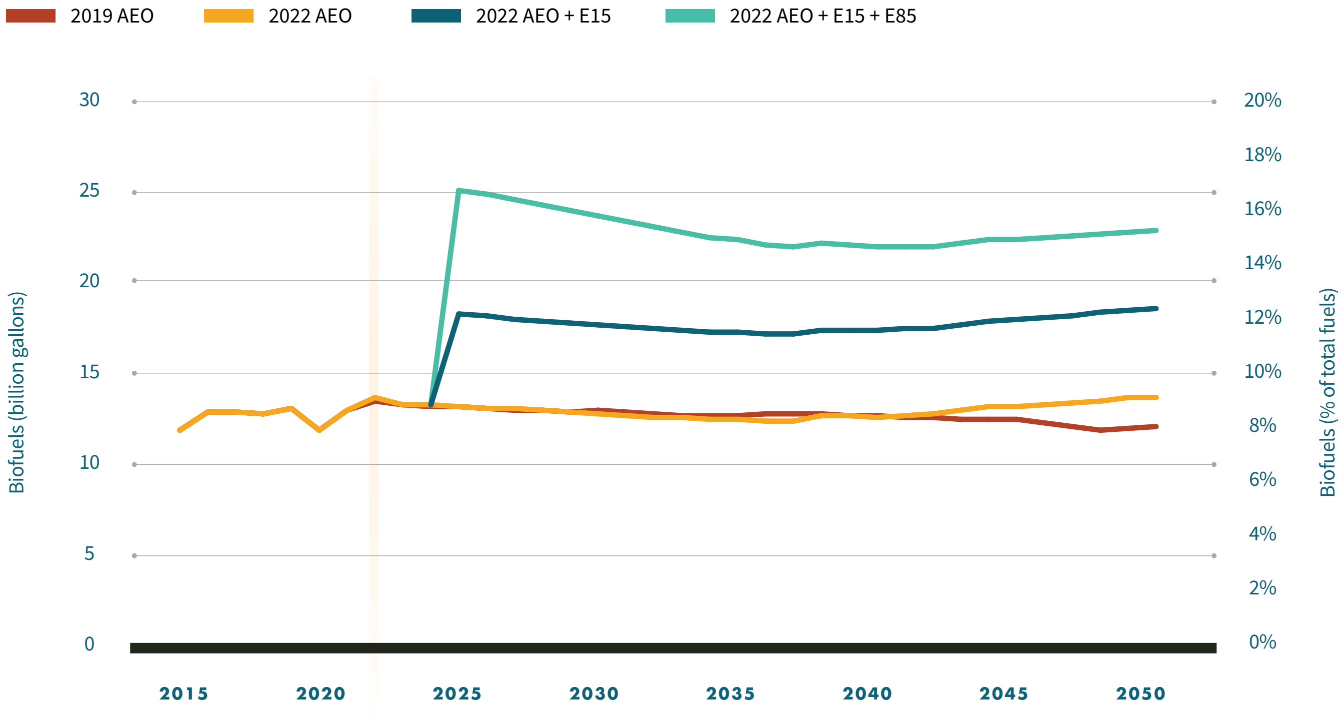
Biofuels

On-road Demand

In order to demonstrate how biofuels present the most promising near-term option for supplying the existing ICEV fleet with its required fuel supply, we must first examine the expected on-road demand for fuel.

For this analysis, we use two biofuel demand projections derived from two versions of EIA's Annual Energy Outlook (AEO) (2019 and 2022) as baseline scenarios to establish biofuels' potential and evaluate future fuel advancements. The key differences between the two demand projections stems from the assumed EV migrations which significantly impact biofuel sales after 2035. It is also noteworthy that neither AEO shows significant growth in BD or RD from 2021 through 2050. This limitation on estimated demand for diesel biofuels is based on assumptions concerning the available supply of feedstocks for these fuels. On the gasoline side, we examine additional ethanol demand assuming E15 blends beginning in 2025 for all gasoline vehicles and assuming the existing flexible-fueled vehicles (FFV) fleet refuels half of the time on E85 as opposed to refueling with E85 less than 2% of the time today. (Figure 34)

FIGURE 34. BASELINE TOTAL BIOFUEL DEMAND PROJECTIONS

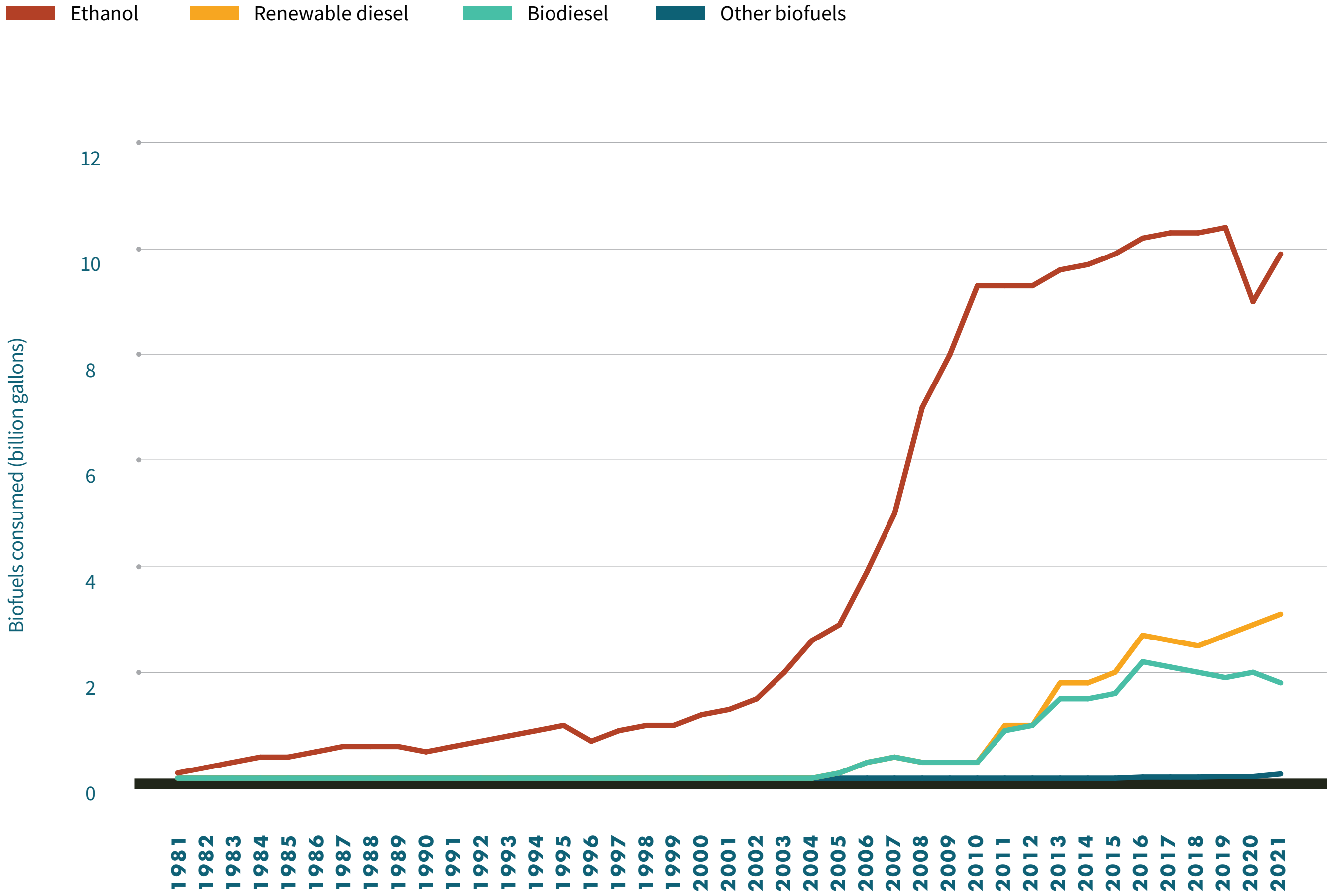


Source: EIA AEO 2019 and 2022 Reference Case projections

9.1 DEMAND FOR BIOFUELS

Biofuels have been routinely used in on-road vehicles in the U.S. for over 40 years. The three main fuels shown below are compatible with vehicles and infrastructure at the concentrations where they are commonly used. Various federal biofuel subsidies have incentivized biofuel production including the lapsed 2005 Volumetric Ethanol Excise Tax Credit ($0.45 per ethanol gallon)[82] and the BTC ($1.00 per gallon of biomass-based diesel, BBD), the latter of which has been in place for nearly 20 years and was recently extended through 2024 with the Inflation Reduction Act of 2022 (IRA).[83] The IRA also established a sustainable aviation fuel (SAF) tax credit of $1.25 to $1.75 per gallon (depending on carbon intensity) through 2025 and created the new clean fuels production credit (CFPC) with a base credit amount of $1.75 per gallon of SAF or $1.00 per gallon of other qualifying transportation fuels.[84] (Figure 35)

FIGURE 35. HISTORIC BIOFUELS USED IN ON-ROAD TRANSPORTATION



Source: Stillwater Associates analysis of EIA, Table 10.2c: Hybrid and Electric Vehicle Sales – Compiled by the Transportation Research Center at Argonne National Laboratory, 2022: Transportation Energy Data Book, Edition 40, table 6.2

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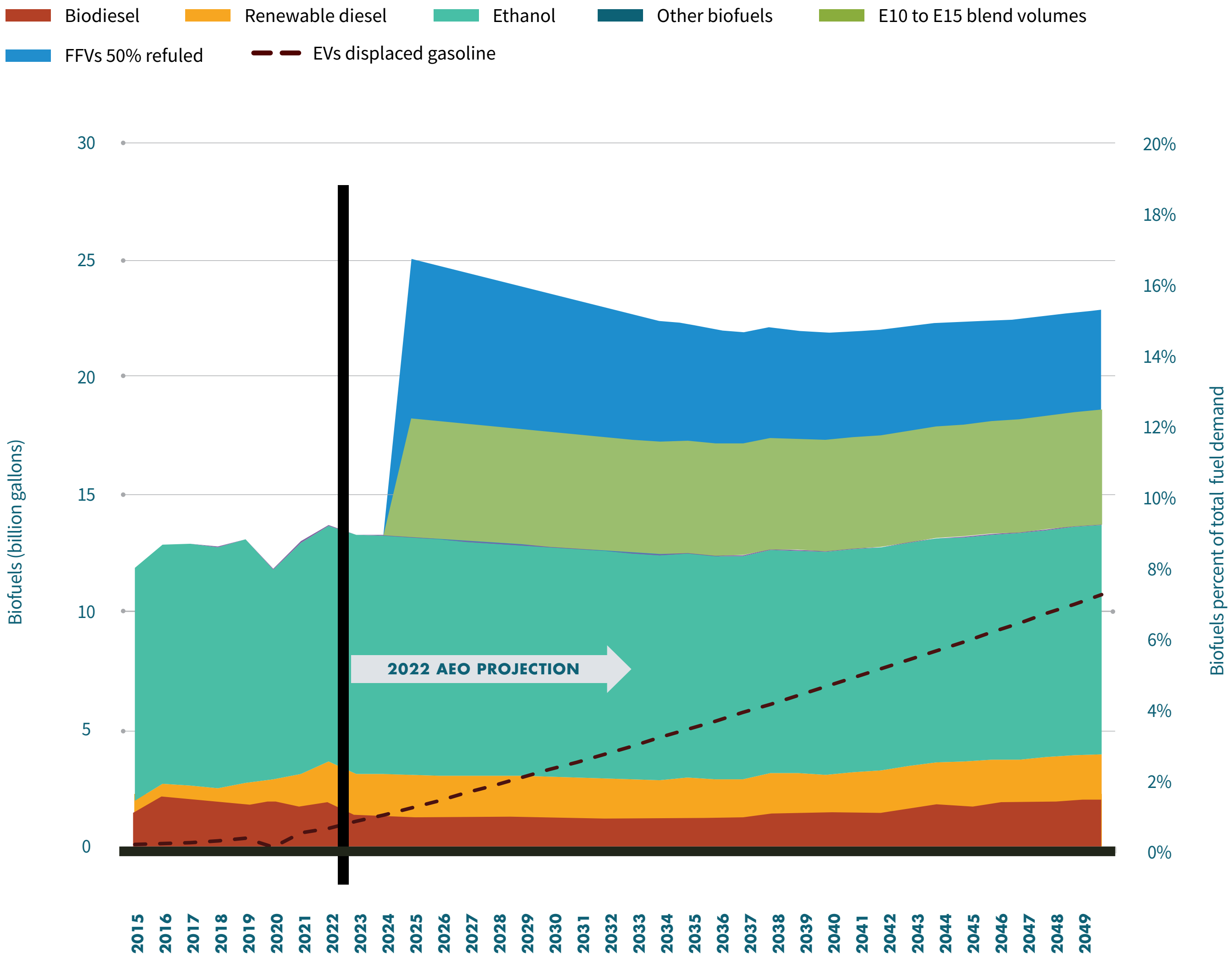
[82] Murse, Tom / Understanding the Ethanol Subsidy.

[83] 117th Congress / Public Law 117-169.

[84] The value of the CFPC varies with CI; a minimum CI of 50 kg CO_2e/mmBTU (47gCO_2e/MJ) is required to qualify for any credit and a CI of zero is required to qualify for the base credit. Eligibility for this credit is also subject to requirements for wages and apprenticeships.

According to EIA, use of conventional biofuels are projected to continue at the same proportions as today through 2050.[85] Ethanol has been used as a 10% blend in gasoline in nearly all U.S. gasoline since 2010, RD and BD have grown from 1% of diesel sales in 2010 to 5% by 2020. In 2021, biofuels displaced nearly 13 billion gallons of gasoline and diesel. With regulatory action, by 2025 ethanol could be expanded to predominant use of 15% blends using existing plants, feedstocks, and gasoline vehicles. Additional expanded ethanol use is possible if existing FFV owners refueled their vehicles 50% of the time on E85 as opposed to historically lower refueling rates.[86] Other biofuels such as renewable natural gas (RNG) are a negligible but growing fuel option. For context, the AEO 2022 projects EVs displacing greater than 5% of the total gasoline and diesel pool by 2050.

FIGURE 36. LOW EV CASE TRAJECTORY OF ON-ROAD DEMAND FOR BIOFUELS



Source: EIA AEO 2022 Reference Case and Stillwater Associates analysis for E15 blends

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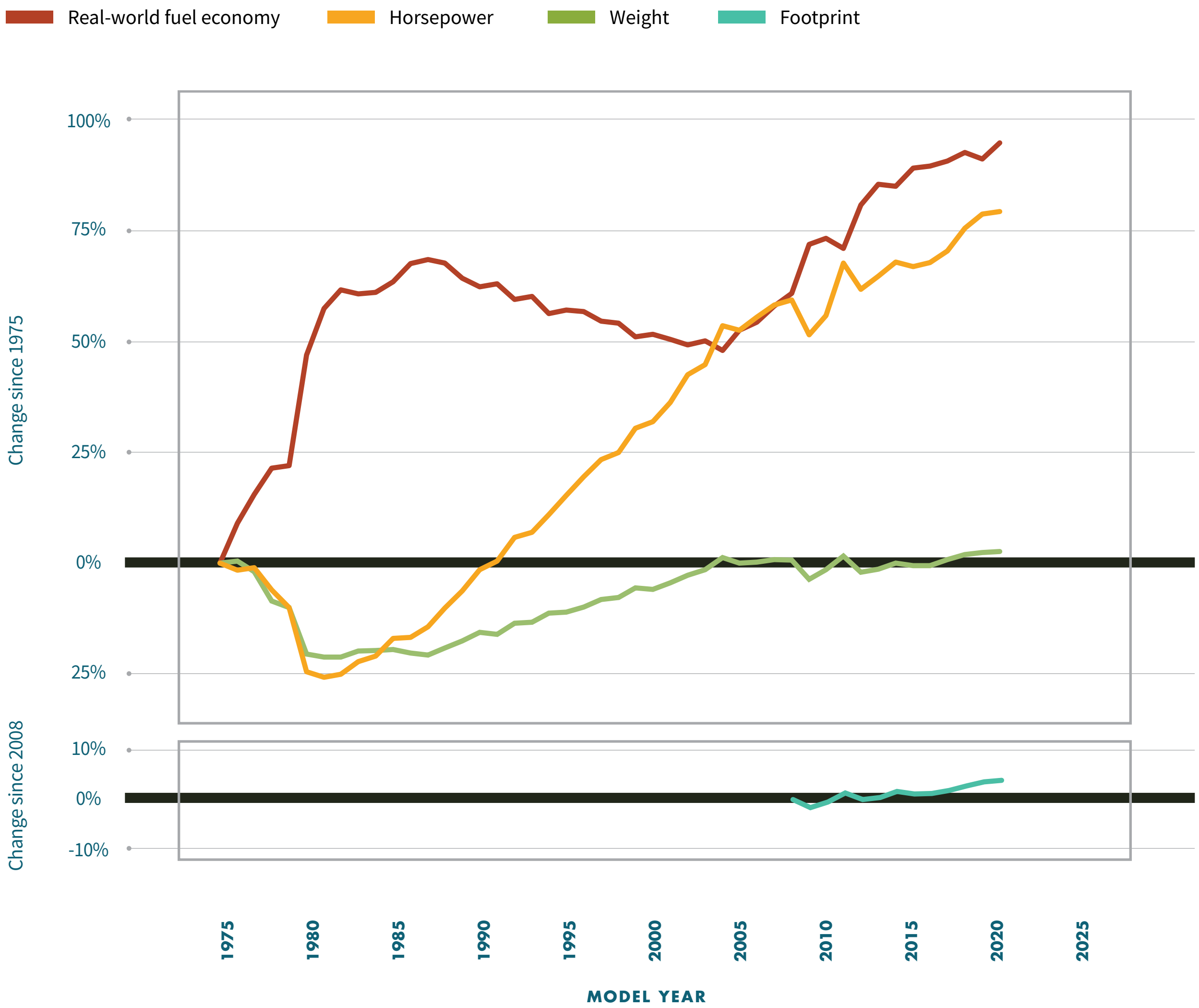
[85] EIA / AEO 2022 Reference Case.

[86] AEO 2022 Reference Case implies FFVs are refueled less than 2% of the time on E85.

9.2 ADVANCEMENTS IN FUELS AND LIGHT-DUTY VEHICLE TECHNOLOGIES

As shown in Figure 37, over the past 50 years, the U.S. fleet of light-duty vehicles (cars, SUVs, vans, and pickup trucks) has seen substantial improvements in engine efficiency; manufacturers have used these improvements to offset increasing vehicle weight and increase available horsepower as well as improve fuel economy. The ebb and flow of vehicle fuel economy over this period reflects consumer preferences during periods of lower or higher gasoline prices as well as regulatory requirements for average fleet fuel economy.[87]

FIGURE 37. RELATIVE CHANGE IN FUEL ECONOMY, WEIGHT, HORSEPOWER, AND FOOTPRINT[87]



Source: The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975 (EPA-420-R-21-003, November 2021)

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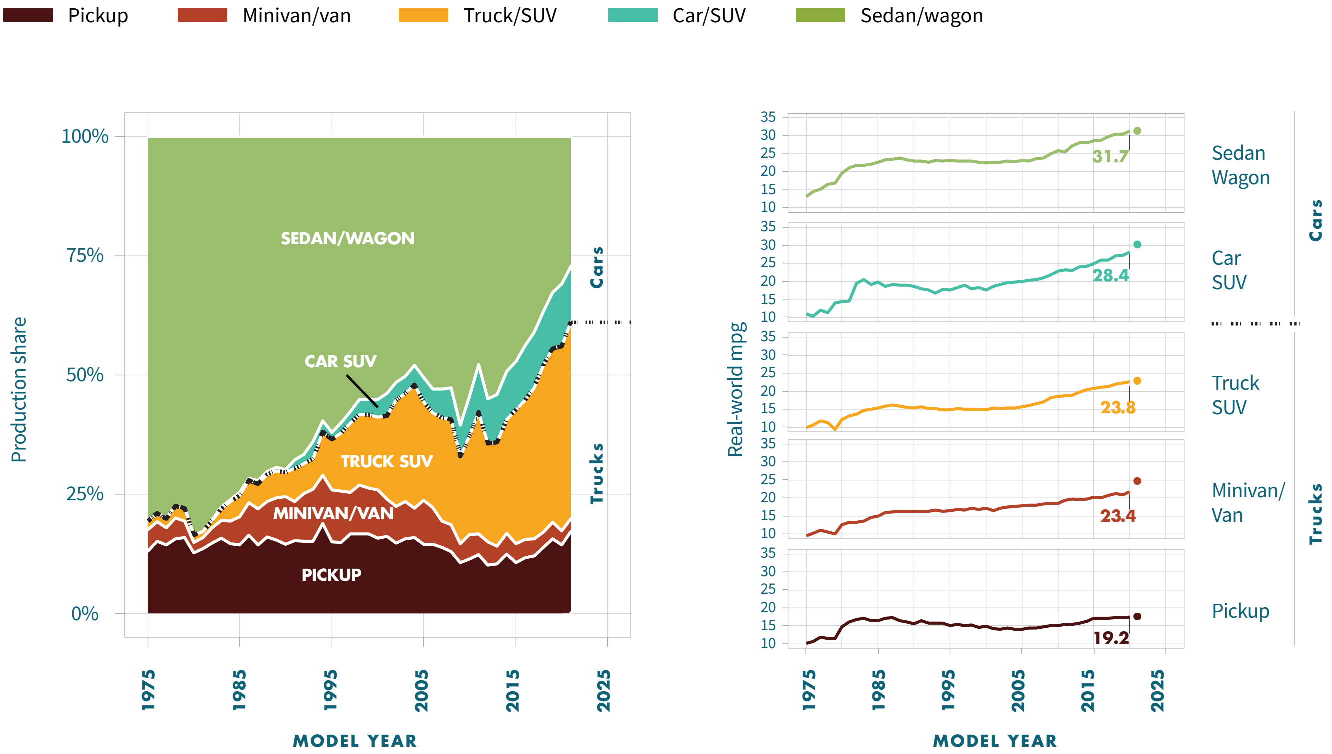
[87] Vehicle footprint is the basis for the current CO_2 emissions and fuel economy standards. Footprint is the product of wheelbase times average track width (the area defined by where the centers of the tires touch the ground).

As average fuel economy has improved across the light-duty fleet, however, consumer preference has shifted toward the larger vehicles in this category—trucks, SUVs, and vans, as shown in Figure 38. These vehicle types have lower fuel economy than cars although all show improving fuel economy. Importantly, the larger light-duty vehicles are a good fit for FFVs fueled with E85 or diesel engines fueled with RD as opposed to E10 gasoline.

FIGURE 38. PRODUCTION SHARE AND ESTIMATED REAL-WORLD FUEL ECONOMY

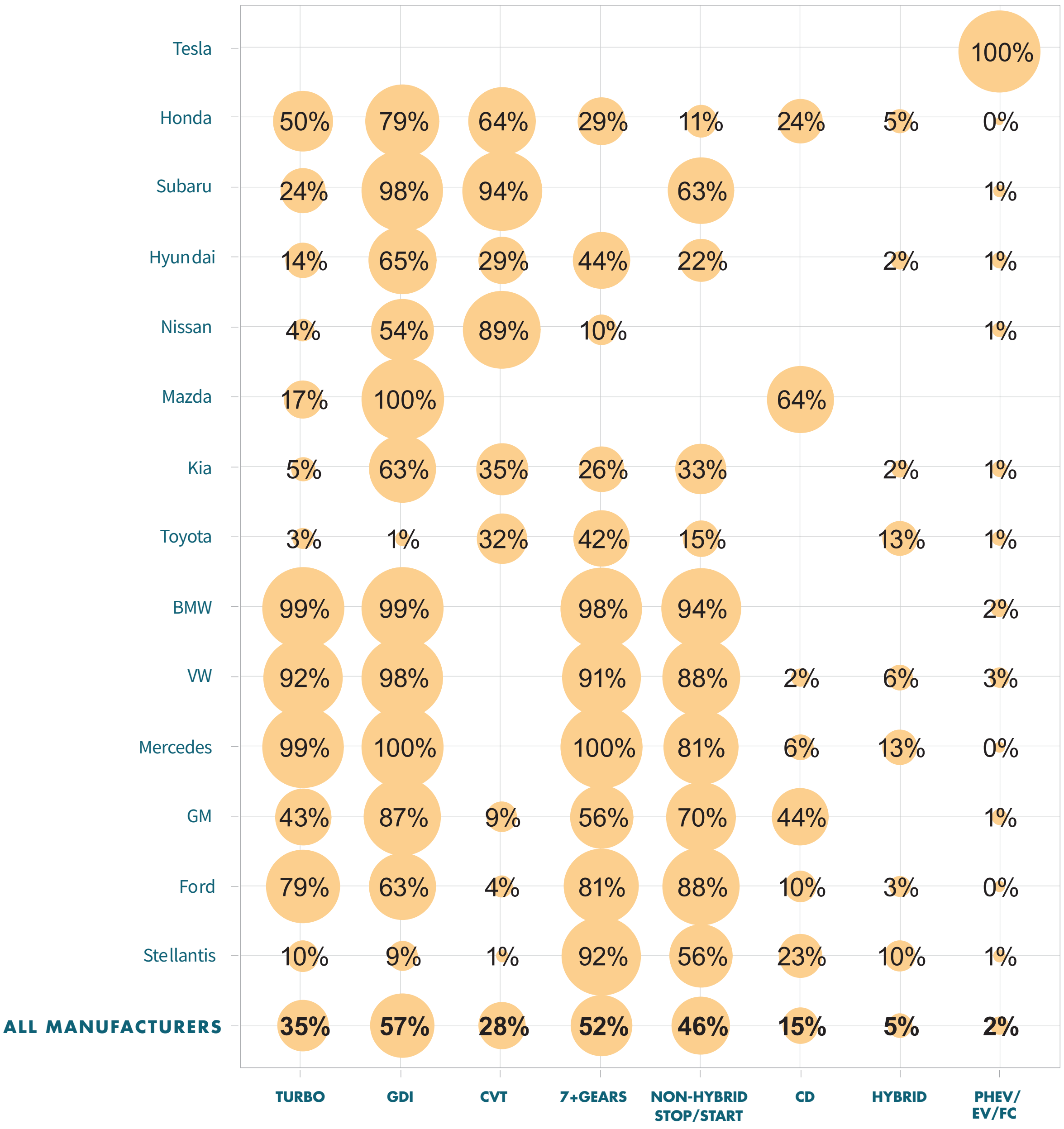


Source: The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975 (EPA-420-R-21-003, November 2021)

9.3 OEM PLANS AND INTENTIONS

Automotive engineers and designers are constantly creating and evaluating new technology and deciding how, or if, it should be applied to their vehicles. Vehicle manufacturers' strategies to develop and adopt new technologies are unique and vary significantly. Each manufacturer is choosing technologies that best meet the design requirements of their vehicles, and in many cases, that technology is changing quickly. The technologies in Figure 39 are all being adopted by manufacturers to increase fuel economy and reduce CO_2 emissions. Each of the 14 largest manufacturers have adopted several of these technologies into their vehicles, with many manufacturers achieving high penetrations of several technologies.

FIGURE 39. MANUFACTURER USE OF EMERGING TECHNOLOGIES FOR MODEL YEAR 2020



	TURBO	GDI	CVT	7+GEARS	NON-HYBRID STOP/START	CD	HYBRID	PHEV/ EV/FC
Tesla								100%
Honda	50%	79%	64%	29%	11%	24%	5%	0%
Subaru	24%	98%	94%		63%			1%
Hyundai	14%	65%	29%	44%	22%		2%	1%
Nissan	4%	54%	89%	10%				1%
Mazda	17%	100%				64%		
Kia	5%	63%	35%	26%	33%		2%	1%
Toyota	3%	1%	32%	42%	15%		13%	1%
BMW	99%	99%		98%	94%			2%
VW	92%	98%		91%	88%	2%	6%	3%
Mercedes	99%	100%		100%	81%	6%	13%	0%
GM	43%	87%	9%	56%	70%	44%		1%
Ford	79%	63%	4%	81%	88%	10%	3%	0%
Stellantis	10%	9%	1%	92%	56%	23%	10%	1%
ALL MANUFACTURERS	**35%**	**57%**	**28%**	**52%**	**46%**	**15%**	**5%**	**2%**

Source: The 2021 EPA Automotive Trends Report: Greenhouse Gas Emissions, Fuel Economy, and Technology since 1975 (EPA-420-R-21-003, November 2021)

We briefly discuss the benefits of each of these emerging technologies:

- **Turbo:** Turbo chargers provide increased power and performance and improved fuel economy when used in a smaller engine.
- **Gasoline Direct Injection (GDI):** The most frequently used "new" technology is GDI—a more advanced version of fuel injection systems where fuel is injected directly into the combustion chamber instead of the intake port. Direct injection improves combustion efficiency, increases fuel economy, and generally lowers emissions. This technology was first used in 1996 and by 2021 has reached 57% of all new vehicle sales.
- **7+ Gears and Continuously Variable Transmission (CVT):** Additional transmission gears (shown as 7+ Gears in the figure) and CVT are combined in 80% of all new vehicles. These are relatively new technologies used to improve fuel economy and vehicle performance. More gears enable engines to spin slower, using less fuel, and to exploit GDI fuel injection low-engine-speed advantages.
- **Non-hybrid Stop/Start:** These systems are designed to conserve fuel by reducing idle time when a vehicle is stopped. In city driving, where traffic lights are frequent, the stop/start system will shut down the engine as the vehicle comes to a stop and will automatically restart the engine when the brake pedal is released.
- **Cylinder Deactivation (CD):** This technology refers to deactivating some of the cylinders in the engine when the car runs on light loads. Large engines operating at light loads are very inefficient. Disabling some cylinders in these circumstances greatly improves fuel economy, while retaining the larger engine capabilities for more appropriate situations. This technology is especially used in larger engine light-duty trucks and SUVs, where the greatest fuel economy gains are made.
- **Hybrids, Plug-in Hybrids (PHEVs), Electric Vehicles (EVs), and Hydrogen Fuel Cell Electric Vehicles (FCEVs):** These technologies offer greater fuel economy improvements than the above listed options; each option has successively higher fuel economy. Conventional hybrids were introduced in 2000, and by 2011 PHEVs, EVs, and FCEVs were introduced. Most hybrids, PHEVs, and EVs utilize regenerative braking to recapture energy that otherwise would have been lost as heat, thus further improving vehicle efficiency. This "spectrum of electrification" creates a wide range of technology implementation strategies in modern vehicles and offers numerous pathways to improve vehicle efficiency, emissions, and performance.

THE BIG PICTURE: Vehicles with engines that operate exclusively on gasoline (including hybrids, but not plug-in hybrids which also use electricity) have historically made up at least 95% of the light-duty vehicle fleet. PHEVs, EVs, and FCEVs have added to the increasing array of technology available in the automotive marketplace and have been capturing a small but growing portion of the market. These vehicles captured 2.2% of the market in model year 2020,[88] and according to Wards Intelligence, EV, PHEV, and FCEV combined accounted for 6.7% of light-duty vehicle sales by 2022. Gasoline-fueled vehicles remain a promising area for emissions reductions through biofuel utilization.

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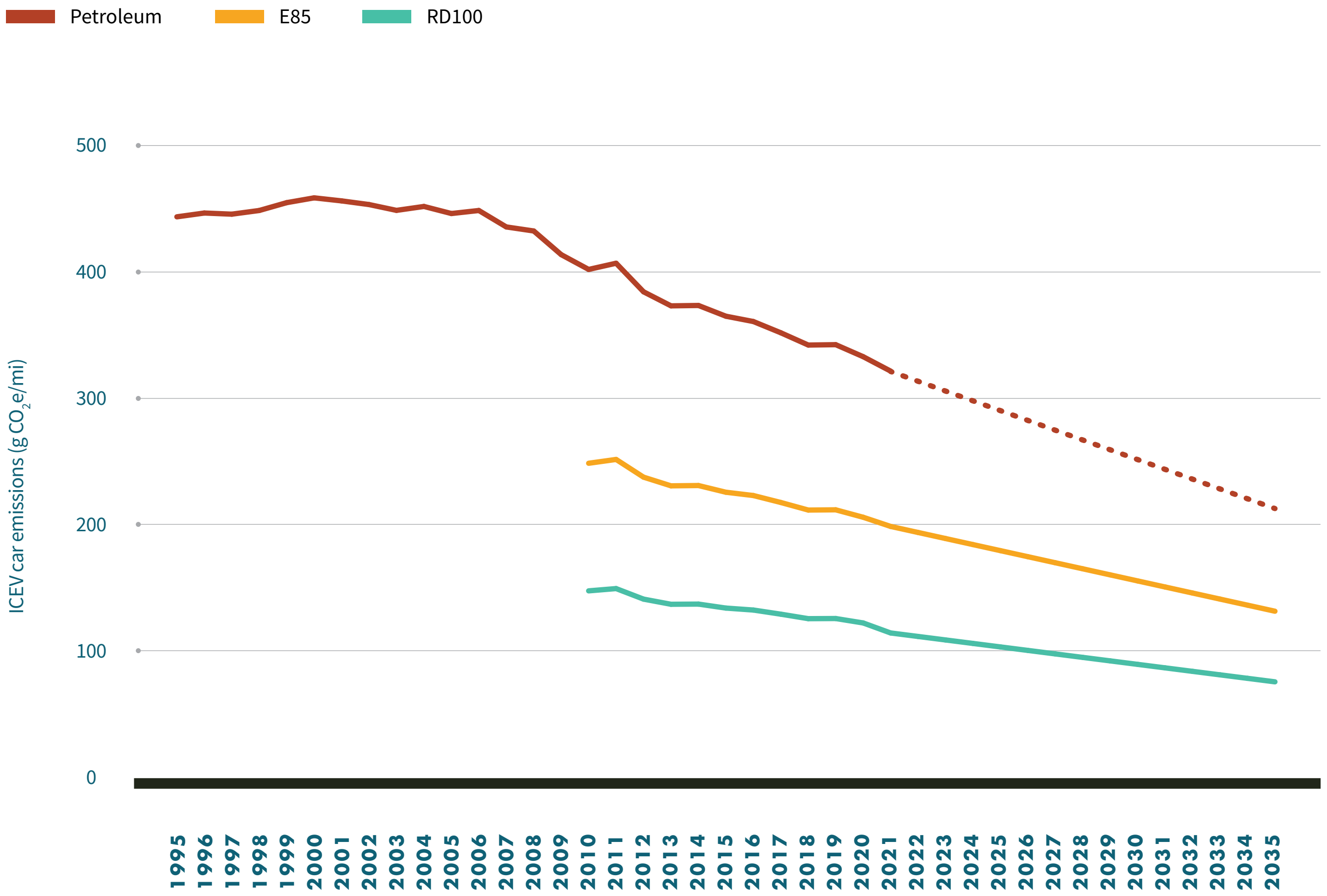
[88] EPA / The EPA Automotive Trends Report 2021.

9.4 IMPACT OF VEHICLE EFFICIENCY ON LIQUID FUEL DEMAND

Using the technologies listed in the section above has improved ICEVs' fuel economy and reduced on-road CO_2 emissions. Figure 40 shows the historical trend of declining CO_2 average gasoline vehicle emissions due to higher fuel economy vehicles. Replacing conventional gasoline with E85 or replacing petroleum diesel with RD or BD blends up to B20 significantly improves GHG emissions of the ICEV fleet. Biofuels shown in Figure 40 are displayed using a constant CI value over the timeframe to illustrate the declining CO_2 emissions from vehicle fuel efficiency and advancing ICEV technology.[89]

FIGURE 40. ICEV GHG TREND DUE TO FUEL ECONOMY IMPROVEMENTS AND BIOFUELS



Source: Stillwater Associates analysis of Power Plant Emission Trends | US EPA

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[89] The chart uses GREET 2022 CI values of 64 gCO_2e/MJ for E85, 34 gCO_2e/MJ for RD and 91 gCO_2e/MJ for gasoline.

9.5 OPPORTUNITIES AND CHALLENGES TO EXPANDED USE OF LOWER CARBON FUELS IN ICEVs

There are three primary opportunities to immediately lower carbon emissions of ICEVs using existing biofuels: 1) transition from E10 to E15, 2) expand use of E85, and 3) expand production and use of BD and RD. We discuss these three pieces of "low-hanging fruit" in this section. A deeper dive into all potential opportunities to reduce GHG emissions from ICEVs and their related implementation challenges are discussed in the Market Transition Requirements section of this report.

9.5.1 TRANSITION FROM E10 TO E15

One comparatively easy way to incorporate more biofuels into the existing fleet is increasing the amount of ethanol blended into gasoline from 10% to 15%. Moving the U.S. from E10 to E15 ethanol gasoline blends would raise biofuel use while reducing CO_2 emissions.

According to the Alternative Fuels Data Center, the transition to E15 has already begun. E15 is available in 30 states at more than 2,400 stations.[90] Stations are not required to sell E15, but some have started offering it due to state and federal incentives for upgrading equipment and better profit margins when compared with regular gasoline. Many hurdles for the movement to E15 have already been overcome. EPA approved E15 for use in light-duty conventional vehicles of model year 2001 and newer. On January 15, 2021, EPA proposed changes to E15 fuel dispenser labeling requirements— a move to expand E15 use nationwide. Furthermore, proposals currently in Congress to extend the favorable Reid vapor pressure (RVP) treatment provided to E10 to E15, if adopted, would also facilitate growth in E15. Logistically, underground storage tank manufacturers approved their tanks for blends up to E100 in 1990, so the E15 in-ground infrastructure is mostly already in place.[91] Existing retail stations can add E15 pumps for $4,400—a relatively low-cost modification.[92] For new construction sites, these higher ethanol dispensing retail pumps are available for no additional cost by at least one pump supplier. Some consumers would seek E15 blends for the higher octane—88 AKI (AntiKnock Index) vs 87 AKI for E10. Other consumers may be compelled to buy E15 for its frequently lower price; that lower price, however, is also due to the reduced energy content of E15, resulting in lower fuel economy, equivalent to a discount of $0.05-$0.07 per gallon.[93]

9.5.2 EXPANDED E85 USAGE

FFVs are designed to operate on gasoline, E85, or any mixture of the two fuels. This is existing technology but its availability in new vehicles is fading due to expired federal fuel economy credits. Figure 41 shows the number of FFV models sold in response to fuel economy regulations providing incentives for the sale of FFVs. As can be seen, when the federal program that provided fuel economy credits phased out by 2016,[94] vehicle manufacturers generally discontinued FFV production. Reauthorizing FFV fuel economy credits could potentially restart this technology option. There were over 20 million FFVs in the U.S. in 2021.[95] This population is 10 times larger than all the other alternative-fueled vehicles combined. This FFV population represents a large, missed opportunity to lower the CO_2 emissions from the ICEV fleet.

The market challenge for E85 fuel was that, on

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[90] Alternative Fuels Data Center / E15.

[91] National Renewable Energy Laboratory / E15 and Infrastructure.

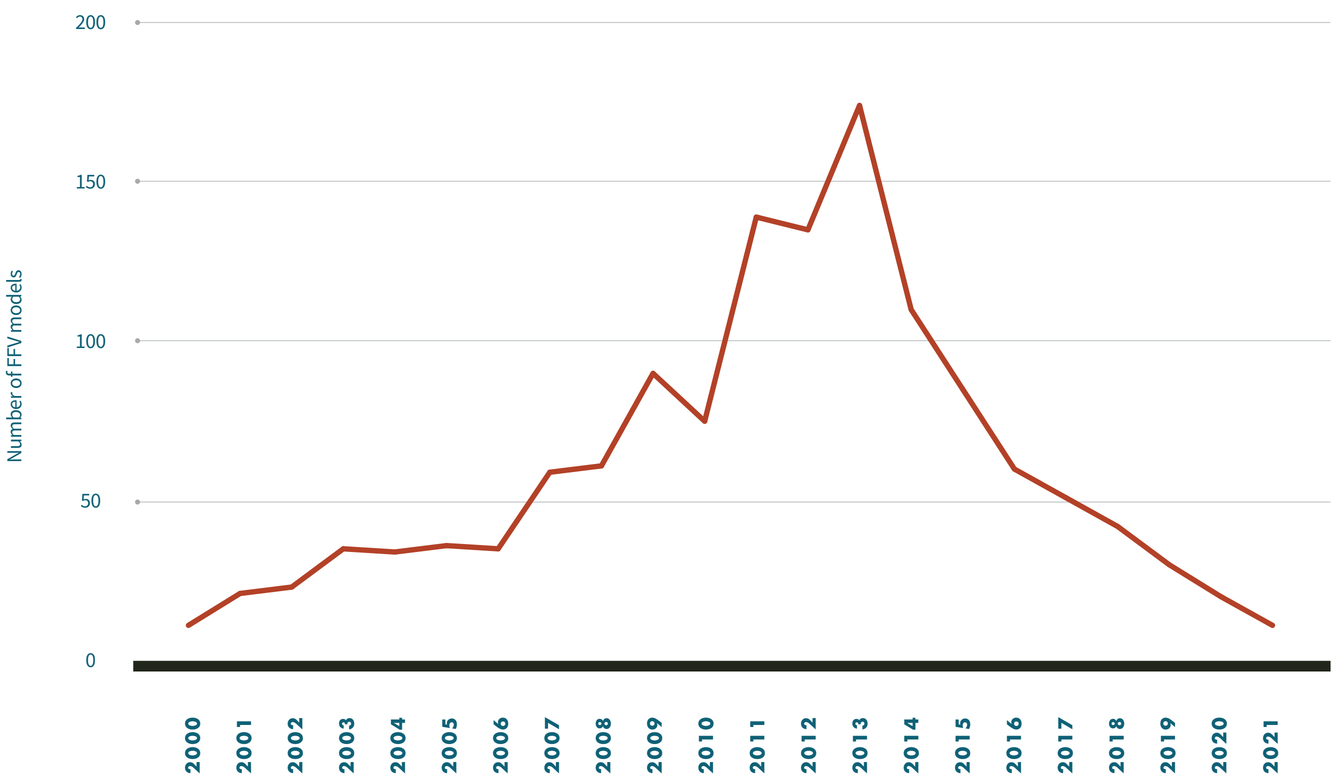
[92] Environmental and Energy Study Institute: Fact Sheet | High Octane Fuels: Challenges & Opportunities.

[93] Per GREET 2022, E15 has 1.73% less energy than E10. This lower energy content directly reduces fuel economy by the same amount. Assumed retail gasoline prices of $3 and $4 per gallon would raise consumer cost by 5 or 7 cents per gallon, respectively.

[94] The Corporate Average Fuel Economy (CAFE) program did not phase out entirely, but its credits were significantly reduced starting with the 2016 model year when EPA shifted to assuming FFVs were typically operated on conventional gasoline rather than E85.

[95] EIA / AEO 2022, Table 39.

FIGURE 41. NUMBER OF FFV MODELS AVAILABLE



Source: Stillwater Analysis of U.S. EPA Fuel Economy Guides 2000-2021

average, FFVs used E85 fuel less than 2% of the time.[96] Many customers may not have been aware that they had purchased an FFV during the period when federal fuel economy credits existed (shown in Figure 41) because nearly all models produced by some major manufacturers were FFVs, and the vehicle technology was mostly "invisible" to the buyer.[97] Thus, some customers who purchased vehicles in this timeframe are likely unaware they were capable of operating on ethanol blends up to 85%. Using E85 lowers fuel economy 26% but still results in lower carbon emissions per mile driven. The E85 retail market rarely reduced the E85 fuel price sufficiently to account for E85's lower energy density and thus its 26% fuel economy loss. For example, $3.50 per gallon gasoline market requires a $1.00 per gallon ethanol discount for the E85 retail price to match the fuel economy loss. However, E10 is sold at the same price as gasoline; thus, the ethanol industry would have to accept a $1.00 per gallon discount for the E85 market to grow. One remedy would be to require retail gas stations to display the gasoline equivalent prices along with E85 retail prices, while the pump would measure the gasoline gallon equivalent (GGE) dispensed (this would be similar to the way that CNG and LNG are priced and dispensed at retail). Federal and state biofuel incentives have significantly increased and are poised to continue encouraging growth in future biofuel volumes.

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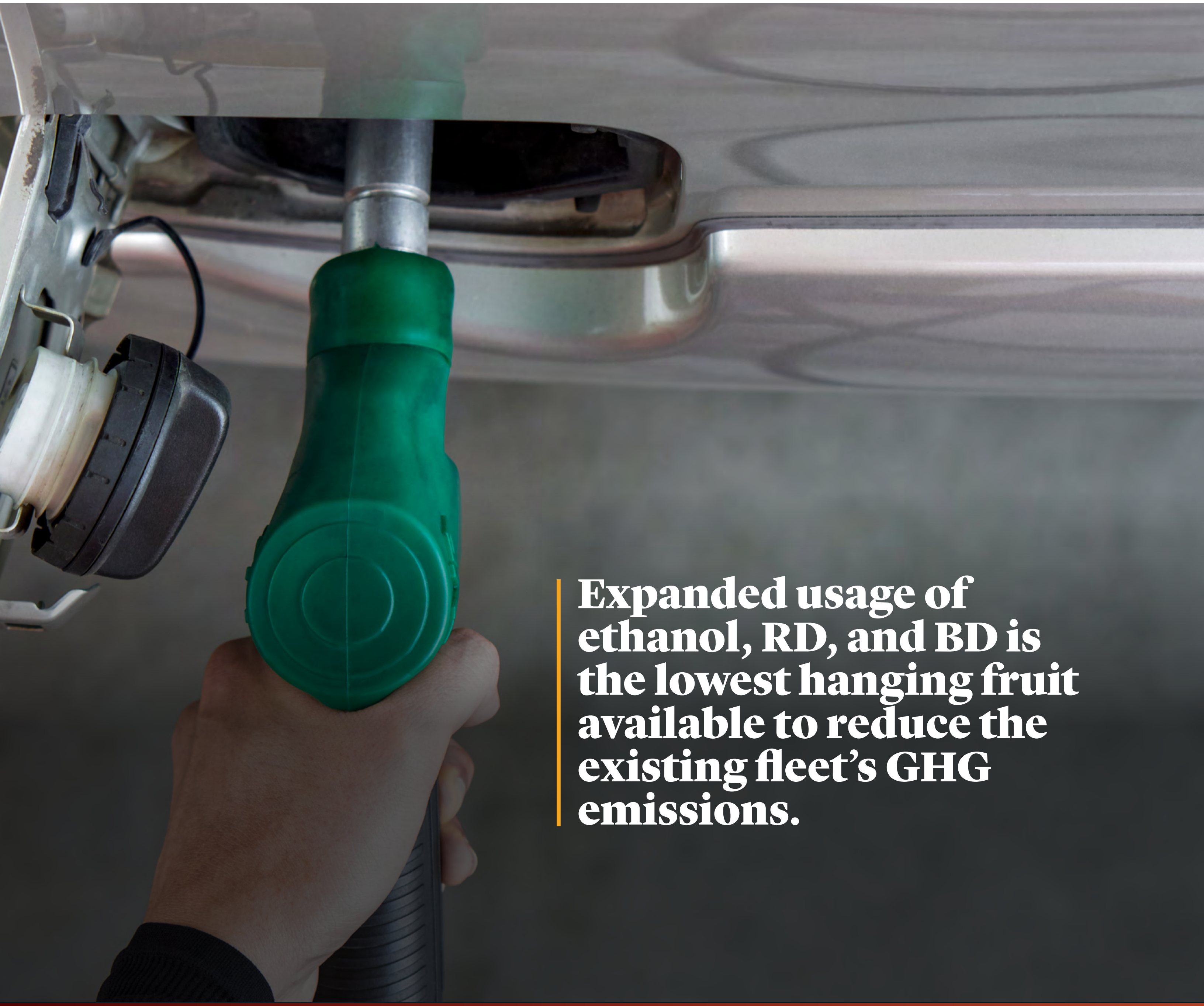
[96] AEO 2022 Reference Case suggests FFVs are refueled less than 2% of the time on E85.

[97] All FFVs did have unique, yellow-colored gas caps, a yellow ring around capless fuel fillers, or a flex fuel label on the fuel door. Labels on the outside of the car often read "E85," "FFV," or "Flex Fuel," but significant customer usage of the flex fuel capability of these FFVs did not materialize.

9.5.3 EXPANDED PRODUCTION AND USE OF RD, BD, AND E85

Expanding the production of RD, BD, and E85 and their retail availability has significant GHG reduction potential because of the large population of vehicles on the road today and for the near future that can use these fuels. RD and BD are growing renewable fuels; however, their use is limited to diesel vehicles and feedstock supply. Unlike E85 gasoline fuel replacements, RD is a unique fully drop-in petroleum diesel replacement, and its use does not suffer with a fuel economy loss compared to petroleum diesel—this is a significant consumer competitive advantage. BD is a limited blend volume fuel that is compatible with RD and petroleum fuels and has a limited (but significant) role to play in expanding biofuel options. Low-BD blends have energy similar to petroleum diesels, but B20 blends have 1.4% lower energy per gallon, equivalent to a five-cent per gallon discount. FFVs are already on the road, and expanded availability and usage of E85 fuel that is competitive with gasoline prices could reduce GHG emissions by a cumulative total of nearly 13,000 MT from 2025 to 2035.



Expanded usage of ethanol, RD, and BD is the lowest hanging fruit available to reduce the existing fleet's GHG emissions.

Feedstock Options

The production of biofuels in the form of ethanol, RD, and BD has expanded rapidly in the U.S., making it the largest producer of ethanol in the world and the second largest producer of BD after Indonesia. RD and BD are made from the same edible oils and animal fats, but different manufacturing methods result in distinct end-product characteristics such that RD is a drop-in fuel that can be blended with petroleum diesel without any constraints. Both RD and BD are together referred to as biomass-based diesel (BBD).

The U.S. still imports some ethanol, primarily from Brazil, but since 2010 the country has been a net exporter of ethanol. The U.S. transitioned from being a net exporter to a net importer of biodiesel after 2013, due to a more than proportionate increase in domestic demand.[98] Production of RD has grown rapidly in the U.S.; in 2021 the U.S. was responsible for about 31% of global production of RD and was second to the EU, which was responsible for about 45% of global production of RD.[99]

Biofuels in the U.S. are currently largely produced from food/feed crops, specifically corn and soybeans, and are using a substantial share of the production of these two crops. Renewable natural gas (RNG) used in natural gas vehicles (NGV) is produced from landfills, wastewater, food, and animal wastes. Municipal solid waste (MSW), while a promising source of biomass material, is largely

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[98] U.S. Department of Agriculture (USDA) Environmental Research Service (ERS) / U.S. Bioenergy Statistics.

[99] EIA / Biofuels Explained.

landfilled or recycled. In 2018, 12% was burned for energy recovery.[100] A small amount of landfill gas is collected and accounted for 0.2% of total U.S. utility-scale electricity generation in 2021.[101] Recently, Fulcrum Bioenergy has started the first commercial-scale plant to convert landfill waste to low-carbon synthetic crude oil. Additionally, microalgae, seaweeds, and duckweed are also potential feedstocks for producing biofuels but there has been no commercial production yet.[102]

Policy support has been a major impetus for biofuel production in the U.S., and the design of federal and state policies has significantly influenced the volume and mix of first-generation biofuels, corn ethanol, and BBD production. Although policies have sought to promote production of second-generation biofuels from nonfood, cellulosic feedstocks, supply of these biofuels has not emerged at the scale and cost needed due to technological and other market barriers. The outlook for biofuels is dependent on policy developments and design, the extent of electrification of vehicles, and technological breakthroughs in the production of biofuels from nonfood crops.

In the subsections that follow, we discuss:

1. **The policy and market drivers that have influenced the supply and consumption of biofuels to date and ways in which future policies and market conditions can affect the mix and level of consumption of biofuels.**
2. **Trends in first-generation biofuel production and feedstock production historically and their implications for land use changes and crop prices.**
3. **Projections for biofuel production and their feedstocks over the coming decades as well as their implications for land use change and crop prices.**
4. **Emerging feedstocks for biofuel production and factors affecting their large-scale production.**
5. **Risks and uncertainties associated with cellulosic biofuel production and its implication for feedstock supply.**

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100 EIA / Biomass Explained.

101 EIA / Biomass Explained.

102 Hochman, Gal and R. R. Palatnik / The Economics of Aquatic Plants: The Case of Algae and Duckweed.

10.1 POLICY DRIVERS FOR THE VOLUME AND MIX OF BIOFUELS

A major impetus for the growth in biofuel production has been the Renewable Fuel Standard (RFS), which requires blenders to incorporate a specified percentage of renewable fuel with gasoline and diesel each year. The RFS was established by the Energy Policy Act of 2005 and expanded in 2007 by the Energy Independence and Security Act (EISA). It began with requiring 4 billion gallons of renewable fuel in 2006 and set a goal of blending 36 billion gallons of biofuel in 2022. The RFS specified volumetric targets for different types of biofuels that differed in the feedstocks used to produce them and the threshold level of GHG intensity savings they were required to have relative to the conventional gasoline or diesel being replaced. The categories consisted of conventional biofuel (primarily corn ethanol) that was produced from cornstarch and was required to be at least 20% less carbon intensive than gasoline, advanced biofuels (such as sugarcane ethanol) and biomass-based diesel that were expected to be at least 50% less carbon intensive than gasoline, and cellulosic biofuels (from biomass) that were expected to be at least 60% less carbon intensive than gasoline, as shown in Table 10.[103]

TABLE 10. TYPE OF BIOFUELS WITH VOLUMETRIC MANDATES UNDER THE RENEWABLE FUEL STANDARD

FUEL TYPE	GHG REDUCTION REQUIREMENT	FUEL
Cellulosic Biofuel	60%	Cellulosic ethanol, cellulosic naphtha, cellulosic diesel, renewable CNG/LNG, etc.
Biomass-based Diesel	50%	Biodiesel, renewable diesel, etc.
Advanced Biofuels	50%	Sugarcane ethanol, renewable heating oil, biogas, etc.
Renewable Fuel	20% or less	Corn ethanol, etc.

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[103] Taheripour, Farzad, H. Baumes, and W. E. Tyner / Economic Impacts of the U.S. Renewable Fuel Standard: An Ex-Post Evaluation.

TABLE 11. VOLUMETRIC GOALS FOR THE RENEWABLE FUEL STANDARD: VOLUME STANDARDS AS SET FORTH IN EISA (BILLION GALLONS)

YEAR	CELLULOSIC BIOFUEL	BIOMASS-BASED DIESEL	ADVANCED BIOFUEL	TOTAL RENEWABLE FUEL	"CONVENTIONAL" BIOFUEL
2009	NA	0.5	0.6	11.1	10.5
2010	0.1	0.65	0.95	12.95	12.0
2011	0.25	0.8	1.35	13.95	12.6
2012	0.5	1.0	2.0	15.2	13.2
2013	1.0	*	2.75	16.55	13.8
2014	1.75	*	3.75	18.15	14.4
2015	3.0	*	5.5	20.5	15.0
2016	4.25	*	7.25	22.25	15.0
2017	5.5	*	9.0	24.0	15.0
2018	7.0	*	11.0	26.0	15.0
2019	8.5	*	13.0	28.0	15.0
2020	10.5	*	15.0	30.0	15.0
2021	13.5	*	18.0	33.0	15.0
2022	16.0	*	21.0	36.0	15.0

**Statute sets 1 billion gallons minimum, but EPA may raise requirement.*

Note: There is no statutory volume requirement for "conventional" biofuels, which are those that do not qualify as advanced. The conventional volumes in the table are calculated by subtracting advanced biofuel volumes from total renewable fuel volumes.

Production targets for these were set as follows: a minimum of 16 billion gallons of cellulosic biofuel, 1 billion gallons of BBD, and 4 billion gallons of other advanced biofuels (sugarcane ethanol) by 2022. The rest could be met by producing conventional biofuel (corn ethanol) to a maximum of 15 billion gallons, as shown in Table 11.[104] Although the RFS specified volumetric mandates, the refineries or importers of gasoline or diesel were obligated to achieve it by meeting specified blend rates.

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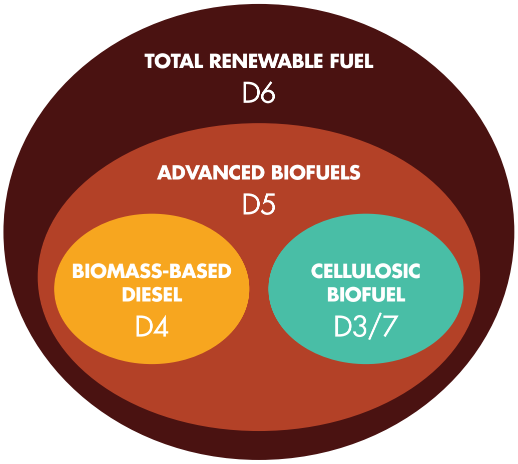
[104] EPA / Overview for Renewable Fuel Standard.

The RFS has a nested structure, as depicted in Figure 42. Given this nested structure, cellulosic ethanol qualifies in the cellulosic, advanced, and conventional biofuel categories. BD production enables compliance with BBD, advanced, and conventional biofuel categories. Advanced biofuels qualify for advanced and conventional biofuel components, while corn-based ethanol can only be applied to meet compliance with the conventional biofuel component. This nested structure of the RFS has played a key role in influencing the mix of ethanol and BBD currently produced, as discussed further below.[105] It allows blenders the option of choosing to achieve compliance with the conventional biofuel mandate by blending BBD if it is cheaper to do so than through other avenues.

The implied statutory target for conventional biofuels specified in the RFS after 2012 would have required a corn-based ethanol blend rate that was greater than 10% and therefore required a significant amount of ethanol to be sold as a higher blend (beyond the 10% blend in E10). For example, assuming that the cellulosic biofuels obligation was primarily met with cellulosic ethanol, the RFS target for 2017 would have required the gasoline pool to average a 16% blend of ethanol from all sources; this implies that a substantial amount of ethanol would have needed to be sold as E85.[106] For this to occur, E85 had to be priced competitively with E10. However, Zhong and Khanna[107] show that the design of the RFS together with the relatively high cost of producing ethanol compared to biodiesel incentivized blenders to comply with the RFS by overproducing biodiesel blends instead of E85 and reduced incentives to create demand for E85 by pricing at energy equivalent parity with E10.

FIGURE 42. NESTED BIOFUELS CATEGORIES UNDER THE RENEWABLE FUEL STANDARD



Additional policy incentives have supported the U.S. biofuel industry at various points in time. The Volumetric Ethanol Excise Tax Credit was established by the American Jobs Creation Act of 2004 and continued through 2011 at levels varying between $0.40 and $0.60 per gallon of ethanol. Similarly, BBD blenders have received a tax credit of $1.00 for every gallon of BBD since 2010. An ethanol import tariff and restrictions on imports of BBD[108] have also protected the domestic biofuel industry at varying levels over time. Elimination of the reformulated gasoline (RFG) per-gallon oxygenate requirement in June 2006 led refiners to rapidly discontinue the use of methyl tert-butylether (MTBE) in RFG,[109] replacing it with ethanol as a cheap and nontoxic substitute. Since 2009, the corn ethanol price has generally been below gasoline price, and this has led refiners to use ethanol as an octane enhancer and blend it with lower-cost 84-octane gasoline to yield an 87-octane blend at the pump. As a result, the U.S. gasoline pool transitioned to be predominantly E10 faster than was required by the RFS.

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[105] Zhong, Jia and M. Khanna / Assessing the efficiency implications of renewable fuel policy design in the United States.

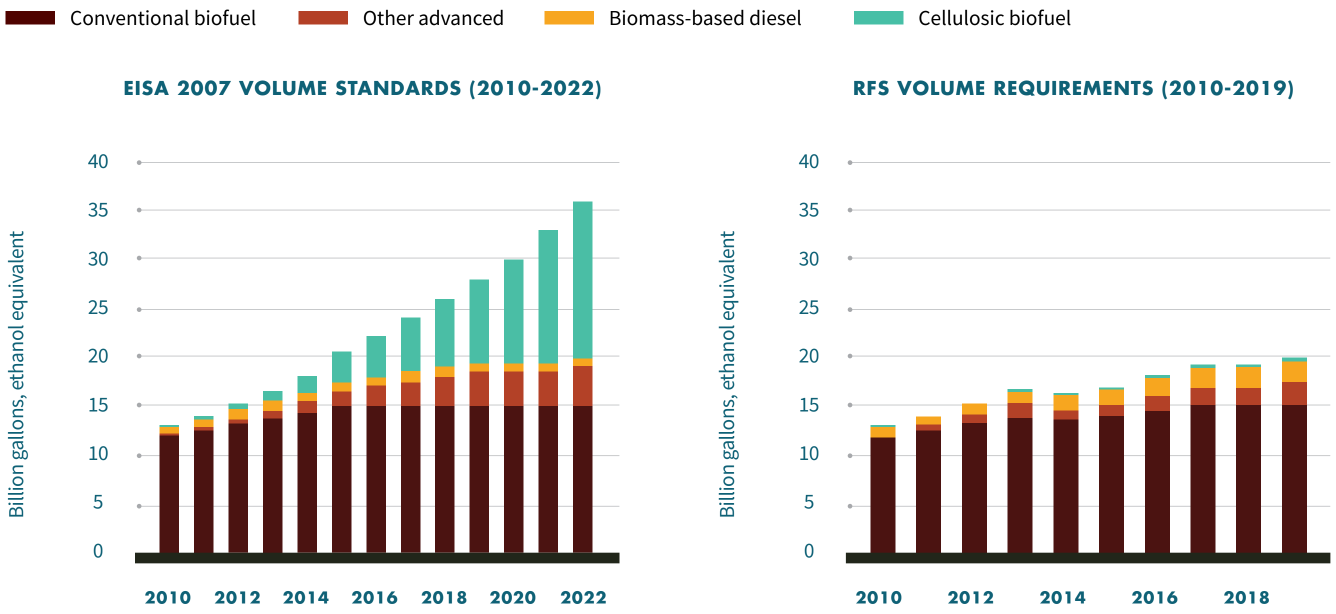
[106] Zhong and Khanna, 2022

[107] 2022

[108] Taheripour et al., / Economic Impacts of the U.S. Renewable Fuel Standard: An Ex-Post Evaluation, and Helmar et al., The Economic Impacts of U.S. Tariffs for Ethanol and Biodiesel.

[109] While MTBE critics commonly cite its listing as a probable carcinogen, the most immediate concern which led to its discontinuation was multiple incidents of MTBE from gasoline leaks and spills contaminating drinking water supplies where its taste and odor made the drinking water unpalatable at levels well below any health risk. This was compounded by the fact that MTBE does not readily biodegrade and there were no easy ways to remove it from contaminated water.

FIGURE 43. MANDATED AND ACHIEVED BIOFUEL PRODUCTION TARGETS



Source: EIA, based on EPA's Renewable Fuel Standard program
Note: Data for biomass-based diesel are actual gallons, not ethanol equivalent.

In addition to these federal policies, a key state-level policy that has incentivized blending of biofuels is the Low Carbon Fuel Standard (LCFS) enacted by several states. It was first initiated by California in 2010 and has since been enacted in Oregon and Washington. An LCFS program reduces the carbon intensity of transportation fuels within a specified jurisdiction and timeframe by granting credits to fuels that have a CI lower than the established target and penalizing with deficits those fuels in the transportation fuel pool with CIs higher than the target. A fuel producer with deficits must acquire enough credits through generation and acquisition to be in annual compliance with the standard. Some states, such as California, also have a carbon cap-and-trade policy that generates an implicit price for carbon and penalizes high carbon fossil fuels and subsidizes low-carbon biofuels. Ethanol and BBD consumption in California increased from about 250 million gallons in 2011 to 350 million gallons by 2016[110] and almost all of the RD currently being produced in the U.S. is consumed in California to comply with the LCFS.

Although the production of corn ethanol has grown significantly since 2007, the implied statutory targets for corn ethanol use set by the RFS in 2007 have not been met,[111] while the production of BBD has exceeded the targeted level, as shown in Figure 43. Additionally, the supply of cellulosic biofuels has fallen far short of the quantities mandated by the RFS, and 99% of the cellulosic biofuels that are being produced are in the form of RNG, not ethanol.[112] The absence of a supply of cellulosic biofuels at commercial scale and limited demand for ethanol has led EPA to lower the volumetric targets, particularly for cellulosic biofuels (which were expected to be primarily in the form of

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[110] Yeh, Sonia, J. Witcover, G. E. Lade, D. Sperling / A review of low carbon fuel policies: Principles, program status and future directions.

[111] EPA / Annual Compliance Data for Obligated Parties and Renewable Fuel Exporters under the Renewable Fuel Standard (RFS) Program.

[112] EIA / EPA finalizes Renewable Fuel Standard for 2019, reflecting cellulosic biofuel shortfalls.

cellulosic ethanol). EPA lowered overall volumetric goals by 30% in 2018 but raised the target for BBD to 2.43 billion gallons in 2020. It also lowered the cellulosic biofuel requirement by exercising its cellulosic waiver authority. Incentives for cellulosic biofuel production have been further diminished by allowing blenders the option to waive their blending of cellulosic biofuels by paying a cellulosic biofuel waiver fee through the purchase of cellulosic waiver credits (CWCs) and blending an equivalent amount of non-cellulosic advanced biofuel to comply with the advanced biofuel and total renewable fuel obligations.

TABLE 12. PROPOSED VOLUME TARGETS (BILLION GALLONS)

	2023	2024	2025
Cellulosic Biofuel	0.72	1.42	2.13
Biomass-based Diesel	2.82	2.89	2.95
Advanced Biofuel	5.82	6.62	7.43
Renewable Fuel	20.82	21.87	22.68
Supplemental Standard	0.25	N/A	N/A

Source: Stillwater analysis of U.S. EPA Fuel Economy Guides 2000-2021

In December 2022, EPA announced the volumes required for compliance with the RFS in 2023-2025. This will raise total biofuel production to 22.68 billion gallons by 2025, and of this, BBD production is expected to increase by 2.95 billion gallons per year and cellulosic biofuels by a little over 2.1 billion gallons per year, as shown in Table 12.[113] Substantially all of the increase in the cellulosic biofuel targets in 2024 and 2025 is expected to come from electricity produced from biogas or RNG and utilized to charge EVs (known as eRINs).

The outlook for biofuel volumes and the mix of BBD, ethanol (first- and second-generation) and drop-in fuel for gasoline will depend on both technology development and policy incentives. Policy incentives and the design of policy will affect the demand for different types of biofuels. If the current nested design of the RFS with the cellulosic biofuel waiver provision together with the biodiesel tax credit is maintained, then it will continue to promote BBD production and limit incentives for selling higher blends of ethanol unless the marginal costs of producing BBD become larger than those of corn ethanol. However, with the proposed phaseout of the CWC and BTC and provision of the clean fuels production credit (CFPC), incentives for producing lower carbon biofuels from cellulosic feedstocks

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[113] EPA / Proposed Renewable Fuel Standards for 2023, 2024, and 2025.

and waste products can be expected to increase.[114] Additionally, anticipated reduction in demand for gasoline in the future with increasing fuel efficiency of conventional vehicles, together with growing demand for EVs, can be expected to reduce demand for E10. Thus, it is likely that there will be limited incentives to increase capacity to produce ethanol from first- or second-generation feedstocks in the near future under the current policy regime. As noted above, however, proposals currently in Congress to extend the favorable RVP treatment provided to E10 to E15, if adopted, would facilitate growth in E15.

However, concerns about climate change and further reduction in the dependence on fossil fuels as well as technology breakthroughs that lead to drop-in biofuels that can be blended with gasoline (similar to RD for diesel vehicles) could alter incentives to increase consumption of biofuels. Despite the growing interest in EVs, conventional vehicles are still expected to have a dominant share in the near to medium term. While annual sales of EVs have been growing in the U.S., the total EV share of on-road light-duty stock was about 1% in 2021 and, according to AEO 2022, is expected to grow to 9% in 2050, based on laws and regulations current as of November 2021.[115] The 2022 federal Infrastructure Investment and Jobs Act[116] and Inflation Reduction Act[117]—which together provide substantial support for EV manufacturing, consumer purchase, and recharging infrastructure—were enacted after publication of the AEO 2022 and, thus, were not considered in that outlook. These new policies will be considered in the AEO 2023, published in March 2023; this updated outlook, also subject to consumer preferences and acceptance, is expected to project a more rapid transition to EVs than AEO 2022. Thus, demand for ethanol in the long run will depend on the extent to which policy and technology can raise the blend rate with gasoline and induce compliance by incentivizing consumers to buy higher blends by pricing them appropriately.

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[114] Including used cooking oil (UCO), distillers corn oil (DCO), and inedible tallow.

[115] EIA / AEO 2022, Motor gasoline remains the most prevalent transportation fuel despite electric vehicles gaining market share.

[116] 117th Congress / Public Law 117-58.

[117] 117th Congress / Public Law 117-169.

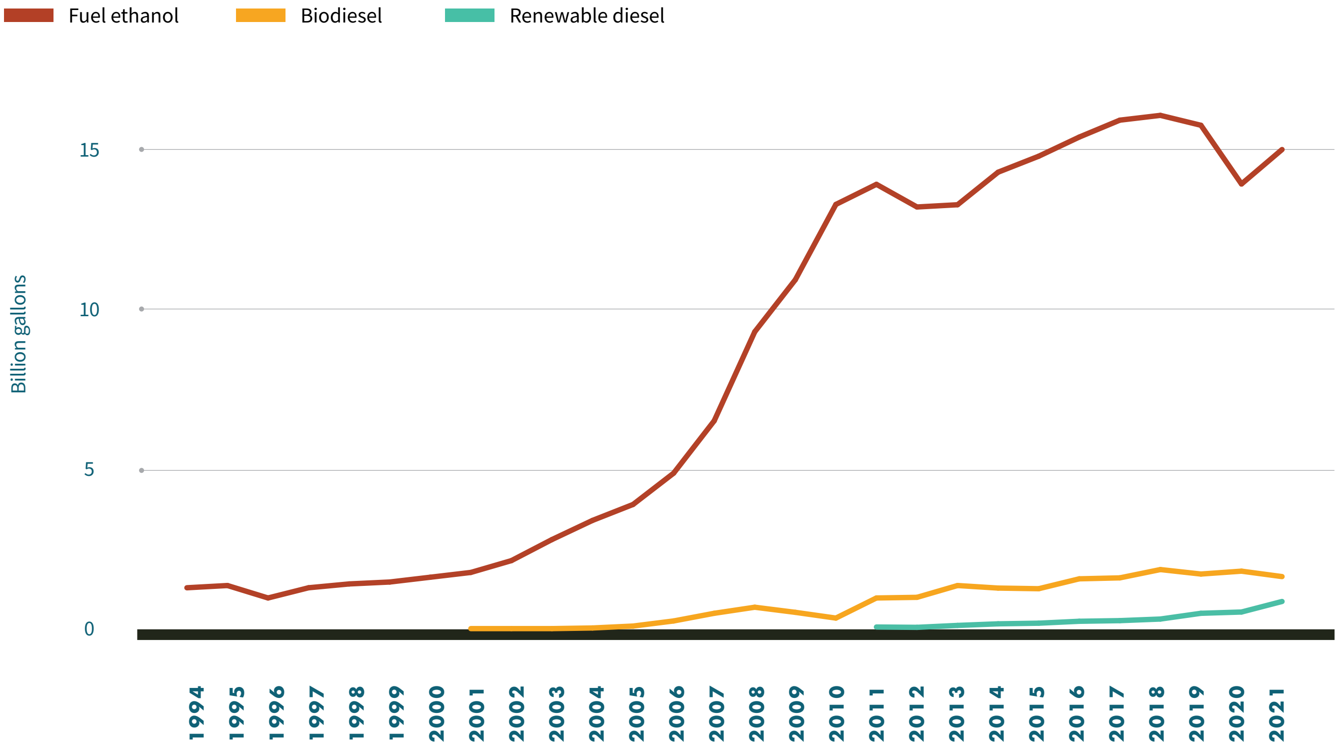
10.2 MARGINAL AND INCREMENTAL FEEDSTOCKS

Any discussion of the future growth in biofuel production and consumption begins with the historical trend in biofuel production and a look at marginal and incremental current feedstocks. We begin with production levels of ethanol and BD.[118]

Ethanol production in the U.S. had grown from less than 2 billion gallons in the year 2000 to 6.5 billion gallons in 2007 at the time of the passage of the RFS. Since then, it increased to over 16 billion gallons in 2018, when it accounted for 52% of world output. Following the decline in gasoline consumption due to the pandemic and slow growth in its consumption since then, ethanol production has declined and was about 15 billion gallons in 2021. The U.S. is both an importer of sugarcane ethanol from Brazil and a growing exporter of corn ethanol to the rest of the world. Ethanol imports have been small and declining in recent years while ethanol exports have grown to about 1.2 to 1.8 billion gallons a year in recent years.

As can be seen in Figure 44,[119] BD production has grown from negligible levels in 2002 and doubled between 2011 and 2016, reaching about 1.5 billion gallons in 2016, accounting for 20% of world output. Over time, the amount of RD produced has also grown and is now equal to that of BD in the U.S.; together they reached a peak of about 2.4 billion gallons in 2020. In 2021, the U.S. produced 1.64 billion gallons of BD and 0.86 billion gallons of RD.

FIGURE 44. BIOFUEL PRODUCTION IN THE U.S.



Source: USDA, ERS

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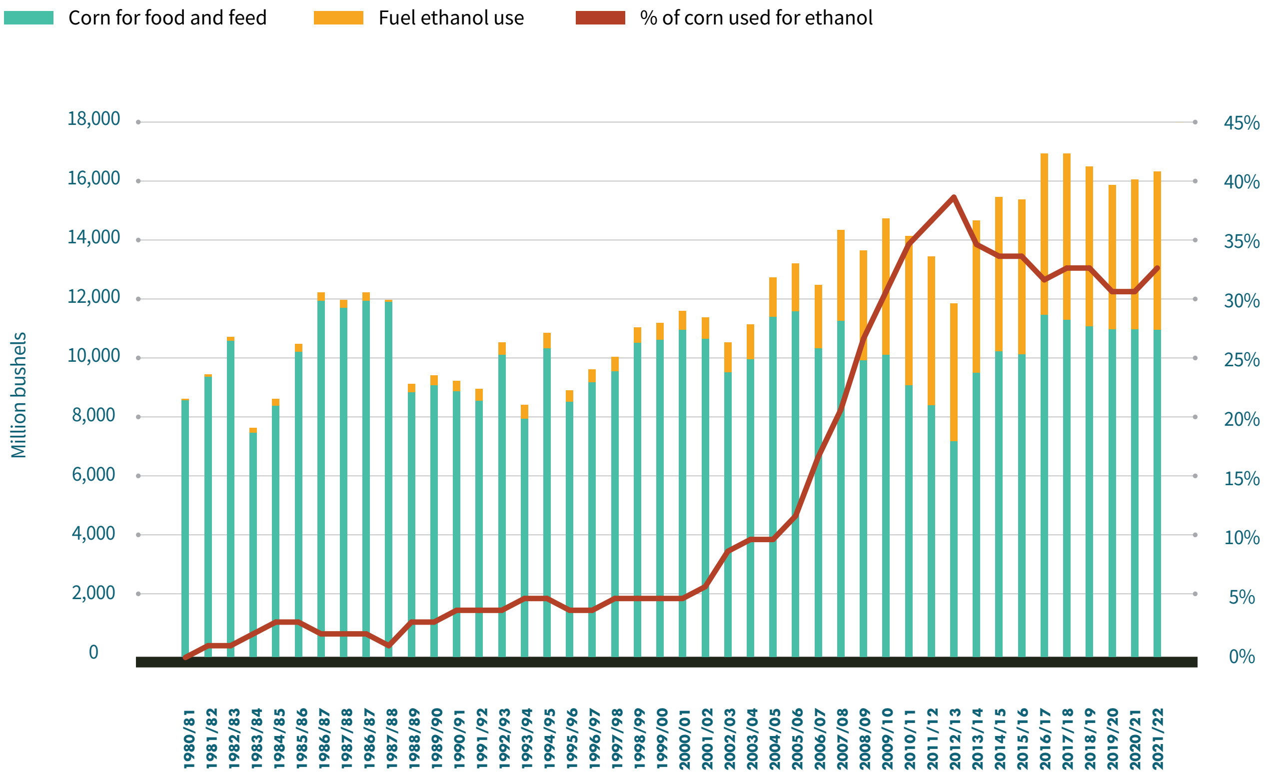
[118] USDA ERS / U.S. Bioenergy Statistics.

[119] USDA ERS / U.S. Bioenergy Statistics.

10.2.1 TRENDS IN FEEDSTOCK PRODUCTION FOR BIOFUELS

Corn production has grown over the past four decades to over 16 billion bushels in recent years. The amount of corn used for food and feed has fluctuated around 10 billion bushels over the 1980-2022 period.[120] Meanwhile, U.S. corn exports have slowly increased since the initiation of the RFS to over 2 billion bushels annually.[121] Over this same period, an increasing share of corn is being converted to ethanol. As shown in Figure 45, [122,123] the share of corn being converted to ethanol has increased from less than 5% prior to 2000 to 33% in 2022, after peaking at 40% in 2012.

FIGURE 45. CORN USE FOR FOOD, FEED, AND ETHANOL



Source: USDA, ERS

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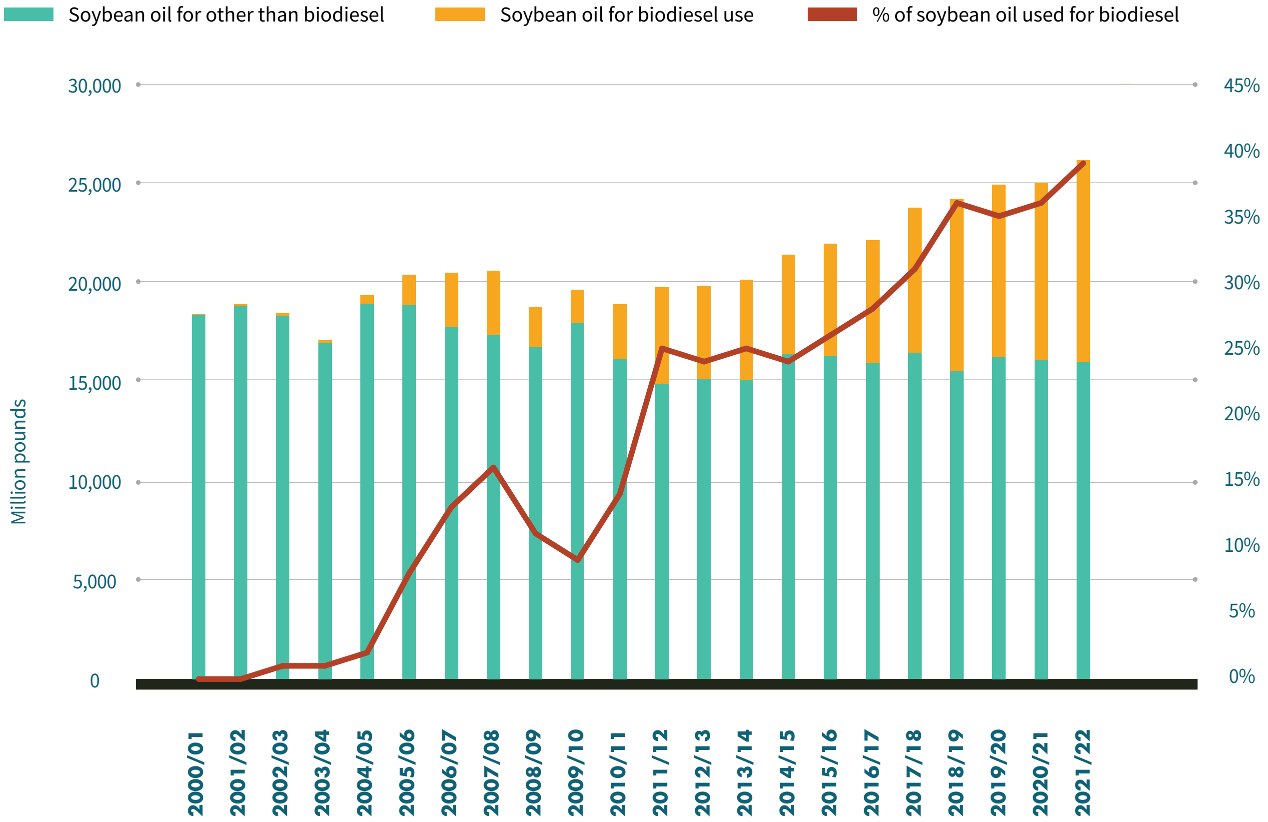
[120] USDA ERS / U.S. Bioenergy Statistics.

[121] USDA / WASDE Report.

[122] USDA ERS / U.S. Bioenergy Statistics.

[123] USDA / WASDE Report.

FIGURE 46. SOYBEAN OIL FOR BIOMASS-BASED DIESEL AND OTHER USES



Source: USDA, ERS

In 2021, 23.8 billion pounds of feedstock were converted to BBD. Two feedstocks were the primary source of BBD that year—soybean oil accounted for 68%, and corn oil accounted for 20%. Almost a third of the corn converted to ethanol is converted to a byproduct called dried distillers grains with solubles (DDGS) and contains all of the protein and fiber content of the corn after the starch content is converted to ethanol. This is used as animal feed and to produce corn oil which is then converted to BD and RD.[124] (Figure 46 [125])

Soybean production in the U.S. has grown from about 2.8 billion bushels to about 4.5 billion bushels over the last two decades, with exports growing from about 1 billion bushels to over 2 billion bushels annually. According to the U.S. Department of Agriculture's 2022 projections, soybean production will increase to about 5 billion bushels by the end of this decade. BBD production started growing in about 2005, and the share of soybean oil used for BBD has grown to 10 billion pounds, which accounts for 40% of the soybean oil produced in 2022. This growth in demand for BD and RD production has resulted in soybean oil exports falling from a recent high of 2.8 billion pounds (2019/20 marketing year) to a projected 1.1 billion pounds (for the 2022/23 marketing year).

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[124] EIA / Biofuels Explained.

[125] USDA ERS / U.S. Bioenergy Statistics.

10.2.2 LAND USE AND ECONOMIC IMPLICATIONS OF BIOFUEL FEEDSTOCK PRODUCTION

Demand for biofuels increases demand for the feedstock needed for conversion to biofuel. In the case of food crop-based biofuels, this demand is met through many sources. This demand for feedstock may be met by reducing the amount used for food/feed, reducing exports, increasing production, and reducing existing supplies of feedstock. Production increases come in the form of increased per-acre yields and reallocation of farm acreage from other, less valuable, crops. All of these changes are induced by higher crop prices that result from increasing demand with an upward sloping supply curve for the crop. By increasing demand for the crop, biofuel mandates increase crop prices, at least in the near term. This creates incentives to bring more land into the production of that crop. This can lead to land under other crops being converted to produce biofuel feedstock crops as well as non-cropland being brought into crop production.[126] Conversion of non-cropland, particularly permanent pastureland or grasslands, to crop production raises concerns about the release of carbon stored in soils and vegetation to the atmosphere. The extent to which each of the mechanisms described above is utilized to meet the demand for biofuel feedstock depends on the price responsiveness of the demand for food/feed and the price responsiveness of the feedstock supply function. In the long run, increases in crop yields at a rate faster than the increase in demand for food/feed can result in an increase in supply of feedstocks for biofuels, and this can reduce the adverse impact of biofuel demand on crop prices.

The extent of crop price increase and land use change due to biofuels has been a controversial issue, primarily because it is not directly measurable by comparing prices or land use before and after biofuel mandates. Other factors influence land use and crop prices, and it is difficult to separate the effects of biofuels from those of other accompanying changes. In fact, USDA annual reporting of crop acreage indicates that total U.S. land use for crops has actually declined since the enactment of the RFS.[127] Instead, attributing crop price changes and land use changes to biofuels requires a “with and without biofuel” comparison holding all other factors constant. This requires comparing outcomes in a scenario with policy-induced biofuels to a counterfactual scenario with no biofuels policy and analyzing the difference in crop prices and land use. A counterfactual scenario can be constructed using economic models that simulate market behavior, market clearing crop prices, and allocation of land to various uses by varying the amount of biofuel produced and assuming that consumers and producers seek to maximize their net benefits. These economic models differ in the number of sectors they consider, temporal resolution (annual or multiyear), spatial resolution (regional, crop reporting district), and the degree of market detail. A wide range of literature offers estimates for the land use and crop price effects of corn ethanol; a few studies have also analyzed these effects of BBD.[128]

As biofuel production has expanded since 2007, land enrolled in the Conservation Reserve Program (CRP)[129] has declined from 36.7 million acres in 2007 to 22.6 million acres in 2018, and studies show that cropland in the vicinity of ethanol plants has

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[126] By statute, crops used as feedstocks for RFS-compliant renewable fuels can only be “…harvested from agricultural land cleared or cultivated at any time prior to the enactment of this sentence that is either actively managed or fallow, and nonforested.”

[127] USDA / Acreage.

[128] Austin, K.G., J.P.H. Jones, and C.M. Clark / A review of domestic land use change attributable to U.S. biofuel policy; Taheripour et al., / Economic Impacts of the U.S. Renewable Fuel Standard: An Ex-Post Evaluation; Helmar et al., The Economic Impacts of U.S. Tariffs for Ethanol and Biodiesel; Chen, Xiaoguang and M. Khanna / Effect of corn ethanol production on Conservation Reserve Program acres in the US; Wang, Weiwei and M. Khanna / Land Use Effects of Biofuel Production in the US.

[129] The Conservation Reserve Program (CRP) is administered by the Farm Service Agency. In exchange for a yearly rental payment, farmers enrolled in the program agree to remove environmentally sensitive land from agricultural production and plant species that will improve environmental health and quality. Contracts for land enrolled in CRP are from 10 to 15 years in length. The long-term goal of the program is to re-establish valuable land cover to help improve water quality, prevent soil erosion, and reduce loss of wildlife habitat.

The impact of using a growing share of corn for fuel instead of food has declined over time due to increasing crop yields, corn-to-biofuel conversion process efficiency, and improvements in extraction.

increased since 2007. Wright et al.[130] estimate that 4.2 million acres of non-cropland were converted to crop production within 100 miles of biorefinery locations between 2008 and 2012; this included 3.6 million acres of converted grassland. These data implicitly assume that this cropland expansion was entirely due to corn ethanol expansion as it occurred over the same period of time. Comparing cropland acres before and after these two points in time is somewhat misleading since it does not consider changes in cropland acres that have occurred since; instead, it is preferable to compare land use with and without biofuels at a point in time (holding all else the same). Cropland acres have declined after 2014 as crop prices declined. Li et al.[131] analyzed the extent to which cropland within a 25-kilometer radius of corn ethanol refineries expanded due to ethanol production as well as cropland expansion that occurred in response to an increase in corn and other crop prices. They examined changes between 2008 and 2012 and also between 2008 and 2014. They showed that cropland expansion occurred due to increases in both ethanol capacity and crop prices. They found that keeping all other factors unchanged, the increase in ethanol capacity led to a 2.9 million acre (3.1%) increase in corn acreage and a 2.1 million acre (0.9%) increase in total crop acreage by 2014 when compared to 2008; this was equivalent to a cropland expansion of 0.43 million acres per billion gallons (2008-2014). This is consistent with findings by other studies that have sought to examine the extent to which these changes in land use can be attributed to biofuel production. This estimate is close to the estimates ranging between 0.4 and 0.45 million acres per billion gallons obtained in Chen and Khanna.[132] A review of the literature by Austin et al.[133] found a median estimate of 0.47 million acres per billion gallons, with the recent estimate by Lark et al.[134] of 0.94 million acres per billion gallons being at the upper end.[135]

In a more recent analysis, Wang and Khanna[136] examine the annual changes in total cropland expansion per unit of the annual increase in corn ethanol production in each year (2008-2018). They considered two scenarios, one that allowed permanent pastureland to be converted to cropland and one that did not. They found that the estimate ranged between 0.41 and 0.57 million acres of cropland conversion per billion gallons without inclusion of pastureland; the corresponding estimate with inclusion of pastureland is 0.71 to 0.75 million acres per billion gallons. They estimate that the quadrupling of corn ethanol production to 16.1 billion gallons in 2018 relative to 3.9 billion gallons in the counterfactual scenario (with no RFS) led to a 2.4% increase in total cropland used for crop production in 2018.

There have been relatively few studies of the impact of BBD production on land use change. Such an analysis is complicated by the fact that all BBD feedstocks in the U.S. are byproducts from the production of other commodities.[137] In a recent study, Wang and Khanna[138] find that BBD production is much more land-intensive than corn ethanol. They estimate that it required 0.78-1.5 million acres per billion gallons of BBD in the 2008-2018 period, depending upon assumptions about whether or not pastureland can convert to crop production.

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[130] Wright, Christopher K., B. Larson, T. J. Lark, and H. K. Gibbs / Recent grassland losses are concentrated around U.S. ethanol refineries.

[131] Li, Yijia, R. Miao, M. Khanna / Effects of Ethanol Plant Proximity and Crop Prices on Land-Use Change in the United States.

[132] Li et al., / Effects of Ethanol Plant Proximity and Crop Prices on Land-Use Change in the United States.

[133] 2022

[134] Lark, Tyler J. et al., / Environmental outcomes of the US Renewable Fuel Standard.

[135] This differs from the estimate reported in Austin et al (2022) which incorrectly reports their land use change estimate as 2.1 million acres instead of 2.1 million hectares.

[136] in review

[137] Example: Soybean oil is a byproduct of soybean meal production, corn oil is a byproduct of ethanol production, tallow is a byproduct of meat production.

[138] in review

10.2.3 EFFECT OF BIOFUEL FEEDSTOCK PRODUCTION ON CROP PRICES

A number of studies have conducted ex-ante simulations (based on forecasts rather than actual results) of the impact of biofuels on food crop prices.[139] These simulations rely on a number of different assumptions, including those about the responsiveness of crop yields to higher crop prices, technological improvements, the availability of marginal/idle land, and the ease with which farmers can double crop and convert land across uses. These studies show that the impact of biofuels on crop prices has varied over time and was between 10% and 30%, with the impact depending on the period of analysis, the modeling approach used, and other factors such as crop inventories, growth in demand, energy prices, and restrictive trade policies. Hochman et al.[140] show that the rise in biofuel production in 2007-2008 caused crop inventories to decline significantly, which affected corn prices. They estimate that biofuels accounted for about 20% of the increase in corn prices between 2001 and 2007 and another 10% of the price increase between 2008 and 2011.

Wang and Khanna[141] estimate that relative to a no-policy scenario with corn ethanol and BBD production at 2005 levels, the increase in demand for corn for ethanol raised corn prices by 31.4% and soybean prices by 20.6% in 2018. It also increased land rents by 30%. The addition of demand for BBD led to a further increase in land rent by 6.6% in 2018 compared to corn ethanol alone. It also raised corn and soybean prices by 4.3% and 8.2%, respectively, in 2018 relative to a scenario with corn ethanol alone.

Hochman and Zilberman[142] found that the impact of biofuels was stronger in agricultural commodity markets than in markets for final consumer products; in the long term, biofuels were estimated to increase corn prices by an average of 14%, while the impact on final consumer prices in the U.S. was estimated to be around 1%.

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[139] Khanna, Madhu, D. Rajagopal, and D. Zilberman / Lessons Learned from US Experience with Biofuels: Comparing the Hype with the Evidence.

[140] 2014

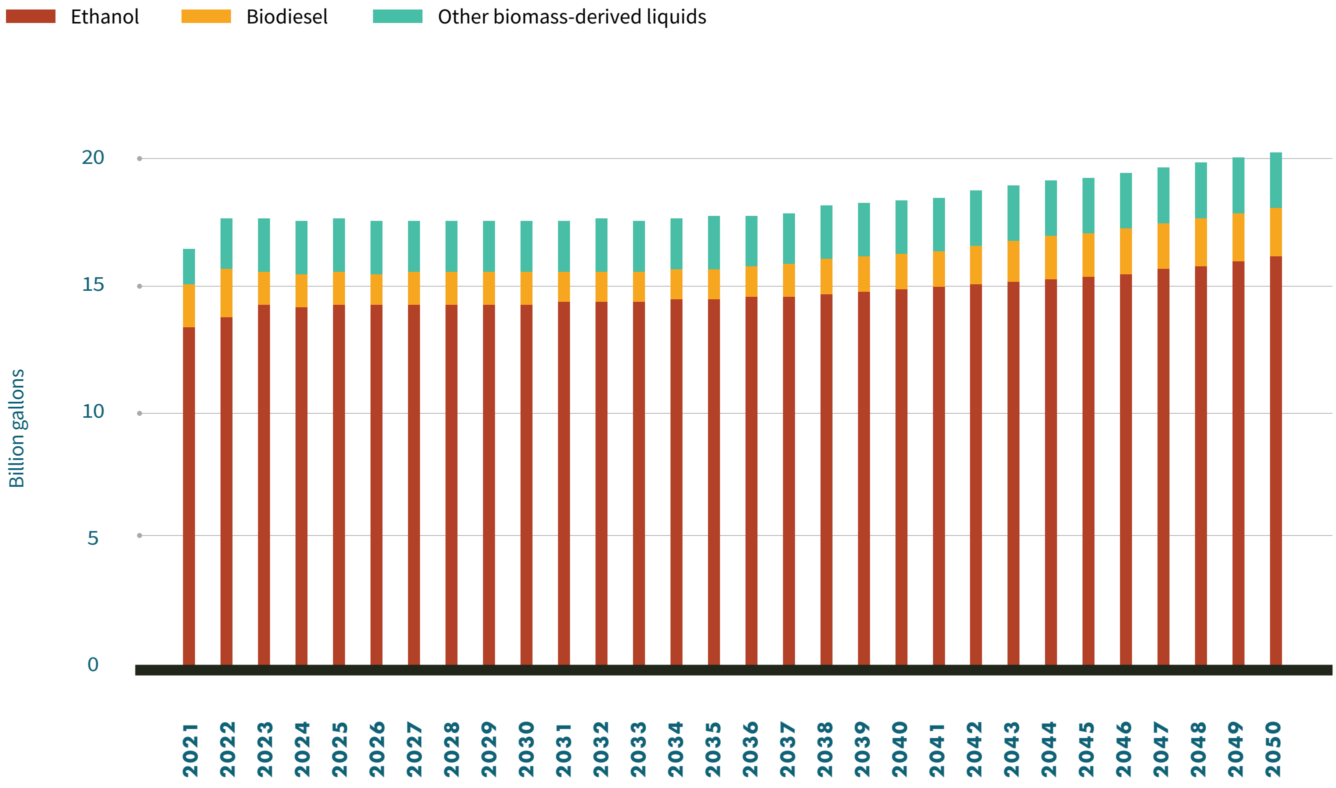
[141] Wang and Khanna (in review)

[142] 2018

10.3 PROJECTIONS OF DEMAND FOR BIOFUELS AND BIOFUEL FEEDSTOCKS

EIA's AEO 2022 projects that U.S. biofuel production will increase slowly up to 2050 in the Reference Case scenario, assuming current laws and regulations, as shown in Figure 47.[143] Ethanol production is projected to increase from 13.3 billion gallons in 2021 in the Reference Case scenario to 16.1 billion gallons (an increase of 20%); estimates could range between 13.9 and 17.3 billion gallons in the low oil price and high oil price scenarios, as shown in Figures 47 and 48 respectively. EIA expects that U.S. gasoline use will decline by 4.5% between 2023 and 2037, and that in 2037 gasoline demand will be lower than 2021 levels despite population growth that increases the demand for transportation. After 2037, U.S. gasoline use is expected to grow as population increases offset the declines in per-capita gasoline use. Declining gasoline consumption is expected to lower ethanol consumption since ethanol is mainly expected to be consumed as E10. E85 consumption is projected to remain flat over this period, given current policies. Ethanol imports and exports are expected to remain small and flat at least over the next decade.[144]

FIGURE 47. PROJECTED BIOFUEL PRODUCTION IN THE U.S. IN THE AEO REFERENCE CASE



Source: AEO 2022

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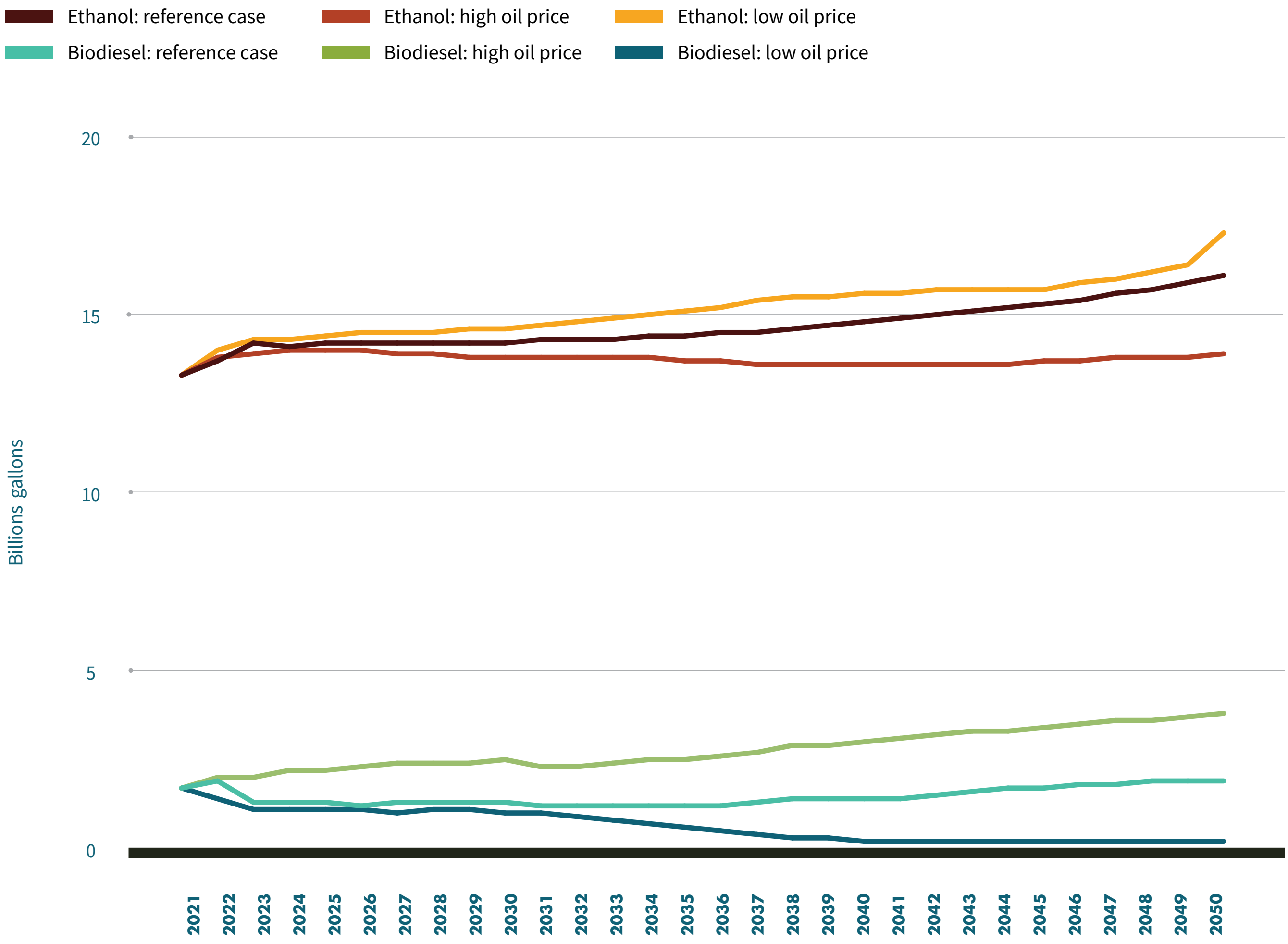
[143] Biofuels are defined here to include denatured ethanol, biodiesel and other biomass derived liquid fuels, including pyrolysis oils, biomass-derived Fischer-Tropsch liquids, biobutanol, and renewable feedstocks used for the on-site production of diesel and gasoline.

[144] USDA, 2022

Biomass-based diesel production is expected to increase, particularly in the AEO 2022 high oil price scenario, as it substitutes for the more expensive diesel. RD production levels are anticipated to exceed those of BD production from 2022 onwards driven by demand induced by the California LCFS, which is currently consuming nearly all of the RD produced in the U.S.[145] RD is more expensive to produce than BD but its production is expected to grow due to compatibility with existing infrastructure and engines, state and federal targets for renewable fuel, and incentives for conversion of existing petroleum refineries into RD refineries. RD production is projected to increase from about 2 billion gallons in 2022 to 2.22 billion gallons by 2050, while BD production is projected to decrease from 1.9 billion gallons in 2022 to 1.4 billion gallons by 2040 and then increase back to 1.9 billion gallons by 2050. The USDA[146] expects that RD will continue to rely primarily on non-soybean oil feedstocks but will also increasingly use soybean oil. (Figure 48)

FIGURE 48. PROJECTED BIOFUEL PRODUCTION IN THE U.S. IN HIGH AND LOW OIL PRICE SCENARIOS



Source: AEO 2022

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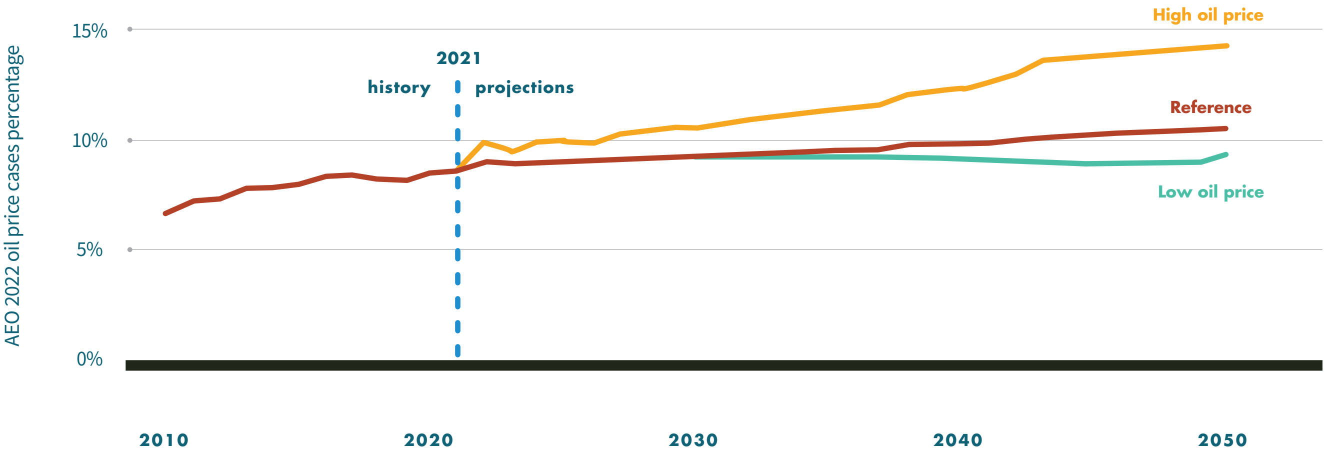
[145] EIA / EIA Projects U.S. renewable diesel supply to surpass biodiesel in AEO2022.

[146] 2022

AEO 2022[147] projects that biofuels as a percentage of U.S. motor gasoline and diesel will remain fairly flat in the Reference Case scenario and increase to 10.3% by 2050 as shown in Figure 49. This is in part due to a projected increase in the share of biomass-based diesel in petroleum diesel from 6% in 2020 to about 8% by 2050 and partly due to a mild increase in ethanol production and flat gasoline consumption over this period, as shown in Figure 50.

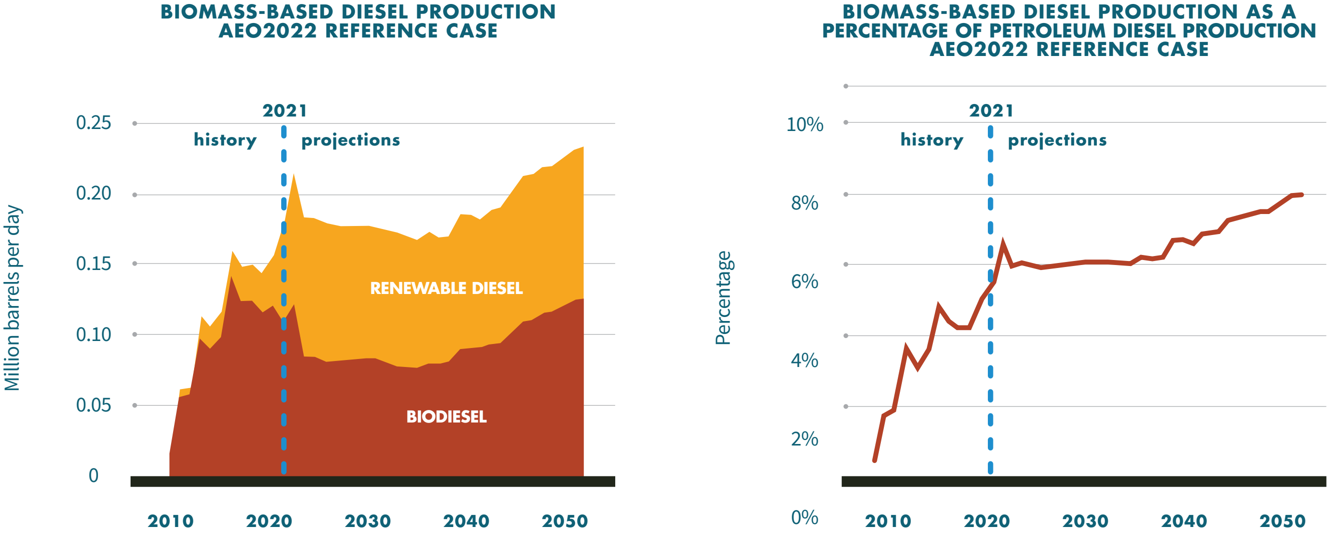
As can be seen in Figure 50, BD production is projected to decline in the next two decades and then increase by 2050, while RD is projected to stay flat and then grow steeply after 2040.

FIGURE 49. BIOFUELS AS A PERCENTAGE OF U.S. MOTOR GASOLINE AND DIESEL CONSUMPTION



Source: AEO 2022

FIGURE 50. BIOMASS-BASED DIESEL PRODUCTION IN THE AEO REFERENCE CASE



Source: AEO 2022

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147 EIA / Annual Energy Outlook 2022 Chart Library.

USDA[148] projects that corn production will continue to grow over the next decade to meet increasing demand for meat production while planted acreage will remain stable at 90 million acres and then decline gradually to 89 million acres as yields continue to grow. Corn is expected to be the primary feedstock for ethanol and to account for more than 98% of ethanol production. Over the next decade, the amount of corn used for ethanol production is projected to remain relatively flat, decreasing by less than 0.2% over the decade. The amount of corn used for ethanol is expected to grow mildly from 5.1 to 5.2 billion bushels by 2030. Corn used to produce ethanol is expected to continue to be a substantial source of demand for the fuel sector, accounting for about one-third of total U.S. corn use over the next decade.

Assuming that the volumetric requirement for biomass-based diesel under the RFS remains around 2.4 billion gallons, the USDA projects that soybean oil to produce BBD will increase from 8.15 billion pounds in 2021/22 to 8.6 billion pounds by the end of the projection period, supporting an annual production of over 1.1 billion gallons of soybean oil-based BBD.

10.3.1 EFFECTS OF CORN ETHANOL MANDATE ON LAND USE AND CROP PRICES IN 2030

Chen et al.[149] projected the effects of a 15-billion-gallon mandate maintained until 2030 and compared them to the effects with no biofuel policy after 2007 (with corn ethanol at the 2007 level of 6.5 billion gallons). They find that demand for corn for biofuels would result in a 23% increase in corn acreage that would be met partly by reducing acreage under other crops, such as soybeans, wheat and others, and partly by increasing total crop acreage. Total crop acreage would be 5.4% or 15 million acres higher than with no biofuel policy; of this, a 10-million-acre increase would be on land that would have become idle otherwise, and a 5-million-acre increase would be on land that was marginal/idle in 2016.

About 33% of corn produced would be used for ethanol production (5.2 million bushels). Corn prices would be 12% higher, soybean prices would be 7% higher, and land rents would be 11% higher compared to the no-biofuel policy case. (Table 13)

TABLE 13. EFFECTS OF THE CORN ETHANOL MANDATE ON LAND USE AND CROP PRICES IN 2030

	NO BIOFUEL POLICY	TOTAL RENEWABLE FUEL	"CONVENTIONAL" BIOFUEL
Total Crop Acreage (M acres)	270.2	284.7	5.4%
Corn Acreage (M acres)	67.8	83.2	22.6%
Soybean Acreage (M acres)	83.5	82.2	-1.6%
Corn Production (M bushels)	13227.2	16020.9	21.1%
Soybean Production (M bushels)	4393.1	4297.8	-2.2%
Corn for Ethanol Production (M bushels)	2079	5222.5	151.2%
Corn Price ($ per bushel) *	3.2	3.6	11.9%
Soybean Price ($ per bushel) *	7.1	7.6	7.1%
Land Rent ($ per acre) *	82.3	91.2	10.8%

Source: Chen et al. (2021)

**All prices are in 2016 dollars*

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[148] USDA / USDA Agricultural Projections to 2031.

[149] Luoye, Chen et al / The economic and environmental costs and benefits of the renewable fuel standard.

10.4 NEXT GENERATION FEEDSTOCKS

Significant increases in the volume of biofuel production in the future can be expected to require reliance on nonfood crops since significant shares of current food crops—corn and soybeans—are already being converted to biofuel. Fats, oils, and waste greases are also being converted to BBD, but their quantities are limited and dependent on supply conditions in other markets. Nonfood crop options for biofuels offer the potential for increasing dedicated supply of feedstock without displacing food crops and minimizing diversion of cropland to fuel production. These feedstocks include cover crops like pennycress and carinata, which can be converted to BBD, as well as biomass from residues of corn and wheat and from dedicated energy crops. High-yielding energy crops which are typically perennials, like miscanthus, switchgrass, and energy cane, as well as short rotation woody crops, like poplar and willow, and some annual crops, notably energy sorghum, are being considered for biofuel production.

10.4.1 COVER CROP FEEDSTOCKS FOR BIOMASS-BASED DIESEL

Pennycress

Pennycress is a winter/annual cover crop that can be grown throughout the Midwest. Pennycress is being improved as a biofuel feedstock with higher oil and protein content through gene editing and breeding, and the converted product is known as CoverCress or golden pennycress.[150] It can be converted to RD or sustainable aviation fuel (SAF). As a winter oilseed, pennycress can be grown during the fallow season with existing rotations in the Midwest and avoid the need for land use change. It can also provide ecosystem benefits by reducing soil erosion, breaking disease and pest cycles, recycling nutrients in the soil, reducing nutrient loss, and reducing weed problems. Only the seed is harvested, and the rest of the biomass is returned to the soil, which increases soil carbon and soil fertility. It is not invasive and has minimal impact on yield of soybean crops that follow pennycress. It provides an additional source of income for the farmer and can be produced using the same farm equipment as soybeans.

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[150] Phippen, Winthrop B. et al / From Farm to Flight: CoverCress as a Low Carbon Intensity Cash Cover Crop for Sustainable Aviation Fuel Production. A Review of Progress Towards Commercialization.

Carinata

Carinata (Ethiopian mustard or *Brassica carinata*) was introduced in the southeastern U.S. in 2010 through a joint research collaboration between the University of Florida and Agrisoma Biosciences Incorporated. Carinata grows in the winter months and, like pennycress, provides cover to the bare ground with consequent ecosystem benefits to soil and water. Carinata is more frost tolerant and has higher oil content than other oilseed crops in the southeastern U.S.

Camelina

Camelina (*Camelina sativa* L.) is a summer annual oilseed crop that is grown in Montana and Oregon. It is a short season crop that matures in 85 to 100 days and can be grown on marginal land. Camelina oil can be used in both edible and industrial products. It can grow under drought stress conditions and is suited to low rainfall regions. Camelina has an oil content of 26-42% with an average of 35% and an average yield of 1,600 pounds per acre.[151]

Additional detail on next generation cover crop feedstocks can be found in Appendix A.

10.4.2 CELLULOSIC BIOMASS FEEDSTOCKS FOR BIOFUELS

Cellulosic biomass for biofuels can be obtained from various sources. These include crop residues which are a by-product of corn or wheat as well as biomass produced from dedicated energy crops that require switching land from conventional crops or low-quality land that is currently idle to energy crops. There are several choices for energy crops that differ in their features such as yields, length of their lifetime, establishment lag (between planting and obtaining a harvestable yield), input requirements, suitability of growing conditions, and riskiness of production. These features affect the costs and benefits of energy crops relative to each other, and these costs and benefits will vary across locations for a given feedstock. Farmers will need long-term firm contracts for biomass and an assured price for biomass from biofuel producers to convert land to energy crops and incur the upfront costs of establishing perennials. If such a contract is available, then farmers must decide not only whether to grow an energy crop but also which energy crop to grow. Since these dedicated energy crops may be competing for the same land and for achieving compliance with a given implied volumetric target for cellulosic biofuels, assessing the mix of feedstocks likely to be produced requires a comprehensive modeling analysis that takes into account the relative yield, costs, and returns from alternative energy crops, the price of biomass, and the availability of various types of land to grow them.

Additional information concerning the various herbaceous agricultural feedstocks that are considered promising for cellulosic biofuel production can be found in Appendix B.

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[151] Oregon State University Extension Service / Economics of Oilseed Crops and Their Biodiesel Potential in Oregon's Willamette Valley.

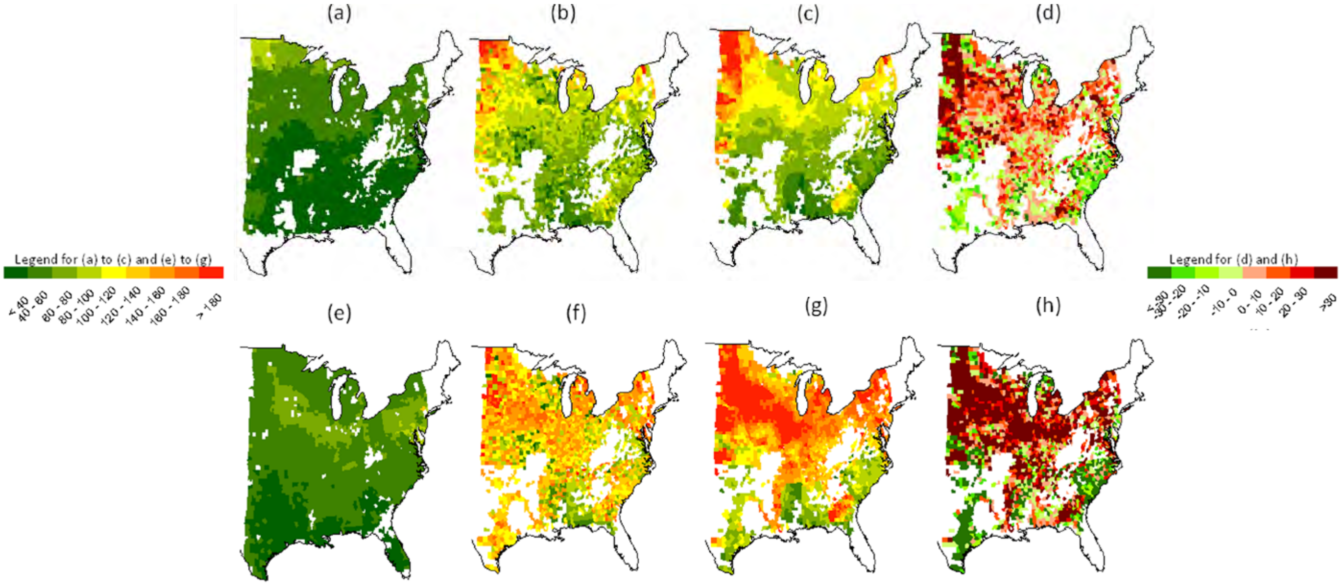
10.5 RISKS AND UNCERTAINTIES AFFECTING CELLULOSIC FEEDSTOCK PRODUCTION

Cellulosic feedstock production faces several risks and uncertainties that affect feedstock supply and costs and the demand for cellulosic biofuels. While corn stover is a readily available feedstock as a by-product of corn production, it has relatively low yield per acre, and its quantities are likely to be limited by available land under corn. Furthermore, its harvest for bioenergy can have negative impacts on soil organic matter and soil erodibility. Thus, large-scale cellulosic biofuel production will require a transition from corn stover to perennial energy crops. There are a number of risks and uncertainties that affect farmers' willingness to grow energy crops and investors' willingness to build cellulosic biorefineries. We discuss these briefly in the subsections below, with more detail available in Appendix C.

10.5.1 AVAILABILITY OF MARGINAL LAND

The potential to grow energy crops on marginal land is appealing because it implies that these crops can be grown, at least to some extent, without diverting cropland. Use of marginal land for energy crop production would result in lower cost feedstock for biofuels. The availability of this land and the costs of converting land to energy crop production can significantly affect biomass supply and costs. As shown in Figure 51, in general, the average breakeven price of miscanthus and switchgrass is about twice as high on cropland as on marginal land, suggesting that it would be economically rational for landowners to prefer growing these crops on their available marginal land. Identifying this land at fine spatial resolution is challenging in the absence of economic data on returns to land, and uncertainty about the availability of this land creates uncertainty about biomass supply and cost.

FIGURE 51. BREAKEVEN PRICES ($/MT) OF MISCANTHUS AND SWITCHGRASS ON MARGINAL LAND AND CROPLAND



Source: https://www.choicesmagazine.org/choices-magazine/theme-articles/economic-and-policy-analysis-of-advanced-biofuels/are-bioenergy-crops-riskier-than-corn-implications-for-biomass-price

(a): Breakeven prices of miscanthus grown on marginal land under risk neutrality scenario.

(b): Breakeven prices of miscanthus grown on cropland under risk neutrality scenario.

(c): Breakeven prices of miscanthus grown on cropland under risk aversion scenario.

(d): Breakeven prices of miscanthus grown on cropland under risk aversion scenario minus those of under risk neutrality scenario.

(e)-(h) are the counterparts of (a)-(d) for switchgrass.

10.5.2 RISKS AND UPFRONT COSTS OF PRODUCING ENERGY CROPS

Unlike annual crops, energy crop production can involve high upfront costs of establishment and require several years before a harvestable crop is obtained. If the land was previously producing profitable crops, the forgone income from the land during those early years adds to the upfront costs of establishment. Energy crops can also expose farmers to a yield risk that is different from that of a conventional crop. A risk-averse farmer's willingness to produce biomass and that farmer's choice of biomass crops will depend not only on the average returns from the crop's production but also on its yield riskiness, the temporal profile of the returns, and its potential to diversify the crop portfolio. Willingness to convert land to biomass production will depend on the risk and time preferences of the farmer, the presence of a credit constraint (e.g., the availability of loans to finance perennial crop establishment), and the location of their farmland.

The disincentive for producing energy crops is likely to be particularly large if farmers are risk averse, preferring lower variability in returns at a point in time and over time, and if they have high discount rates (preferring income today instead of receiving the same amount in a future year) combined with a constraint on credit to cover the costs of establishment. These disincentives imply that a farmer will need to receive a higher price for producing energy crops compared to the price needed in the absence of risks, upfront costs, and easy availability of credit to cover those costs.

Miao and Khanna[152] estimate the extent to which risk-averse landowners will require higher prices for energy crop production to cover a risk premium. A positive risk premium is needed if the returns with energy crops are riskier than returns with row crops. The risk premium for an energy crop depends on the yield risk and price of corn and soybeans, as well as on the production costs of both the energy crop and corn and soybeans. They find that the risk premium is positive, on average, in the rainfed U.S., even though miscanthus has a lower relative yield risk than corn in most counties in the lower Midwest and large tracts of the South. This is because of the high fixed costs of producing miscanthus, which increase the relative variability of profits in response to variability in yields. The risk premium needed to induce conversion of cropland to switchgrass is even higher than for miscanthus due to the larger variability in switchgrass yields and the high opportunity costs of cropland.

10.5.3 UNCERTAINTY ABOUT DEMAND FOR BIOMASS

Biomass markets are yet to develop, but even when they do, they are expected to be very thin because biomass is costly to transport long distances. A refinery or biomass processor would be expected to obtain biomass from within a 25- or 50-mile radius of the processing plant to keep transportation costs low. With life spans of 10 to 15 years or even longer, perennial energy crops expose farmers to the risk of lack of demand for their crop if the refinery or processing plant nearby shuts down. In the event of the shutdown, the standing crop would lose significant value before the farmer has had time to recover the upfront investment in establishing it.

Demand for biomass is highly dependent on policy related to the use of bioenergy for transportation or electricity generation. In the past, uncertainties in the implementation of the cellulosic biofuel mandate component of the RFS and the cellulosic biofuel waiver policy have limited incentives to invest in biorefineries that would use energy crops as feedstock. With greater policy-induced assurance of demand for biomass and the CFPC incentives, supply of biomass from energy crops is more likely to emerge.

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[152] 2014

Investment in perennial energy crops also suffers from a chicken-and-egg problem. Farmers will be unwilling to convert land to produce an energy crop without certainty of a functioning biorefinery to purchase the biomass. Likewise, without preestablished energy crop production, a refinery seeking to produce cellulosic biofuel will be unable to secure funding or commence operation. Since it can take two to three years to establish an energy crop, contracts for energy crop production would need to start several years before the refinery can expect to be operational and demand biomass.

Programs such as the Biomass Crop Assistance Program (BCAP), established by the Food, Conservation, and Energy Act of 2008, can mitigate these problems. The BCAP provided matching payments that provide a dollar-to-dollar match (up to a limit) to the biomass price per ton paid by a biomass processor to cover costs of collection, harvest, storage, and transportation of eligible biomass; cost-share payments per acre to cover a portion of the establishment cost of perennial crops; and an annual payment of land rent to cover the forgone profit of growing conventional crops.

Another major source of uncertainty limiting investment in cellulosic biofuels is uncertainty about crude oil prices. Oil prices have fluctuated significantly over time, and this affects the competitiveness of advanced biofuels. With the shale gas boom in the last decade or so, concerns about energy security have lessened, and the U.S. has transitioned to becoming an exporter of petroleum products. While concerns about mitigating climate change are growing, and policies to promote renewable energy have emerged, these are yet to create assured markets and demand for advanced biofuels. Instead, the shift in policy interest towards electrification of the fleet is likely to create further uncertainty about investment in the infrastructure needed to support an advanced biofuel industry.

10.5.4 EFFECT OF RISK AND TIME PREFERENCES OF FARMERS ON BIOMASS FEEDSTOCK SUPPLY

The risks and uncertainties discussed above affect farmer incentives to supply biomass and the price that they would need to produce it. The Billion-Ton Report by the DOE did not consider these risks that can affect the price at which risk-averse, present-biased, and credit-constrained farmers would be willing to supply biomass. Miao and Khanna[153] consider these factors and their impacts for the supply of feedstocks. These estimated supply curves are available in Appendix A.

Miao and Khanna find that there is almost no biomass production when biomass price at the farmgate is lower than $30/MT. When biomass price is at $40/MT, almost all biomass production is from corn stover because corn stover is economically viable at this price as a by-product of corn. In most cases, miscanthus and switchgrass production does not commence until the biomass price is higher than $50/MT. The supply of corn stover becomes fairly vertical as the price of biomass increases above $40/MT because its production is constrained by acreage under corn. The acreage under corn is unlikely to be affected by a market for corn stover since corn stover profit only accounts for a small portion of profit from corn. As biomass price increases, corn stover faces increasing competition from miscanthus and switchgrass and thus in some cases corn stover production may decrease as biomass price increases. Miao and Khanna show that a high discount rate, high risk aversion, and credit constraint significantly discourage miscanthus production due to its long establishment period and high establishment cost.

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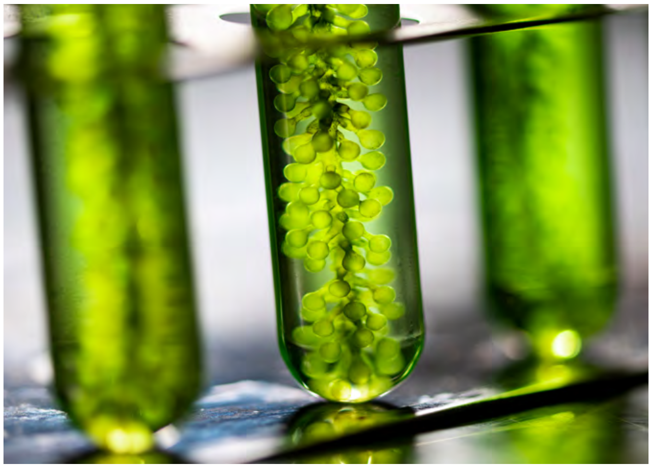
[153] Miao, Ruiqing and Madhu Khanna / Effectiveness of the Biomass Crop Assistance Program: Roles of Behavioral Factors, Credit Constraint, and Program Design.



10.6 ALGAE BIOFUELS

Algae emcompass a range of organisms that can be broadly classified into two main categories: microalgae (microscopic photosynthetic eukaryotic organisms and cyanobacteria) and macroalgae (seaweed). Whereas seaweeds are marine organisms, microalgae are phytoplankton found in both freshwater and marine systems. Algae have much higher solar energy conversion efficiency than most terrestrial crop species and can provide the inputs for a range of low-carbon products, from food to bioproducts and bioenergy. The algae market is growing significantly in diverse areas ranging from food, plant-based proteins, fertilizers, and animal feed to cosmetics and pharmaceuticals. Microalgae is appealing for biofuel production because it grows rapidly, and has a high lipid content and CO_2 absorption rate. According to the U.S. Department of Energy, microalgae have the potential to synthesize 100 times more oil per acre of land than any other plant, including soybeans. Several firms have been working to establish the economic feasibility of microalgae-based biofuels, but commercial production has yet to occur. Similarly, seaweeds, or macroalgae, have high biomass growth rates and high content of organic compounds such as polyunsaturated fatty acids; commercial production of macroalgae for biochar, biogas, and biofuel continues to be investigated.[154]

10.7 SUMMARY

Biofuel production, in the form of ethanol and BBD, has grown dramatically in the U.S. in the last two decades. Biofuels are currently using 40% to 45% of the corn and soybeans produced. This has caused some parties to raise concerns about the potential effects of biofuels production on food crop prices and on its impact on land being converted from non-crop uses to crop production with resulting loss in ecosystem services from that land.

These concerns are partially mitigated by:

1. **Steady improvements in the per-acre yields of corn and soybeans, enabling increasing production of these crops while total U.S. crop acres have actually declined since the start of the RFS;**
2. **Approximately one-third of the corn utilized as ethanol feedstock is returned to the feed market in the form of DDGS, a high-protein feed;**
3. **Oil used as biofuel feed represents only 20% of the weight of a soybean—the rest of the soybean (soybean meal) is a widely used high-protein animal feed with steadily increasing demand; and**
4. **U.S. exports of corn and soybeans have steadily increased since the start of the RFS, indicating that growing biofuels demand has not come at the expense of food supplies to the rest of the world compared to the level in 2007.**

There is a large body of literature analyzing the magnitude of changes to food crop prices and land use and the extent to which they can be directly attributed to biofuel production. These studies show that the impact of biofuels on crop prices has varied over time and ranged between 10% and 30% over the past two decades. Studies also show that

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[154] Hochman and Palatnik, 2022

corn ethanol production has led to indirect land use change of 0.47 million acres per billion gallons of corn ethanol on average while the corresponding estimate for soy BBD is about twice as large. Further increases in domestic U.S. ethanol demand are limited by market and regulatory constraints on demand for E15 and E85. This “blend wall” has largely limited consumption to 10% blend with gasoline as E10 because current policy design of the RFS does not provide sufficient incentives to lower the price of higher blends like E85 to levels at parity with E10 on an energy equivalent level. In the past, this, together with the tax credit for BBD and the CWC, has created incentives to increase production of BBD; these incentives can be expected to change as these policies are phased out and replaced by the CFPC. Projections of biofuel production in the coming decades indicate that corn ethanol production is expected to ramp up very slowly, and the percentage blended with gasoline will stay around 10% unless the favorable RVP treatment currently offered to E10 is extended to E15; if that were to occur, the ethanol content of the U.S. gasoline pool could increase towards 15% over the course of several years. However, production of BBD is expected to increase more substantively, and the blend rate with BBD is expected to increase from 6% currently to 8% by 2050 with a rising share of BBD being in the form of RD.

There are several new non-crop feedstocks that are under research and development to potentially convert to biofuels in the future. These include various types of cover crops that can be grown on cropland while the land is fallow, between crop production cycles and produce oilseeds which can be used to produce biomass-based diesel (BD and RD) and aviation fuel. Carinata, pennycress, and camelina are among the promising feedstocks due to their high oil content and yields; each of these is suitable for production in certain regions of the U.S. In addition to these, crop residues and high-yielding dedicated energy crops can be converted to produce cellulosic biofuels.

Studies show conditions under which the U.S. has the potential to produce over a billion tons of biomass as well as the price and land use requirements to produce the cellulosic feedstocks needed to meet the 16-billion-gallon cellulosic biofuel target set by the RFS in 2007. About half of this mandate could be met by harvesting agricultural residues, and the remaining half by producing energy crops. Miscanthus, as a high-yielding perennial crop, has the potential to meet a large share of the mandated volume. Miscanthus and other energy crops can be produced on marginal land without diverting productive cropland.

There are several risks and uncertainties that need to be considered in assessing the land use requirements, the spatial pattern of production, and the cost of producing biomass for cellulosic biofuels. These include the riskiness and upfront costs for the establishment of energy crops, the absence of assured demand for biomass and uncertainties related to the availability of land, and biofuel policy and oil prices that affect both supply and demand for biomass. Biomass markets are yet to emerge, and these risks and uncertainties need to be addressed in order for a cellulosic biofuel industry to develop.

Regulatory Future

The mix of biofuels has historically been largely determined by the RFS and dominated by corn ethanol. Future renewable and low-carbon policies could take several forms.

One option is extension of the RFS in its current form with slower growth in targets for the various types of biofuels currently included under the program. The RFS may also be expanded to include renewable electricity as an additional renewable fuel as currently proposed by the EPA.[155] Another policy option that may be considered in the future is a transition from the RFS to a national LCFS. Unlike the RFS, which sets volumetric targets for different types of biofuels based on their carbon intensity being below a threshold level, a national LCFS would set an overall goal for the carbon intensity of fuel in the country. It is designed to be a fuel-neutral and technology-neutral policy that allows blenders the flexibility to select the mix and quantity of low-carbon fuels to blend with, or substitute for, gasoline or diesel to achieve compliance with the policy, based on the carbon intensity of alternative choices and their relative costs. Alternatively, a national LCFS could be stacked on an RFS but would create significant complexity for market participants. Unlike the RFS, an LCFS creates much greater incentives to produce lower carbon intensity ethanol and BBD. It can also incentivize renewable fuels beyond those produced from biomass, such as EVs. Chen et al.[156] and Huang et al.[157] show that an LCFS by itself or stacked on the RFS would significantly change the mix of biofuels towards the higher cost but also less carbon-intensive cellulosic biofuels.

In the sections that follow, we discuss potential adjustments to these programs and how they might impact the markets for low-carbon biofuels.

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[155] Federal Register Vol. 87 No. 250 / Renewable Fuel Standard (RFS) Program: Standards for 2023-2025 and Other Changes.

[156] Chen, Xiaoguang, H. Huang, M. Khanna, and H. Önal / Alternative transportaion fuel standards: Welfare effects and climate benefits.

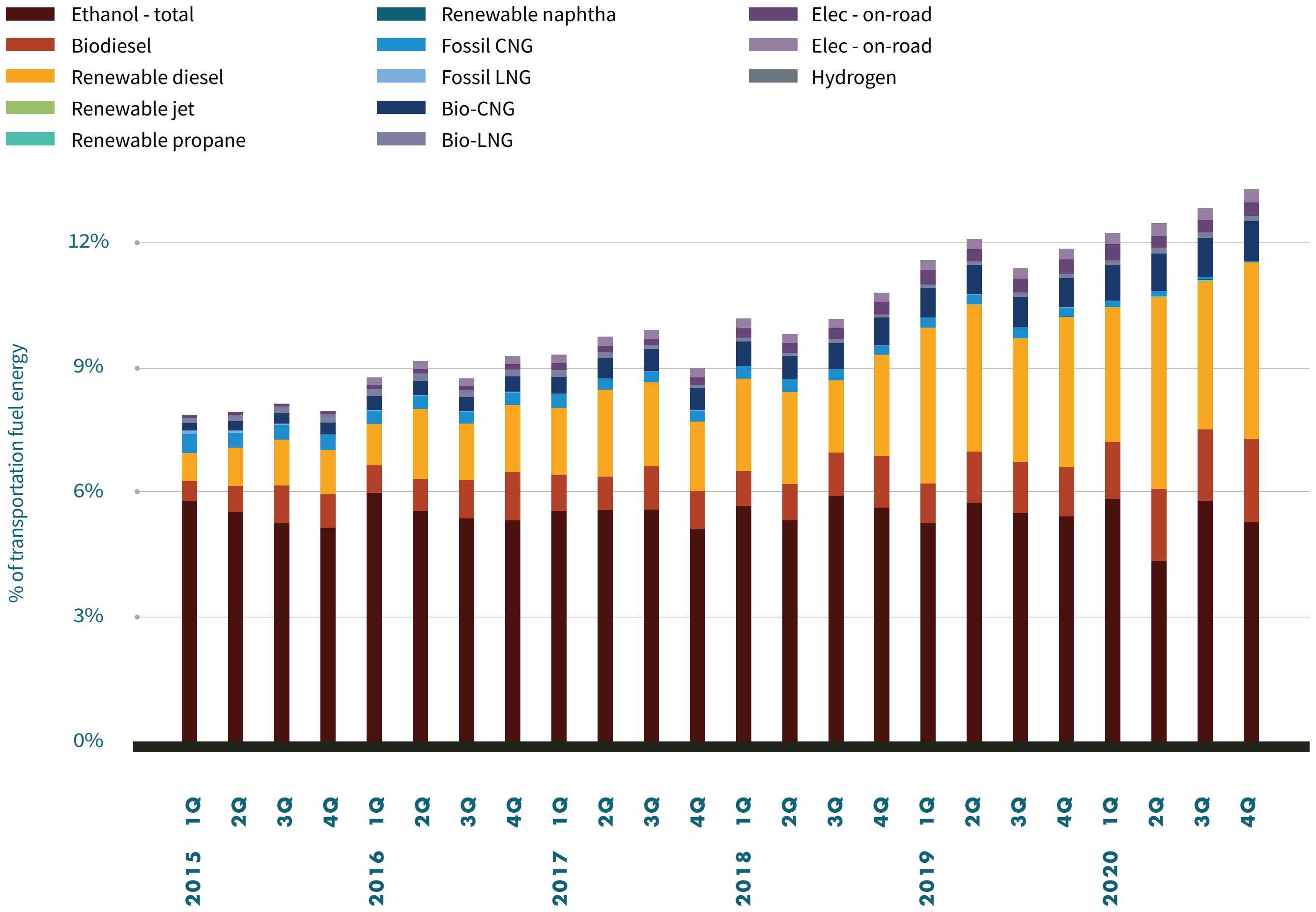
[157] Huang, Haixiao, M. Khanna, H. Önal, and X. Chen / Stacking low carbon policies on the renewable fuel standard: Economic and greenhouse gas implications.

11.1 POTENTIAL LOW-CARBON FUEL STANDARD ADJUSTMENTS

The California LCFS is the most significant nonfederal program promoting low-carbon fuels in the U.S. Its significance comes from a combination of the size of the California transportation fuel market, the innovative and ambitious nature of the program, and the influence which it exerts on policies in other U.S. states and even other countries globally. The scope of the LCFS encompasses all transportation fuels and is managed as part of a suite of California policies aimed at driving the state to carbon neutrality by 2045. The LCFS has had a profound impact on the composition of ICEV fuels marketed in the state as the key driver of reduced GHG emissions from the on-road fleet and this effect is expected to continue in the coming years.

Figure 52 below illustrates the growing role of low-carbon fuels in the California market since the start of the LCFS in 2011. It illustrates how ethanol's energy share of the market has held nearly steady since the beginning of the program while the share of BD and RD has grown considerably from a nearly invisible share in 2011 to being the major contributors today. It can also be seen that the CNG and LNG market has shifted from fossil-based to renewable-based over that timeframe while the contribution of NGVs has steadily grown. The contribution of electricity, both on-road and off-road, has grown significantly in recent years but remains small compared to the contribution of biofuels used in ICEVs. A more detailed discussion of the individual fuels and feedstocks is presented in the following subsections.

FIGURE 52. SHARE OF LOW-CARBON FUELS IN CALIFORNIA SINCE THE START OF THE LCFS

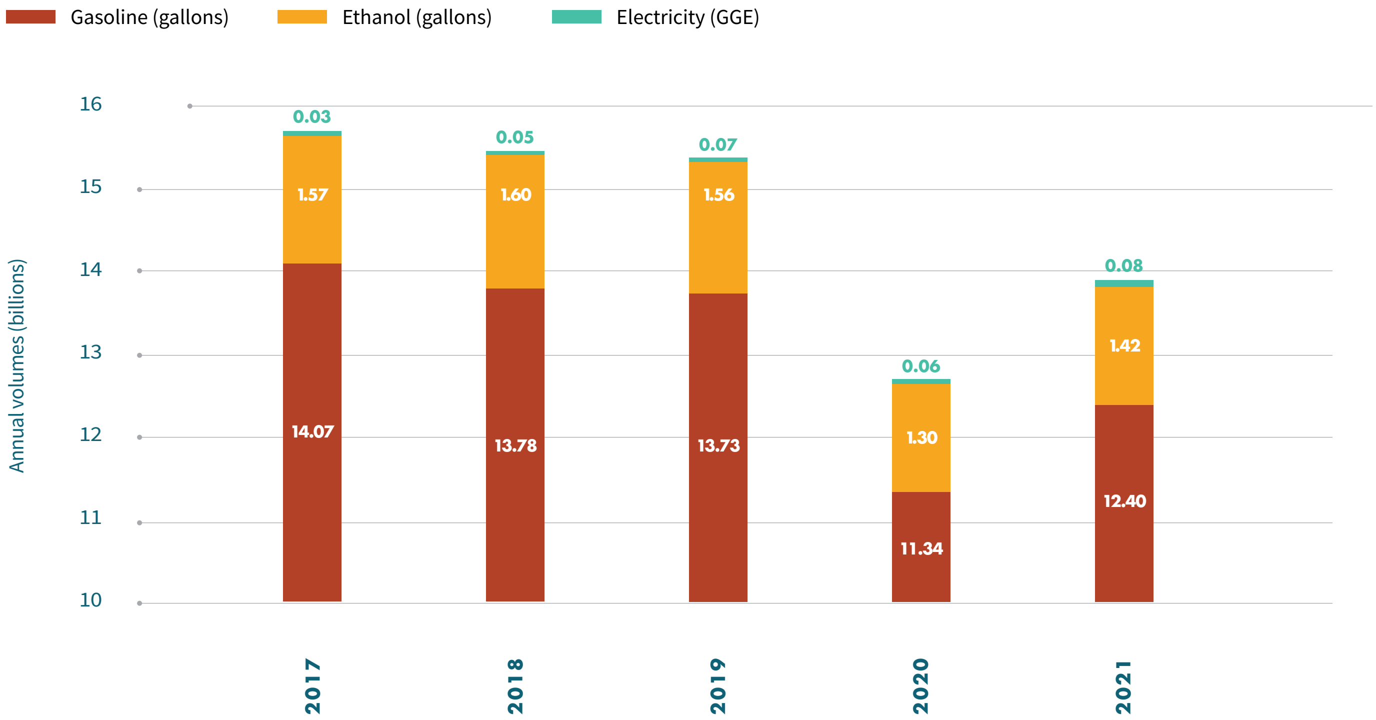


11.1.1 ASSOCIATED SUPPLY AND DEMAND SHIFTS

The volumetric displacement of fossil fuels by low-carbon alternatives can most readily be analyzed by considering the three major fuel/vehicle platforms (light-duty vehicles fueled with gasoline-ethanol blends; heavy-duty vehicles fueled with diesel/BD/RD blends; and natural gas vehicles fueled by fossil or renewable natural gas) individually.

Light-Duty Vehicles (LDVs) – The current LDV fleet in California is dominated by engines fueled with gasoline-ethanol blends. EVs currently represent a small but rapidly growing share of the LDV fleet and the state has mandated that all new LDVs sold in the state after 2035 be ZEVs. Gasoline demand in California is nearly all in the form of blends containing 10% ethanol (E10) as meeting CARB gasoline standards with E0 is not practical and E15 is currently not permitted.[158] A small but growing share of the LDV fuel supply comes from E85 used in FFVs; this will ultimately be limited by the population of FFVs in the state. In-state demand for CARBOB (California blendstock for oxygenate blending, or the unfinished hydrocarbon gasoline prior to blending with ethanol) peaked at 14.1 billion gallons in 2017 and totaled 12.4 billion gallons in 2021; demand for ethanol has declined proportionately. Displacement of gasoline with electricity has only been a small factor in this timeframe as electricity demand by LDVs has increased from 32 million GGE in 2017 to 70 million GGE in 2021; bigger factors have been steady improvements in the fuel economy of the on-road fleet and reductions in VMT (vehicle miles travelled) for commuting and other purposes since the onset of COVID-19. The recent trend in the fuel mix of the California LDV fleet is illustrated in Figure 53 below.

FIGURE 53. CALIFORNIA LDV FUEL MIX



Source: CARB, Stillwater analysis

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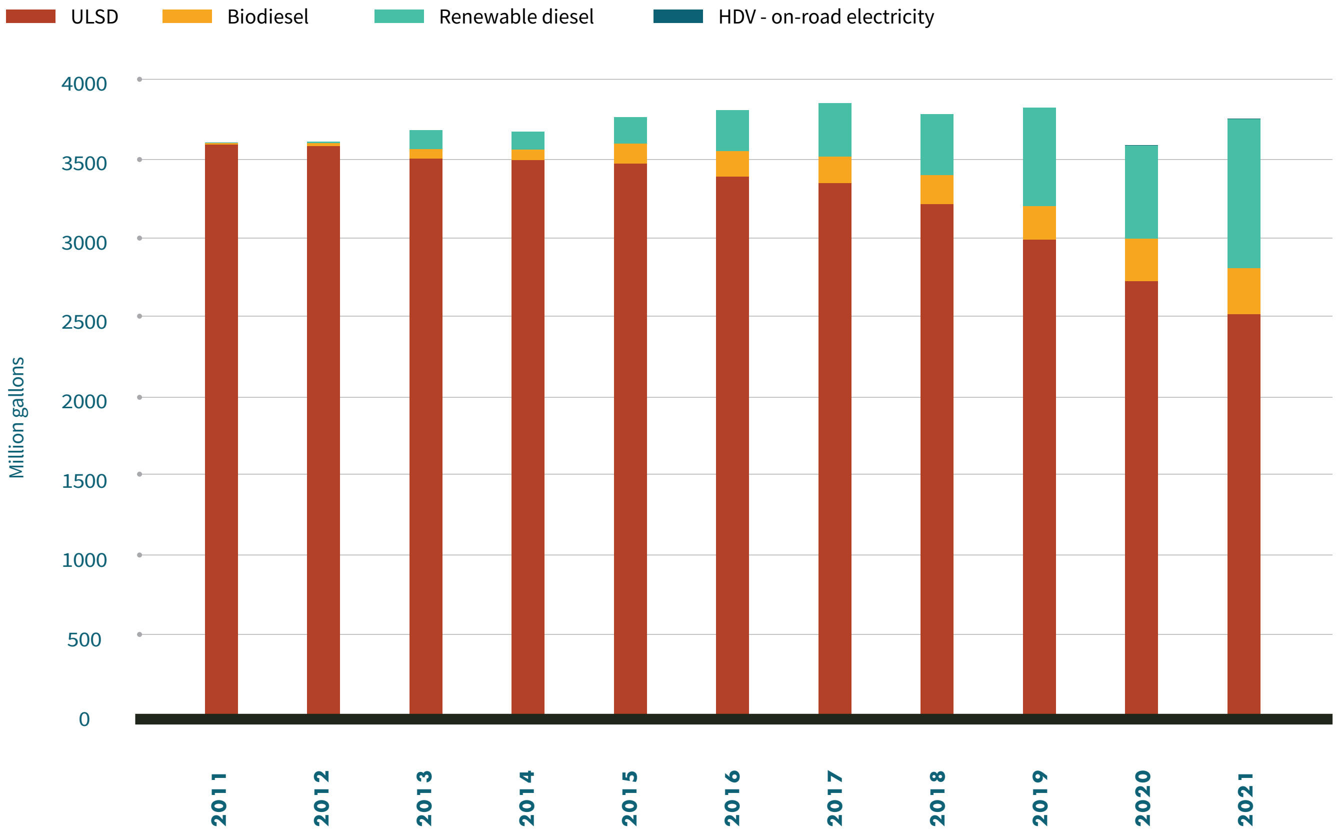
[158] CARB and representatives of the U.S. ethanol industry are currently working on the Multimedia Evaluation (MME) which state law requires before E15 could be approved for use. If that MME is successfully completed with a finding that E15 does not create significant environmental, health, or safety concerns compared with E10, the state may then move to permit the use of E15 consistent with restrictions imposed by EPA regulations.

FIGURE 54. DEMAND FOR HEAVY-DUTY FUELS IN CALIFORNIA



Source: CARB, Stillwater analysis

Heavy-Duty Vehicles (HDVs) – The current HDV fleet in California (excluding NGVs, which will be discussed separately) is dominated by diesel engines consuming blends of petroleum diesel with BD and RD. Demand for these fuels peaked in 2017, bottomed with COVID-19 in 2020, and has since recovered. They are expected to slowly grow going forward as GDP-driven growth in heavy-duty fuel demand is partially offset by a growing share of that demand being supplied, near term, by NGVs and, in the longer term, by electrification. Historical demand for these fuels from the start of the LCFS in 2011 through 2021 (the last full year for which data are available) is illustrated in Figure 54. Notably, the share of petroleum-derived diesel fuel in this mix has declined from 99.6% in 2011 to 67.1% in 2021, while BD has grown from 0.3% to 7.7% and RD has grown from 0.1% to 25.1%. Data for the first half of 2022 show even further displacement of petroleum diesel, primarily through continued growth in RD's share. The RD share of the diesel pool is expected to continue growing for the next several years as available supply grows and LCFS standards grow increasingly stringent. RD is also expected to displace some BD in the mix as both fuels compete for the same feedstocks and RD plants are expected to have more favorable economics once built. Over the longer-term, California's Advanced Clean Truck rule[159] seeks to transition the heavy-duty fleet away from liquid fuels to ZEVs (EVs and FCEVs); by 2035 ZEVs are required to comprise 55% of new sales in classes 2b-3, 75% of new sales in classes 4-8 (straight trucks), and 40% of truck tractor sales.

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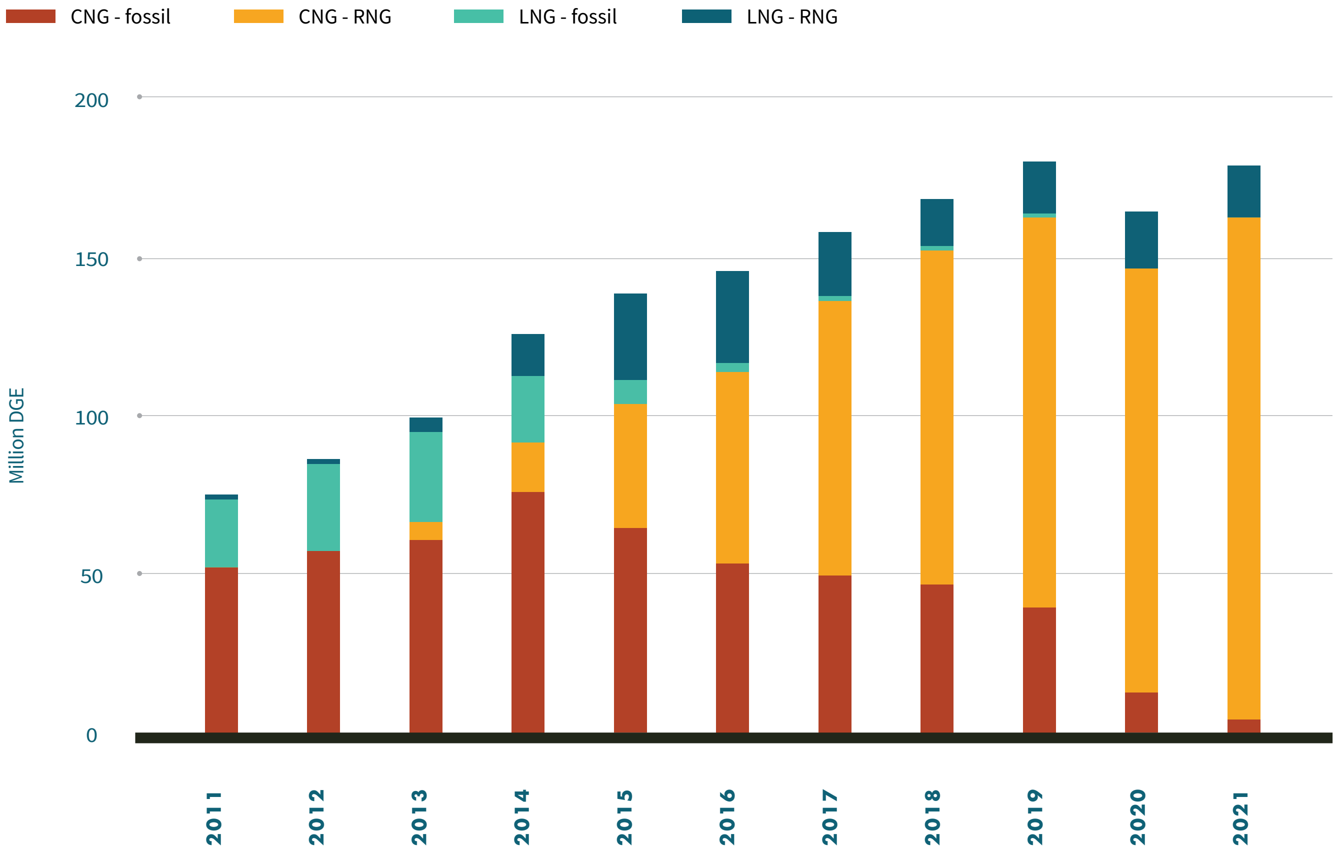
[159] CARB / Advanced Clean Trucks Fact Sheet.

Natural Gas Vehicles – While NGVs nationally represent only a small portion of the heavy-duty fleet, they play a much larger role in California as it is home to nearly half of all U.S. NGVs. California demand for natural gas fuels (both compressed natural gas, CNG, and liquified natural gas, LNG) has more than doubled since the launch of the LCFS, from 75 million diesel gallon equivalent (DGE) in 2011 to a high of 180 million DGE in 2019, even as LNG volumes declined from 22.9 million DGE in 2011 to 16.3 million DGE in 2021. Demand dropped in 2020 with COVID-19 but recovered to nearly 2019 levels in 2021, with future growth expected. As illustrated in Figure 55, the composition of this demand has shifted significantly over this time. In 2011, CNG and LNG were almost entirely supplied from fossil natural gas. By 2020, fossil LNG had nearly all been replaced with LNG produced from RNG. The corresponding transition for CNG vehicles started later, but 97.5% of CNG was derived from RNG in 2021. A key contributor to the shift from fossil to renewable natural gas in this segment is the fact that fossil LNG and CNG shifted from small credit generators at the beginning of the LCFS to small deficit generators as the LCFS CI reduction standards have become more stringent. Simultaneously, production of RNG in the U.S. has grown markedly over this timeframe and the LCFS regulations, which allow the use of book-and-claim accounting for RNG, enable RNG produced nearly anywhere in the U.S. to claim LCFS credits as low as -280 gCO_2e/MJ.

FIGURE 55. DEMAND FOR NATURAL GAS FUELS IN CALIFORNIA



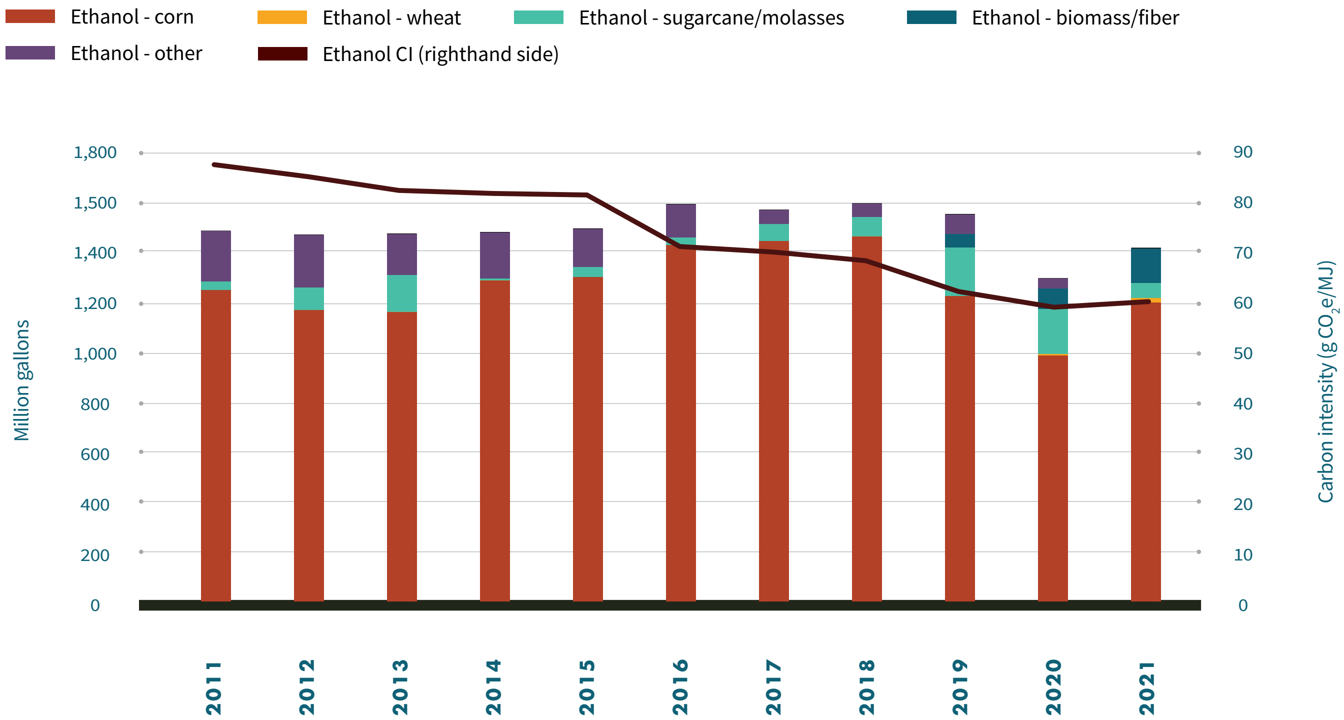
Source: CARB, Stillwater analysis

11.1.2 ASSOCIATED FEEDSTOCK SHIFTS

The mix of feedstocks utilized for the highest volume alternative fuels (ethanol, BD, RD, and natural gas) have evolved since the start of the LCFS and are expected to continue to do so going forward. This mix change comes in response to the need to continuously reduce the CI of the fuel mix enabled by continuing investment by suppliers into new production technologies. Each of these four fuels are discussed individually in the following paragraphs.

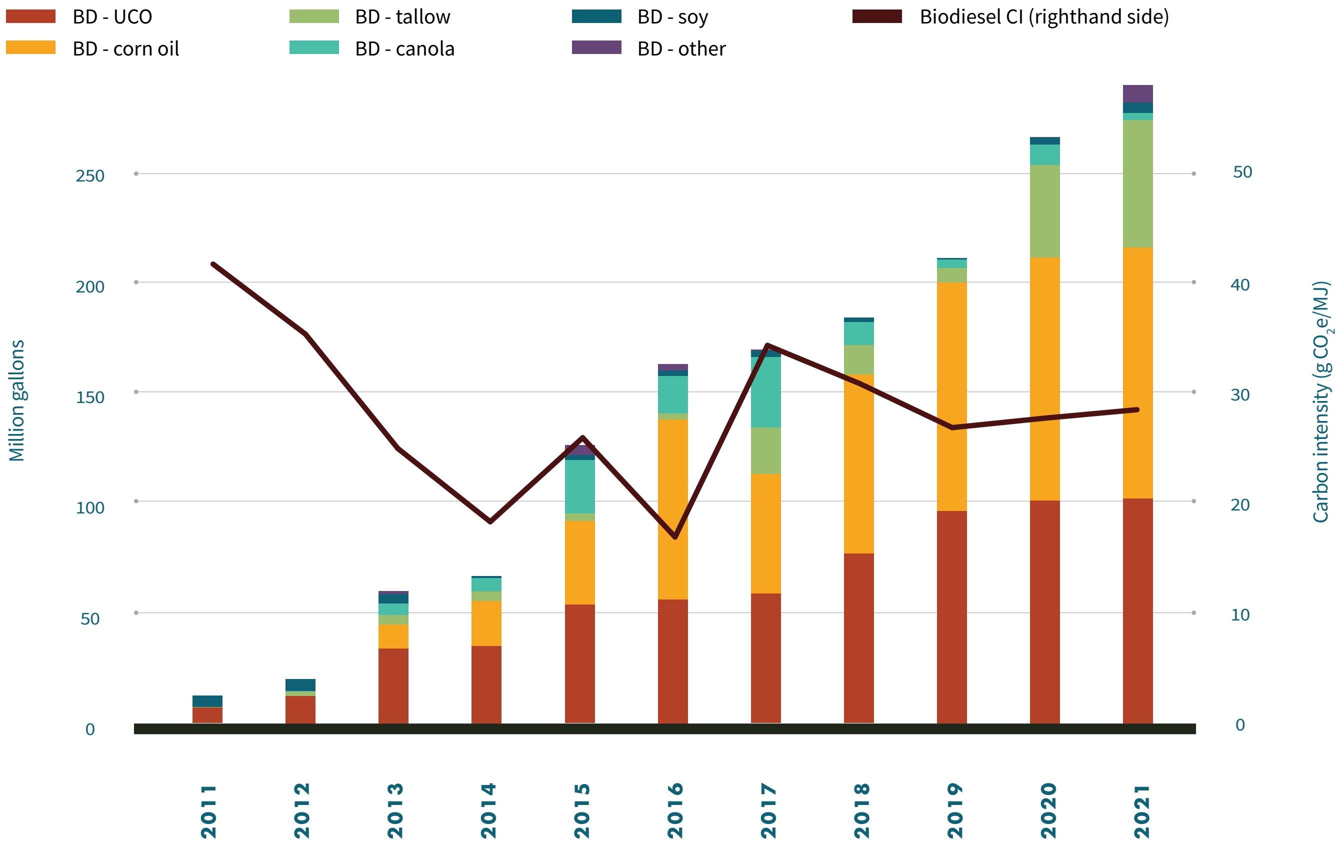
Ethanol – The evolving mix of ethanol feedstocks in California is illustrated in Figure 56. As is the case for the U.S. as a whole, corn is the primary ethanol feedstock for California, ranging from a low of 76% of the mix in 2020 to a high of 92% in 2017 and 2018. It was originally thought that imported sugarcane ethanol from Brazil would be a major component of the mix due to its lower CI, but that has not been realized on any consistent basis due to demand for ethanol in Brazil, competing demands for sugar, and the extended logistics required to enable consistent supplies. It was also thought that cellulosic ethanol would be a major component, but the technology has taken much longer to develop. Since 2019, cellulosic ethanol from corn kernel fiber has been a growing contributor to the mix and can be expected to grow further in the coming years, particularly if EPA begins approving RFS registrations for corn fiber ethanol producers. The contribution of grain sorghum (milo) ethanol (the major contributor to the "Other" category in Figure 56) has slowly decreased over the years. This evolving mix of ethanol feedstocks has resulted in the CI of the California ethanol pool (indicated by the line in Figure 56) declining from over 87 in 2011 to less than 60 in 2020 and 2021; the drop from 81.6 in 2015 to 71.0 in 2016 is largely explained by the 2016 adoption of an updated CA-GREET model which assesses a lower indirect land use change (ILUC) penalty for corn ethanol production.

FIGURE 56. ETHANOL FEEDSTOCKS FOR CALIFORNIA MARKET AND CI TREND



Source: CARB, Stillwater analysis

FIGURE 57. BIODIESEL FEEDSTOCKS FOR THE CALIFORNIA MARKET AND CI TREND



Source: CARB, Stillwater analysis

Biodiesel – BD supplied to California comes from a somewhat different mix of feedstocks than BD supplied to the rest of the U.S. as feedstock is the primary driver of CI, and the California market offers a premium for the lowest CI sources of BD. Figure 57 presents the evolving mix of BD feedstocks used to supply California and the trend in the composite CI. Used cooking oil (UCO) has been a major feedstock for California BD since the start of the LCFS, and corn oil's share has grown with the available supply from corn ethanol plants. Tallow has played a growing role in recent years as an increasing share of the biofuel plants supplying California have added the capabilities required to produce tallow-based BD. Canola and soy have been smaller and more variable contributors to the California BD pool, despite their larger share of the U.S. BD market, due to their higher CI.[160] The composite CI of the California BD pool has generally run close to 30 gCO$_2$e/MJ in recent years, well below the 50+ CI values associated with soy- and canola-derived BD. Going forward, the mix of feedstocks available for California BD production will be impacted by the rapid increase in U.S. RD production as the two fuels compete for the same feedstocks. Due to the larger scale economies and the deeper pockets of RD plant owners compared to BD plant owners, it is expected that RD plants will be able to disproportionately attract the lowest CI feedstocks, and the share of the California BD pool sourced from soy and canola oils will increase, resulting in a gradual increase in the composite CI.

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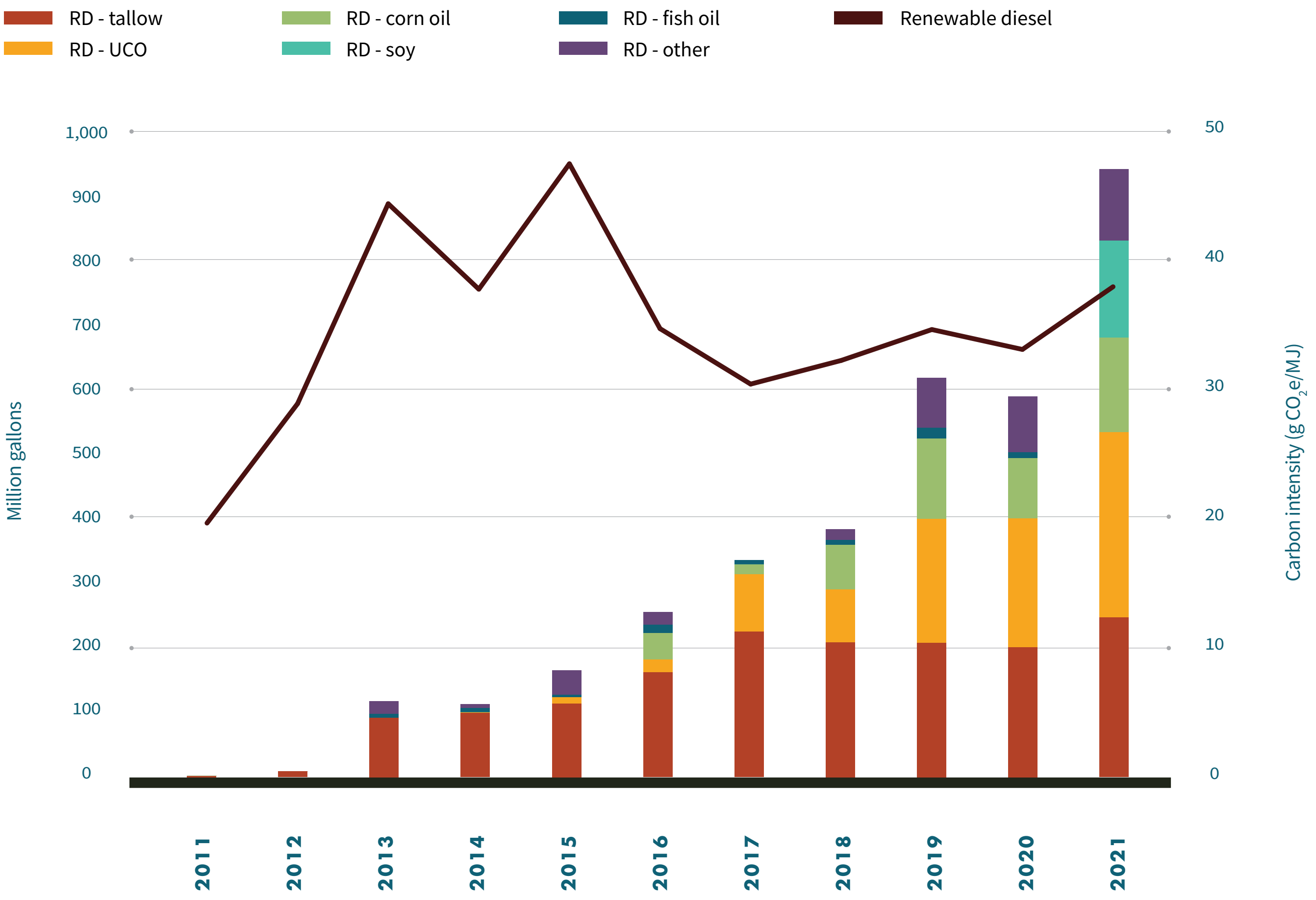
[160] As virgin oils derived from crops, the CI of fuels derived from these feedstocks are assed an ILUC factor in the CI calculation.

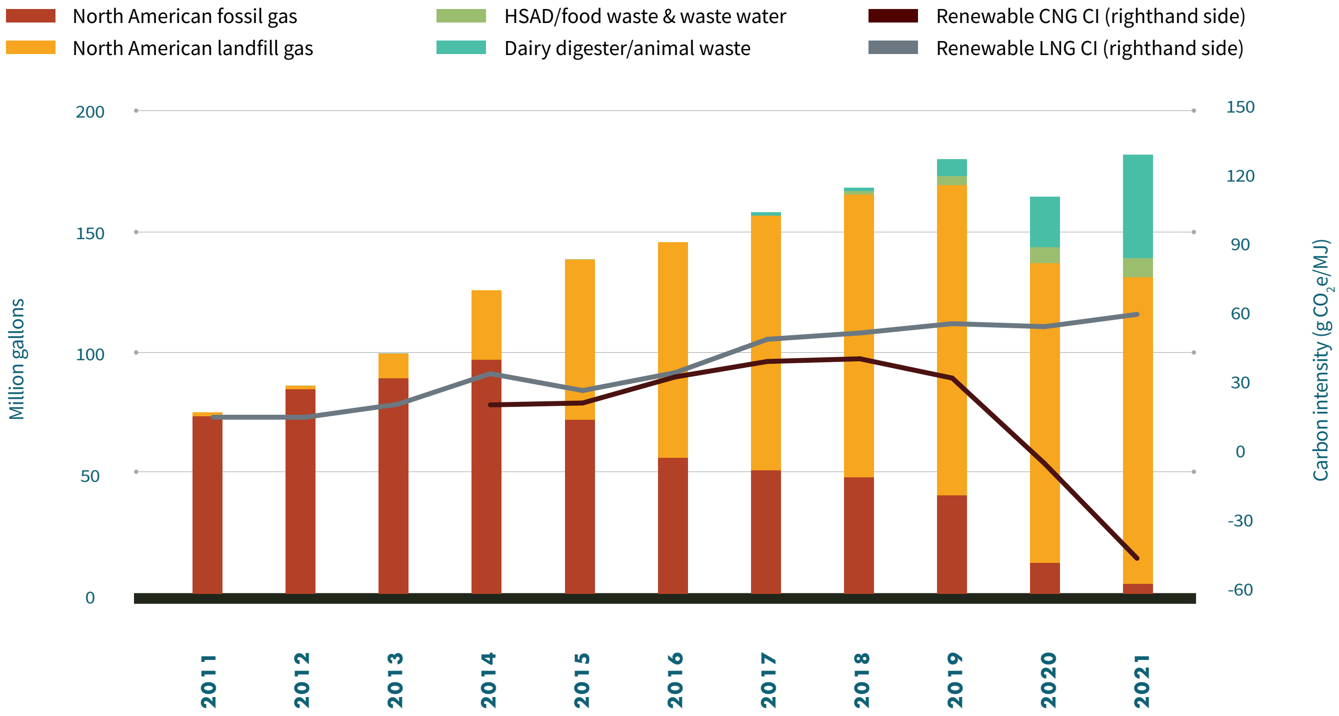
Renewable Diesel – California, due to the LCFS, has always been the primary market for RD supplied to the U.S. market. The initial RD plants were built with the capability of processing tallow and, through 2018, tallow was always the feedstock for greater than 50% of RD supplied to California. As a by-product of meat production, tallow-derived biofuels achieve favorable CIs. As production of RD has grown and BD producers began competing for tallow supplies, producers diversified their feedstock mix, with UCO playing a growing role (surpassing tallow in 2021). Corn oil has also grown as an RD feedstock with growing supply as a coproduct of corn ethanol production. Despite its higher CI, soy-derived RD was first supplied to California in 2021, as new RD plants started up before they could install the pretreaters necessary for them to process the lower-CI feedstocks. Going forward, soy-derived RD is expected to remain and potentially grow its share of the feedstock mix as combined BD and RD production pushes the limit of feedstock availability. If that occurs, it is likely that the composite CI of RD supplied to the California market will gradually increase from recent values between 35 and 40. The historical trend for the RD feedstock mix to California and the associated CI is presented in Figure 58.

FIGURE 58. RENEWABLE DIESEL FEEDSTOCKS FOR THE CALIFORNIA MARKET AND CI TREND



Source: CARB, Stillwater analysis

FIGURE 59. RNG FEEDSTOCKS FOR THE CALIFORNIA MARKET AND CI TRENDS



Source: CARB, Stillwater analysis

Renewable Natural Gas – As discussed above, RNG has almost completely supplanted fossil natural gas as the fuel utilized in California NGVs. This trend occurred first in the smaller LNG segment of the market before moving into the larger, and more diverse, CNG market segment. Initially, the supply of RNG came primarily from landfills, which have been collecting and utilizing their biomethane production for many years. RNG produced by anaerobic digestion of food waste and wastewater plant sludges began entering the market in 2013, and RNG from anaerobic digestion of dairy and swine manure began entering the market in 2017. These sources receive more favorable CIs as they are credited with reducing methane (a potent GHG with a global warming potential 25 times greater than CO$_2$) emissions which would occur were these wastes allowed to naturally decompose.[161] As a result, these new sources of RNG are beginning to displace landfill gas in the California RNG pool (primarily in the CNG portion of the pool) as demand for CNG and LNG begins to level out.[162] Going forward, it is likely that production of RNG from dairy and swine digesters as well as food waste will continue to increase as California seeks to displace food waste from landfills and reduce methane emissions from dairy and swine operations. As a result, fossil natural gas's share of the pool will continue to be small and landfill gas will increasingly need to find other markets.[163] The CI of the LNG pool has been slowly increasing in recent years as it is commonly supplied by older landfill gas generators, while the CI of the CNG pool is rapidly decreasing as the share of dairy and swine digester RNG (with highly negative CIs) displaces landfill gas in these applications. These trends are illustrated in Figure 59.

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[161] Dairy and swine digester RNG is typically credited with a CI of -300 gCO$_2$e/MJ or less. Thus, even a small volume of these fuels earns a substantial number of LCFS credits.

[162] This is occurring because the largest fleets which are appropriate for use of NGVs have already made that conversion, and the state is adopting policies to transition these same fleets to ZEVs as the technology becomes commercially available and cost-effective.

[163] EPA's current proposal for eRINs in the proposed 2023-2025 RFS Set rule, if finalized, will enable electricity produced from combustion of RNG or biogas to generate RINs. Those RINs, referred to as eRINs, can only be separated by EV manufacturers up to the estimated electricity demand of their branded EVs on the road in the 48 contiguous states.

11.1.3 ASSOCIATED MARKET ADJUSTMENTS

The value of LCFS credits has been steadily declining since early 2020 as fuel demand dropped and has only slowly recovered since the onset of COVID-19, RD supply to the California diesel pool has steadily grown, the CI of RNG has rapidly decreased, and the EV share of the California light-duty fleet has rapidly grown. This decrease in credit prices from highs around $220/MT to recent values of $68/MT has put a damper on new investments in the supply of low-carbon fuels for the California market. Simultaneously, California has adopted policies seeking to achieve a 40% statewide reduction in GHG emissions compared to 1990 levels by 2030 and achieve net carbon neutrality by 2045. As transportation fuels represent approximately 40% of the state's GHG emissions, CARB is now moving to adopt more stringent CI reduction requirements for the LCFS. As part of the regulatory development process, CARB is currently evaluating scenarios requiring 25%, 30%, or 35% CI reductions by 2030 instead of the 20% CI reduction currently in the regulations. These proposed reductions would go even further by 2035 and beyond. Once CARB settles on a new regulatory framework and issues formal proposals to begin the amendment process, it is expected that LCFS credit prices will strengthen and developers of low-carbon fuel projects will have greater success in securing the required investments.

11.2 POTENTIAL RENEWABLE FUEL STANDARD ADJUSTMENTS

On December 1, 2022, EPA issued a proposal that included the RFS targeted volumes for 2023, 2024, and 2025. This proposal also addressed how the RFS standards would be set after 2022[164] and proposed how a new eRIN program would work starting in 2024.

After 2022, there are no statutory volume targets; EPA is instead charged with setting the annual volume requirements based on several criteria. EPA's proposed 2023-2025 rule is the first rulemaking of this new era. While EPA's justification process will now change, the actual targeted volume-setting process will remain very similar to EPA's prior process and the targeted volumes are likely to remain consistent with EPA's previous RFS rulemakings.

The new targeted volumes expect increased volumes for RNG and BBD,, while ethanol and other advanced biofuels are expected to have little to no growth in volumes.

11.2.1 ASSOCIATED SUPPLY AND DEMAND SHIFTS

The RFS volumetric displacement of fossil fuels by biofuels is best analyzed by examining the three major fuel/vehicle platforms (LDVs fueled with gasoline-ethanol blends; HDVs fueled with diesel/BD/RD blends; and NGVs fueled by fossil or renewable natural gas) individually.

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[164] 2022 was the last year for which the statute set annual volume targets. The statute gives EPA general guidelines on how they are to set these values for years after 2022. Due to the large shortfall in production of cellulosic biofuels since the very beginning of the RFS, EPA has effectively used its waiver authority to set annual targets below the statutory levels for a number of years.

Light-Duty Vehicles – The current LDV fleet in the U.S. is dominated by engines fueled with gasoline-ethanol blends. As in California, EVs currently represent a small but rapidly growing share of the LDV fleet in the U.S. as a whole. Gasoline demand in the U.S. is primarily E10, although there are small volumes of E15 and E0 dispensed as well. A small share of the LDV fuel supply comes from E85 used in FFVs; this fuel has a low CI but is limited by the population of FFVs in the U.S. Figure 60 shows that ethanol demand is likely to slowly increase through 2050. Figure 61 shows that most of the growth in ethanol usage will be through the growth of E15.

FIGURE 60. U.S. GASOLINE AND ETHANOL DEMAND FORECAST (AEO 2022)

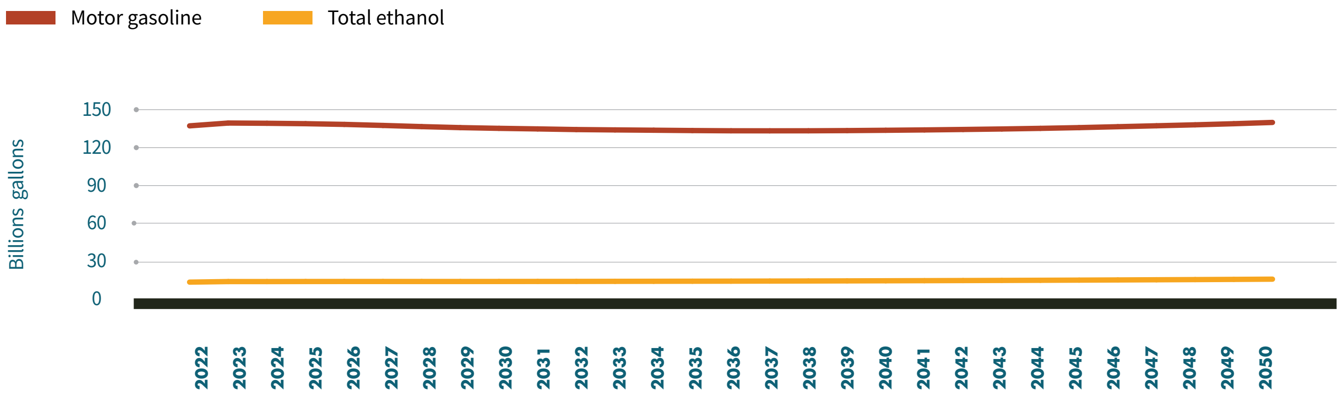
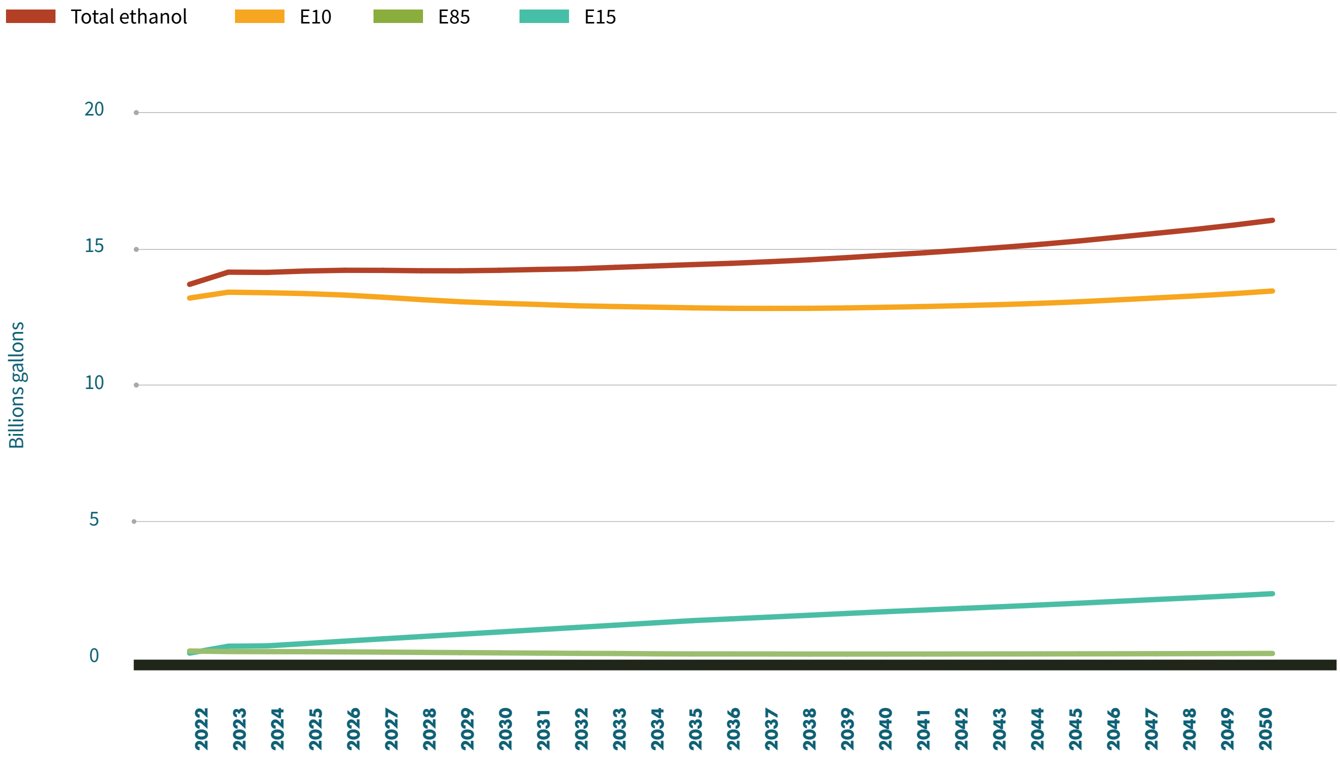


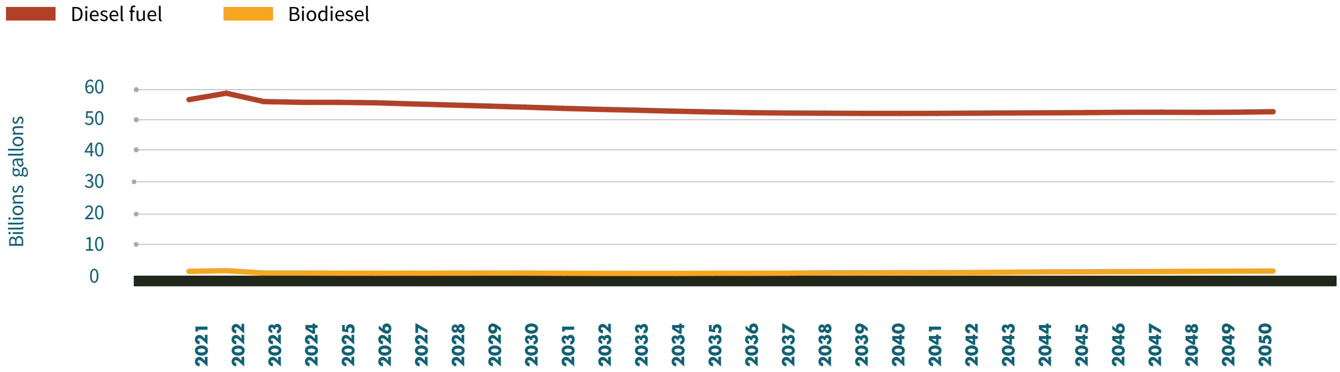
FIGURE 61. U.S. ETHANOL DEMAND FORECAST BY GASOLINE ETHANOL CONTENT (AEO 2022)



Heavy-Duty Vehicles – The current HDV fleet in the U.S. (excluding NGVs, which will be discussed separately) is dominated by diesel engines consuming blends of petroleum diesel with BD and RD. Demand for diesel fuel peaked in 2017, bottomed with COVID-19 in 2020, and has since recovered. Diesel fuel demand is expected to slowly decline through 2035 and then to grow as GDP-driven growth in heavy-duty fuel demand continues. The RFS will drive small demand increases in BD throughout the U.S. except for California, Washington, and Oregon, where LCFS-style programs drive more BD and RD usage than the RFS requires. RD demand will be minimal in the U.S. except for these three LCFS states. Figure 63 shows that the EIA is projecting that RD demand will increase about 0.6 billion gallons per year (BGY) in the 2022-2023 time period while BD demand will drop about 0.6 BGY in the same time period. The RD demand increases will occur mainly in the three LCFS states.

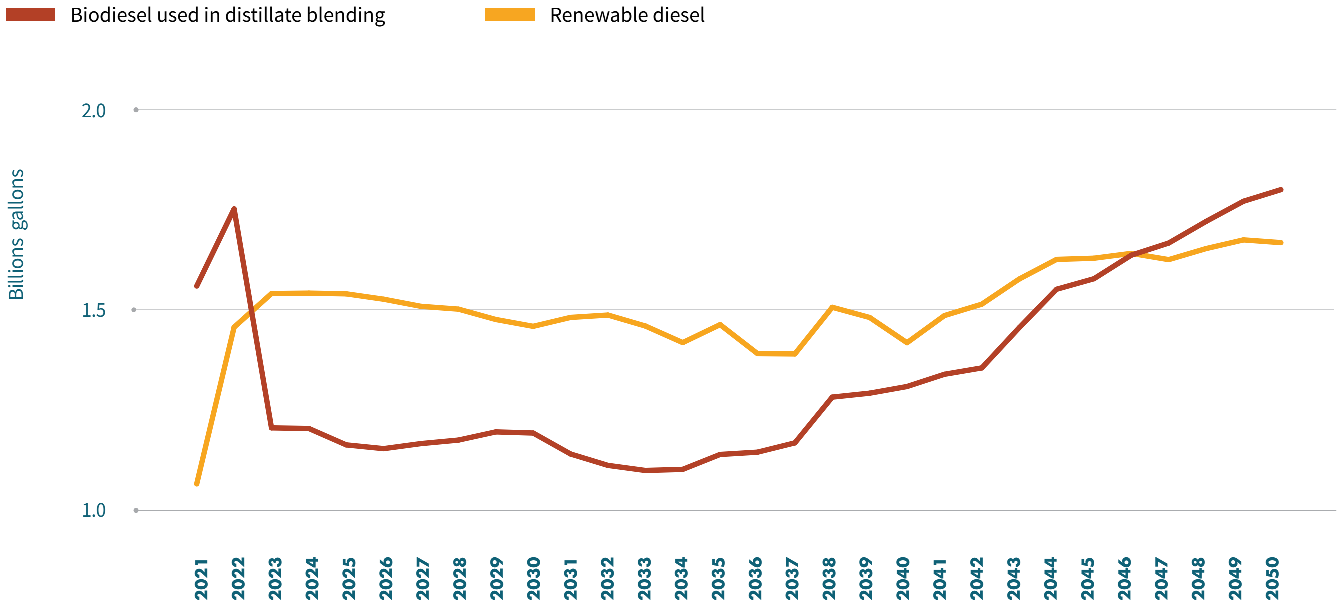
From 2023 through roughly 2037, RD and BD demand will remain roughly constant. After 2037, the demand for both RD and BD generally increases through 2050.

FIGURE 62. U.S. DIESEL FUEL AND BIODIESEL DEMAND (AEO 2022)



Source: AEO 2022

FIGURE 63. U.S. BD AND RD DEMAND



Source: AEO 2022

Natural Gas Vehicles – While NGVs nationally represent only a small portion of the heavy-duty fleet, California is the home to nearly half of all U.S. NGVs. In the rest of the U.S., the RFS will be the primary driver of increases in natural gas fuels (both CNG and LNG). EPA is projecting the generation of D3 cellulosic biofuel RINs to grow at a 13.1% rate for the years 2023, 2024, and 2025. EPA will therefore set the RFS mandated volumes for the cellulosic biofuels category at the values shown in Table 14. Assuming that these mandated volumes are met, EPA will then use the 13.1% in their future cellulosic biofuel calculations. In California, most of the fossil LNG will be replaced with RNG. Once the California demand for RNG has been met, the RFS cellulosic biofuel standard will be the main driver for additional RNG volumes.

TABLE 14. PROJECTED GENERATION OF CELLULOSIC BIOFUEL RINs FOR RNG (ETHANOL EQUIVALENT GALLONS)

YEAR	DATE TYPE	GROWTH RATE	VOLUME (MILLION RINS)
2021	Actual	N/A	561.8
2023	Projection	13.10%	719.3
2024	Projection	13.10%	813.9
2025	Projection	13.10%	920.9

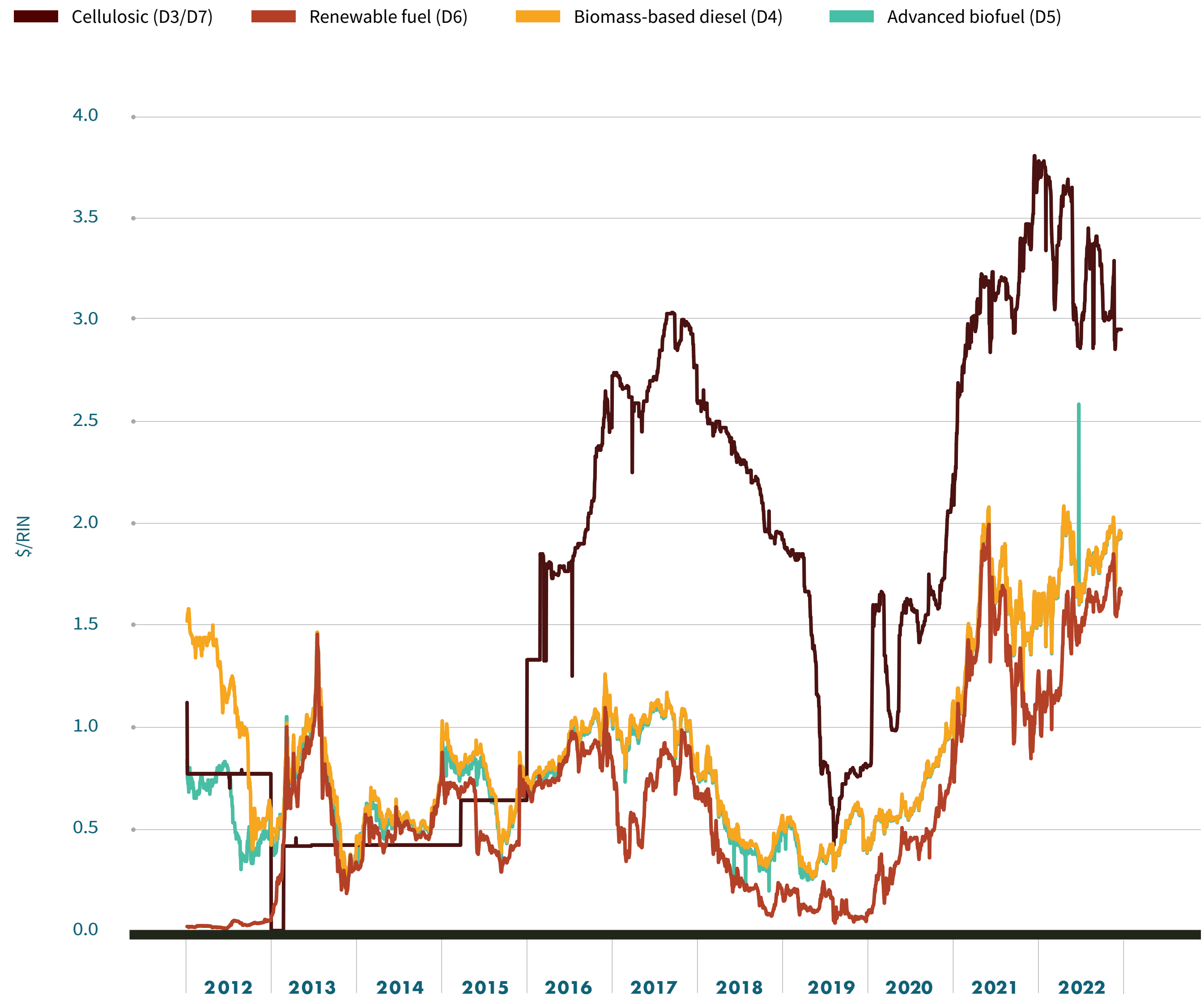
Source: Table III.B.1.a-2 from EPA RFS Proposal for 2023-2025

State-level LCFS programs are driving low-carbon fuel innovation: LCFS-style programs have accelerated the use of renewable fuels beyond what is required by the federal RFS.

11.2.2 ASSOCIATED MARKET ADJUSTMENTS

RIN prices have shown significant volatility over the years due to both fundamentals (supply and demand, volatility in the prices of petroleum products and agricultural commodities) and political uncertainty (EPA under different presidential administrations has taken different approaches to managing the program). Historical RIN prices from 2012 through 2022 are presented in Figure 64 below, and the following paragraphs summarize the issues which impact the individual RIN categories.

FIGURE 64. HISTORICAL RINs PRICING (2012-2022)



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D3 and D7 RINs – D3 RINs (60% required GHG reductions), representing cellulosic biofuels, and D7 RINs, representing cellulosic biofuels which can also be used as a substitute for diesel fuel, are the smallest portion of the RIN market. As discussed above, when the EISA was enacted, it was expected that this category would be composed primarily of cellulosic ethanol and would be the largest category of RINs by 2022. Cellulosic ethanol, however, has not yet been commercialized at material scale.[165] Approximately 99% of D3 RIN production comes from RNG. D7 RIN production is currently minimal. Because this category was designed around the commercialization of new technologies, the annual volume requirement is set by EPA forecasting expected production for each compliance year. In order to preserve orderly markets and pricing if production falls short of this forecast, obligated parties have had the option to comply by purchasing CWCs (cellulosic waiver credits) from EPA at a price set by a formula in the statute.[166] In Figure 64, the price curve for D3/D7 RINs is a series of straight lines representing the CWC price until production of RNG became sufficient to generate market sales of D3 RINs starting in 2016. Fundamentally, D3 and D7 RINs have a floor price set by the value of D5 RINs (as surplus D3 and D7 RINs can be used instead of D5 RINs towards meeting an obligated party's advanced biofuels obligation; the market approached this floor price in mid-2019) and a ceiling set by the CWC price. Large price moves have historically corresponded to announcements of EPA proposals and rumors about potential policy changes. D3 RIN prices were exceptionally volatile in 2022 due to uncertainty over EPA's post-2022 volume-setting process and rapid growth in the availability of D3 RINs from RNG. As currently proposed by EPA, the issuance of eRINs is expected to begin in 2024, and nearly all eRINs are expected to be D3s (as over 99% of RNG qualifies for D3s with the balance being D5s). With the availability of eRINs, nearly all the proposed year-on-year growth in RFS volume obligations in 2024 and 2025 comes from EPA's estimate of eRIN generation. Given anticipated growth in the EV population and substantial potential for biogas and RNG production to surpass any future growth in the NGV fleet, it is likely that eRINs will be the fastest growing element of the RFS for at least the next several years. The impact of that eRIN growth on the valuation of RINs will depend on how accurately EPA can match the annual volume standards with realized growth in eRIN generation. If EPA underestimates eRIN growth, the value of all RIN prices may be reduced; if EPA significantly overestimates eRIN growth, there is a risk that the resultant RIN shortage will require EPA to issue waivers to prevent RIN values from reaching unacceptably high prices.

D4 RINs – D4 RINs (50% required GHG reductions), representing BBD, fundamentally reflect the difference in the marginal cost of production of BD (the largest component of the BBD category) and petroleum diesel–i.e., the value of the D4 RIN compensates the blender for the additional cost incurred by sourcing BD instead of petroleum diesel to supply their customers. This calculation also reflects the value of the $1.00 per gallon federal biomass-based diesel blenders tax credit (BTC). As soybean oil, a by-product of crushing soybeans to produce soybean meal (a high-protein animal feed), is the marginal feedstock for production of BD, the price spread between soybean oil and diesel fuel (often referred to in the market as the heating oil-bean oil, or HOBO, spread) is the major driver of D4 RIN price. As can be seen in Figure 64, this price was high in 2012 (due to tight soybean inventories and low crude prices) and has regularly varied with price fluctuations in these commodities as well as the temporary lapses which have been allowed to occur

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[165] A number of firms made substantial investments in cellulosic ethanol technology following enactment of the EISA but only two commercial-scale plants were ever brought into production (POET-DSM and DuPont), neither of which ever achieved commercially sustainable operations, and neither are currently in operation. There is a limited volume of cellulosic ethanol being produced from corn kernel fiber at several corn starch ethanol plants; EPA has not yet processed most of their pathway applications, so associated RIN generation is minimal. Some plants are producing despite the lack of RINs in order to capture California LCFS credits.

[166] In the proposed rule, published on December 1, 2022, specifying annual volume requirements for 2023, 2024, and 2025, EPA has proposed discontinuing CWCs.

in the BTC. In 2021, D4 RIN prices hit all-time highs, due again to tight soybean inventories; D4 prices eased somewhat with the fall 2021 soybean harvest and then again rose as global vegetable oil markets were roiled by the Russian invasion of Ukraine.

D5 RINs – D5 RINs (50% required GHG reductions) represent advanced biofuels (which are neither cellulosic biofuels nor BBD). This category was created to allow a space for new types of biofuels to be brought into the RFS. It was originally envisaged that sugarcane ethanol imports from Brazil would also be a major component of this category. As surplus D4, D3, and D7 RINs can also be used to fulfil the implied D5 RIN obligation, D4 RINs (typically lower cost than D3/D7 RINs) create a price ceiling for D5s. As surplus D5 RINs can be used towards the implied D6 RIN obligation, the value of D6 RINs acts as a floor for D5 RIN prices. In 2012, soybean prices were relatively high, supporting D4 RIN prices, and there were material imports of sugarcane ethanol from Brazil, so surplus D4 RINs were not used to meet the implied D5 RIN obligation. Since 2012, however, D5 RINs have closely tracked D4 RINs.

D6 RINs – D6 RINs (20% required GHG reductions, although existing facilities are exempted) represent conventional biofuels (i.e., biofuels which are not advanced biofuels). This category is predominantly composed of cornstarch ethanol. Ethanol, regardless of feedstock, is most commonly used in gasoline in a 10% by volume blend (E10). A small amount of ethanol is sold in the U.S. as E85, a blend of 51% to 85% by volume of ethanol with gasoline which can only be used in FFVs. EPA has also approved the use of blends of E15 in all light-duty vehicles produced since 2001 (motorcycles, heavy-duty gasoline vehicles, marine engines, and other non-road equipment are excluded). As all U.S. automobile and gasoline infrastructure has long been compatible with E10, and corn ethanol has generally priced below wholesale gasoline, the value of D6 RINs was very low (approximately $0.02-$0.03) during the early years of the RFS program when the market-driven use of ethanol exceeded RFS requirements. This began to change in 2013 as the implied RFS D6 RIN obligation approached levels equivalent to all U.S. gasoline being sold as E10. As the market share of E85 and E15 has not been sufficient to bring the average ethanol content of U.S. gasoline to the levels required by the implied D6 RIN obligation, the value of D6 RINs since 2013 has generally tracked the value of D4 RINs. This is because D4 RINs in excess of that required to satisfy the BBD and advanced biofuels obligations have been required to cover the shortfall in D6 RIN generation. Deviation from this general trend was seen in 2015 when EPA issued the long-delayed proposed renewable volume obligations for 2014, 2015, and 2016. The D6 RIN price also dropped below the D4 price starting in early 2017 due to market speculation on how the then new Trump administration would enforce the RFS. This gap closed in late 2017 with issuance of the final RVO rule for 2018. There have also been deviations since then due to the market impact of actual and rumored small refinery exemption (SRE) issuances and in 2020 due to market uncertainty over COVID-19 impacts on the gasoline market.

Market Transition Requirements

Overview of Current Fleet and Fuels

A primary foundational element of the U.S. economy and society is the mobility afforded—to individuals and commerce—by an efficient and ubiquitous transportation system. At the heart of this transportation system is on-road transportation, which is based on fuels, vehicles, and interconnected roadway systems developed since the early 20th century. As we have entered the 21st century, the prevalent fuels and vehicle technologies employed—petroleum-based gasoline and diesel fuel coupled with the internal combustion engine (ICE)—have been found to contribute a significant percentage of the anthropogenic carbon dioxide (CO_2) emissions contributing to increased concentrations of CO_2 in the atmosphere. CO_2 is the greenhouse gas (GHG) primarily attributed with causing climate change.

According to the EPA, in 2020 GHG emissions from transportation fuels make up about 27% of U.S. anthropogenic GHG emissions,[167] making transport the largest sector source of GHG emissions in the country, with on-road transportation making up 83% of the anthropogenic GHG emissions. A transition has begun toward on-road transportation fuels and vehicle technologies which reduce transportation carbon emissions. The first step to reduce the carbon intensity of transportation fuels has been to replace fuels from nonrenewable sources with fuels from renewable sources as this has the effect of immediately reducing GHG emissions from those vehicles which are already in use. To best understand the context of the challenges to reducing carbon emissions from transportation fuels, this section will describe the fuel and vehicle systems that supply the existing on-road transportation system.[168]

By providing this context, we aim to highlight the scale, complexity, and successes of the current fuel and vehicle systems and, depending on the transitional fuel, the extent to which a system of similar scale will need to be developed to support the transportation energy transition.

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[167] EPA / Fast Facts on Transporation Greenhouse Gas Emissions.

[168] This report focuses on internal combustion engine vehicles (ICEVs) and their fuels. As electricity and hydrogen are not used in ICEVs, their production, logistics, fuel delivery and vehicle technology are not covered in this report.

12.1 FUEL PRODUCTION

Fuel production is the first step in the process of supplying transportation energy. Until the last couple of decades of the 20th century, transportation fuels were almost entirely fossil-derived. That trend has shifted in recent decades for reasons including increased energy security, lowering dependence on imported energy, and support for domestic agriculture in addition to the desire to reduce GHG emissions from transportation. The production of traditional and emerging fuels used in ICEVs has been discussed in some depth in previous sections of this report. We provide a brief general overview of fuels production here as a basis for the discussion that follows.

Gasoline and diesel represented 87% of the energy used as on-road fuel in the U.S. in 2021.[169] The 130 operable crude oil refineries located across the U.S. produce petroleum gasoline and diesel in excess of that used in the country, with the balance exported. The crude oil used in these refineries comes from both domestic and international sources. Since crude oil is a fossil resource, the products produced from it are considered nonrenewable and high carbon intensity. Of the total volume of products that the refining industry produces, gasoline and diesel make up approximately 78%, which makes the petroleum refining industry very intertwined with on-road transportation fuels.

With gasoline and diesel making up the vast majority of on-road fuel energy used in the U.S., the balance is made up of ethanol (5%), biodiesel (0.3%), renewable diesel (0.1%), fossil and renewable natural gas (0.3%), liquid petroleum gas (<0.1%), electricity (0.1%), and hydrogen (<0.1%).[170]

Ethanol (EtOH) can be produced from most any sugar, starch, cellulose, or plant fiber or can be produced synthetically from natural gas or petroleum. Ethanol from starches and sugar are considered renewable as their feedstock is renewable. EtOH produced from petroleum, natural gas, or coal is not considered renewable. Almost all the ethanol used in transportation fuels in the U.S. is produced from corn. Some EtOH used is produced from other grains, sugarcane, and other sources of sugar. In the U.S., ethanol is produced in 201 production facilities concentrated in the corn belt states in the Midwest.

Biodiesel (BD) is produced from fats, oils, and greases like tallow, used cooking oil (UCO), and vegetable oils and is a fatty acid ester that can be used in a diesel-fueled ICEV. As the feedstocks used are considered a renewable resource, BD is considered a renewable fuel. Because of poor cold weather flow properties and material compatibility, its use is usually limited to up to a 20% blend with other diesels. In the U.S., BD is produced in 72 production facilities with most of the capacity in the Midwest. These domestic facilities produce BD in excess of the U.S. demand, and the surplus production is exported.

Renewable diesel (RD) is produced from the same feedstocks as BD, thus RD is renewable and competes with BD production for feedstocks. Unlike BD, RD is made up of only hydrocarbons and is compositionally very similar to petroleum diesel. Domestically, RD is produced in 11 facilities with most of the capacity along the U.S. Gulf Coast or in the Western U.S.,[171] but there are many other RD projects being developed in North America. There is significant RD capacity internationally, and a significant volume is imported.

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[169] Approximately 130 billion gallons of petroleum gasoline and 47 billion gallons of petroleum diesel were used in the U.S. in 2021.

[170] Stillwater analysis of petroleum supply and AEO 2022 data.

[171] EIA / U.S. Renewable Diesel Fuel and Other Biofuels Plant Production Capacity.

Fossil natural gas is produced from geologic formations, oftentimes along with crude oil. The natural gas is processed to meet the specifications of the natural gas grid that covers most of the country. As a fossil source, it is not considered a renewable fuel.

Renewable natural gas (RNG) is methane produced by the biodigestion of waste material such as animal manure, food waste, or wastewater. Raw gas produced by biodigestion (often referred to as biogas) is upgraded to meet the specifications of the natural gas grid and therefore can be used as a direct substitute for fossil natural gas.

Liquid petroleum gas (LPG) is typically propane and butane that is recovered from fossil natural gas production or from the refining process. Also known as natural gas liquids (NGL), the LPG from these sources is not considered renewable. LPG produced as a by-product of RD production is considered a renewable fuel.

12.2 FUEL DELIVERY LOGISTICS

Each transportation fuel may be distributed from its respective production facility or import point via various methods. We discuss these in turn below.

Petroleum gasoline and diesel are normally transported from the refinery to fuel distribution terminals by multiproduct pipelines. These pipelines can transport different types of petroleum fuels in sequential batches, with each type of fuel routed to a specified tank at a terminal. From the terminals, the fuel is loaded into tanker trucks for delivery to retail service stations or to end users. Much of the final biofuel blending occurs at the terminal or when the fuel is loaded onto a tanker truck. Many of the product pipelines are owned and operated by non-refining companies that specialize in operating pipelines and service the refineries in a geographic area in transporting the fuels. Fuel terminals are often owned and operated by third-party pipeline companies and service multiple marketing companies.

In the U.S., there are approximately 230,000 miles of product pipelines that transport most of the gasoline and diesel to the marketplace. There are 1,300 fuel terminals across the U.S. that supply gasoline and diesel to 145,000 retail sites. Pipelines represent the most efficient and lowest cost method to deliver large quantities of liquid over long distances. In addition to pipelines, some gasoline and diesel fuels are transported by water (barge and tanker), rail (in tanker cars), or over long distances by tanker truck.

Ethanol is not sold to end users as a neat (100% undiluted or blended) product; it is blended with gasoline. Since EtOH will naturally separate from gasoline into an aqueous phase in the presence of water, and water may exist in the gasoline pipeline system, EtOH is not blended into gasoline prior to transport in the pipelines. EtOH could be transported in dedicated pipelines, but few of these are operating in the U.S. Instead, EtOH is transported to the terminals by rail tank cars and/or tanker trucks and stored in dedicated tanks. The common 10% ethanol/90% gasoline blend (E10) is made when the tanker truck that delivers to the retail site is loaded at the terminal rack.

BD is usually transported by rail tank cars, tanker trucks, and/or barge to terminals in the marketplace where it is blended with petroleum diesel prior to delivery. Some BD is blended with petroleum diesel at the BD production facility and delivered directly. Typically, BD can be blended to 5% and shipped in the pipeline system. However, BD is generally forbidden on pipelines that also transport jet fuels as jet fuel specifications have very low limits on BD content.

RD use in the U.S. is highly concentrated in California as it is incentivized under the LCFS regulation. With much of the RD production capacity either inland in the West, on the Gulf Coast, or imported, RD is delivered by rail tank cars, water, and/or truck or pipeline to the terminals in the marketplace. Since RD is almost identical to petroleum diesel in composition, it can be blended at refineries or terminals or sold as R100/R99 (100% or 99% RD).[172] RD can be shipped in the pipeline system; when blended with petroleum diesel, however, it is limited to 5% due to labeling requirements.

Fossil natural gas and RNG used in transportation share the same logistics system with natural gas destined for non-transportation uses since both are injected into the natural gas pipeline grid for delivery to market. In fact, on-road transportation use is a very small fraction of the volumes carried in the natural gas pipeline grid. Some RNG is not injected into the pipeline grid and is used directly to fuel vehicles, but most RNG used in transportation is injected into the grid. Since the methane in RNG is chemically identical to the methane in fossil natural gas, transportation of RNG from supply to user essentially occurs virtually—the RNG is injected into the natural gas pipeline system, and a like quantity of natural gas is withdrawn and delivered to the marketplace and deemed to be RNG via book-and-claim accounting. This RNG is delivered directly to a centralized liquefaction or compression plant where liquified natural gas (LNG) or compressed natural gas (CNG) is created for delivery to fueling equipment. Because RNG prevents methane emissions from entering the atmosphere and displaces fossil fuels, RNG carbon intensities are often significantly net negative.

LPG, like natural gas, has many uses beyond transportation fuel, and the volumes used for transport are small compared to the other uses. Thus, LPG used in transportation piggybacks on the LPG logistics in place to supply household and commercial uses. LPG is typically transported from the production facilities to marketplace terminals by rail, truck, and/or water.

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[172] RD and BD are most often blended with small amounts of petroleum diesel fuel enabling the blender to capture the biomass based diesel blender's tax credit (BTC) at $1 per gallon and separate the corresponding RINs.

12.3 FUELING LOGISTICS

Gasoline and diese—including any blended amounts of EtOH, BD, and RD—are dispensed into the vehicle fuel tanks at retail and fleet fueling outlets. There are 145,000 retail fueling sites across the country, with an average capacity to fuel approximately 12 vehicles simultaneously. At these sites, fuel is delivered to vehicles using fuel dispensers with hoses and standardized nozzles that are matched to the vehicle (gasoline or diesel). The dispensers offer the fuel type, grade selection (commonly three octane grades—regular, mid-grade, and premium for gasoline), and payment processing, and meter the amount of fuel dispensed. The fuels typically offered are E10 and diesel. Depending on the site, E0, E15, and E85 may be offered as alternatives to E10, and B5 to B20, B20+ to B99, and R5 to R99 may be offered as alternatives to regular diesel. In addition to retail sites, cardlock sites and private fueling sites dispense gasoline and diesel. The gasoline and diesel (including the various blends) are delivered to the retail and non-retail sites into tanks (typically underground) from terminals by tanker truck.

Fossil and Renewable Natural Gas utilize the same dispensing system, although CNG (whether fossil or renewable) is delivered slightly differently than fossil or renewable LNG. Natural gas is usually delivered to the CNG fueling site by pipeline from the natural gas grid. At the site it is compressed to over 4,000 pounds per square inch prior to dispensing into the vehicle tank. LNG is usually compressed and liquified at a central site and delivered into tanks at the fueling site for dispensing into the vehicle tanks. There are 1,200 CNG and 160 LNG fueling sites in the country, serving both public and private fleets. For both CNG and LNG, dispensers meter the fuel and have hoses with standardized nozzles for a secure connection to the vehicle.

LPG used in transportation is transported to the fueling site by tank truck into on-site storage. From storage, the LPG can be used to fuel vehicles or can be used for filling cylinders that are used by households or commercial establishments. The dispensers meter the fuel and have hoses with standardized nozzles for a secure connection to the vehicle. As of this writing, there are over 1,200 refueling stations offering LPG for sale to the public.[173]

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[173] Glpautogas.info / LPG Stations in USA.

12.4 VEHICLE TECHNOLOGY

The primary technologies used in on-road transportation are variations of the ICE. ICEs have proven to be a reliable source of mobile power that functionally suits their use in transportation vehicles. The primary conventional ICE technologies are adapted to use either gasoline or diesel fuel and provide different characteristics. The gasoline ICE is spark-ignited and utilizes the characteristics of the fuel to provide a high-speed, responsive performance. The diesel ICE is compression-ignited and utilizes the characteristics of the fuel to provide a high-torque performance that is suitable for heavy loads, high efficiency, and long service life.

The common characteristics of the fuels used in these conventional engines are that they are liquid at ambient temperatures and can be carried in the vehicle in non-pressurized fuel tanks. These liquid fuels also offer a high energy density that provides a favorable fuel-volume-to-vehicle-range ratio. These characteristics also apply throughout the logistics and fuel delivery of these fuels.

The conventional fuel-vehicle technology system has developed and evolved since the early 20th century as the ICE technology was developed along with the fuels available. Late in the 20th century, vehicle technology and the required fuel specifications developed hand-in-hand as the requirements to reduce criteria pollutants required cleaner-burning fuels coupled with advanced vehicle technology. Thus, the conventional transportation fuel system and the vehicle technology are closely coupled.

In addition to these conventional fuel and vehicle technologies, ICEVs have been modified to use alternative fuels such as CNG, LNG, LPG, and EtOH blends up to E85. The ICEV modifications necessary to use CNG, LNG, and LPG involve installation of pressurized or insulated fuel tanks and fuel delivery and control systems. E85 is used in FFVs, which are special ICEVs that can run on E85 and whose materials in the fuel system and engine control mechanisms are compatible with E85.

12.5 SUMMARY OVERVIEW OF FLEET AND FUELS

In summary, the existing fuel production, transport, and dispensing systems are closely coupled with existing ICEV technologies. This fuel-vehicle coupling has evolved over more than a century into a highly efficient system that provides abundant and highly available fuel to compatible vehicles for passenger and commercial transportation. With some adjustments to reduce the carbon intensity of fuels and existing vehicle technologies, this legacy system can be part of the climate solution. Furthermore, carbon-reducing adjustments to the existing system can be executed immediately even as new systems, such as those supporting electrification of transportation, are built out over the coming decades.

Any discussion of reducing the carbon emissions of ICEV has two primary dimensions: 1) the potential reduction in carbon intensity of the various ICE-compatible liquid fuels, and 2) the efficiency of the fuel in the vehicle, often measured in miles per gallon (mpg). In the sections that follow, we discuss the requisite scale, efficiency, and transition challenges of any lower carbon fuel's production, storage, and delivery. We also discuss the potential fuel-vehicle coupling options to reduce the carbon emissions from ICEVs.

Identification of Low-Carbon ICEV Fuels

In this section we identify, categorize, and discuss low-carbon fuels with potential to materially reduce the carbon emissions of the ICEV fleet along with the expected transition hurdles and consumer acceptance issues of the identified fuels. Besides the technical challenges of commercializing production, successful low-carbon ICEV fuels must be able to develop the required scale, achieve efficient deliverability, be able to couple with an ICEV, and be acceptable to the consumer.

13.1 CURRENT DROP-IN FUELS FOR GASOLINE AND DIESEL ICEVs

A number of renewable fuels currently supplied to the transportation fuels market are used in the prevalent gasoline and diesel ICEVs. For this purpose, the term “drop-in fuels” will be used to describe fuels that can be blended with other fuels or used neat (i.e., without blending) in conventional ICEVs. There are four fuels that fit this category: EtOH, BD, RD, and renewable gasoline (RG).

13.1.1 ETHANOL

EtOH is a drop-in fuel that can be used in all existing on-road gasoline ICEVs[174] in an up-to-10% blend with petroleum gasoline and an up-to-15% blend for the majority of vehicles on the road. Although blends greater than 15% will power existing gasoline engines, the 15% limit is set by the limits

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[174] In 2011, EPA approved E15 for use in light-duty conventional vehicles of model year 2001 and newer, through a Clean Air Act waiver request, based on significant testing and research funded by the U.S. Department of Energy. E15 is prohibited for use in motorcycles, non-road, and heavy-duty applications.

of the vehicle's fuel system material compatibility and engine calibration. As discussed above, EtOH produced from starches and sugars are low-carbon renewable fuels. The enhanced 45Q tax credit for carbon capture, utilization, and storage (CCUS) established with the IRA may provide an additional incentive for ethanol produced at plants incorporating CCUS.

13.1.2 BIODIESEL

BD is a chemically dissimilar drop-in fuel that can be used to power diesel engines in concentrations up to 100%. However, due to limitations set by engine manufacturers, diesel specifications, concerns about material compatibility, and poor cold flow properties, BD is limited to 20% in diesel blends. Additionally, BD concentrations over 5% in blend must be labeled at the pump, causing some resistance to BD blends over 5%.[175] The new 45Z CFPC established with the IRA and taking effect in 2025 will provide an additional incentive for BD produced from non-crop feedstocks such as inedible tallow, UCO, and DCO.

13.1.3 RENEWABLE DIESEL

RD is produced from the same feedstocks as BD. Unlike BD, however, RD's chemical composition very closely mimics petroleum diesel and is compatible with diesel engines and specifications at all concentrations. Thus, it is a fully drop-in (or replacement) fuel; it may be used in diesel ICEVs at up to R100 (i.e., without blending with petroleum diesel). RD may be considered a premium diesel as its cetane number is much higher than petroleum diesel. Similar to BD, RD has labeling requirements that may provide some resistance to blends over 5%. The new 45Z CFPC established with the IRA and taking effect in 2025 will provide an additional incentive for RD produced from non-crop feedstocks such as inedible tallow, UCO, and DCO.

13.1.4 RENEWABLE GASOLINE

RG is produced as a by-product of RD production. It is a drop-in fuel when blended with gasoline or can be processed further to improve its qualities.
RG may be of low octane quality, which limits its direct use in gasoline. Since it is produced from the same feedstock as RD, RG is a low-carbon renewable fuel. The new 45Z CFPC established with the IRA and taking effect in 2025 will provide an additional incentive for RG produced from non-crop feedstocks such as inedible tallow, UCO, and DCO.

13.1.5 FISCHER-TROPSCH DIESEL

FT diesel can be produced from several feedstocks that are converted to syngas (a mixture of carbon monoxide and hydrogen) that is the raw material for the Fischer-Tropsch reaction that produces FT diesel and a range of coproducts. The resultant FT diesel product is a high-cetane drop-in replacement for petroleum diesel. All the current production of FT diesel is outside the U.S., using natural gas or coal as a feedstock. Essentially all the production is used in Europe and elsewhere. Since fossil materials are used in its production, the current FT diesel is not considered renewable or low-carbon. To make FT diesel renewable and low-carbon, a low-carbon renewable feedstock such as RNG, municipal solid waste (MSW), or wood waste must be used. The new 45Z CFPC established with the IRA and taking effect in 2025 will provide an additional incentive for FT diesel and coproducts produced from non-crop feedstocks such as RNG, MSW, or wood waste.

13.2 CURRENTLY AVAILABLE ALTERNATIVE FUELS FOR GASOLINE AND DIESEL ICE-AFVs

Alternate fueled vehicles (AFVs) that use ICEV technology are compatible with low-carbon alternative fuels. The low-carbon fuels used in ICE-AFVs are:

13.2.1 RENEWABLE NATURAL GAS

RNG is used as CNG or LNG with the respective fueling systems. Its use requires a natural gas vehicle (NGV).

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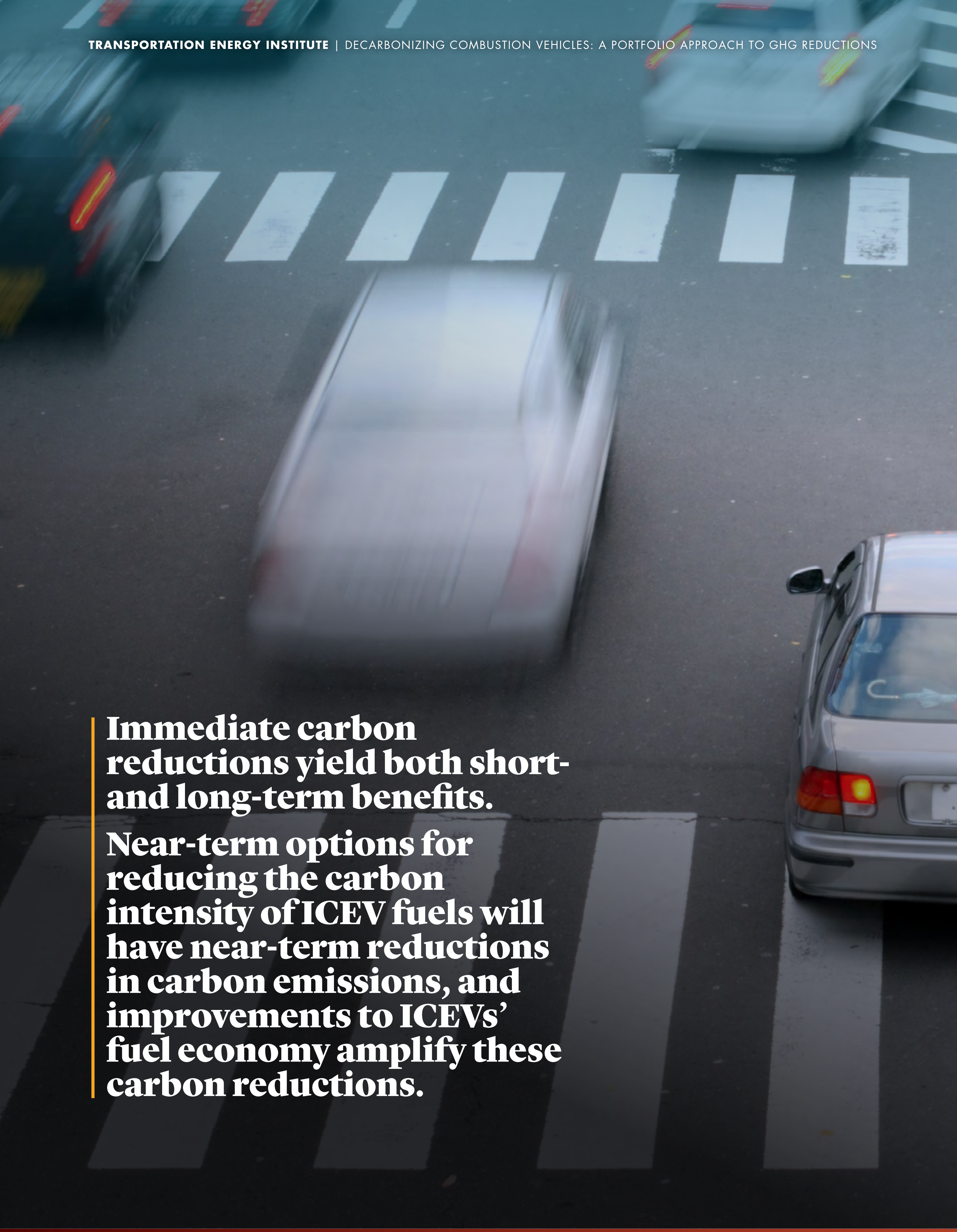
[175] DOE Alternative Fuels Data Center / Biofuel Blend Dispenser Labeling Requirement.



Immediate carbon reductions yield both short- and long-term benefits.

Near-term options for reducing the carbon intensity of ICEV fuels will have near-term reductions in carbon emissions, and improvements to ICEVs' fuel economy amplify these carbon reductions.

13.2.2 RENEWABLE PROPANE

RP is a form of LPG that is a by-product of RD production. It shares the same low-carbon and renewable characteristics as RD and RG. Its use requires an AFV that is designed to use LPG. The new 45Z CFPC established with the IRA and taking effect in 2025 will provide an additional incentive for RP produced from non-crop feedstocks such as inedible tallow, UCO, and DCO.

13.2.3 E85

E85 is a hydrocarbon and ethanol blend of 51%-83% ethanol that can be used in FFVs. E85 is produced by blending ethanol with gasoline, low-octane petroleum, or natural gasoline streams. It can also be blended with renewable gasoline, thus making a 100% renewable fuel. E85 must be used in vehicles designed for its use, must be stored in tanks that are compatible with its high ethanol content, and must be delivered to the vehicle in a fuel delivery system compatible with its high ethanol content.

13.3 POTENTIAL DROP-IN AND ALTERNATIVE FUELS FOR GASOLINE AND DIESEL ICEs AND ICE-AFVs

In previous sections of this report, we identified potential fuels that are yet to be introduced into the transportation fuels marketplace that could lower the carbon emissions of ICEVs. These fuels are for use as drop-in fuels or as fuels for AFVs with ICEs that are designed to use that fuel. The fuels identified are:

13.3.1 PYROLYSIS FUELS (GASOLINE, DIESEL, AND PROPANE)

Pyrolysis fuels are produced from the pyrolysis or thermal decomposition of biomass. Thermal decomposition of biomass can produce a wide mix of liquid, gaseous, and solid products that contain carbon, hydrogen, and oxygen. This mix can be processed to produce hydrocarbons like gasoline, diesel, LPG, and natural gas. To the extent they meet the specifications, these are low-carbon, drop-in renewable fuels.

13.3.2 BIOMASS TO LIQUIDS (BTL)

BTL uses partial oxidation, or gasification, of biomass or waste to produce a syngas (primarily carbon monoxide and hydrogen) that can be the raw material for the Fischer-Tropsch reaction that produces FT diesel or can use a methanol to gasoline process to produce renewable gasoline. BTL produces FT diesel, but since it is from renewable feedstocks, the products are low-carbon, drop-in renewable fuels.

13.3.3 ELECTROFUELS (GASOLINE, DIESEL, PROPANE, AND METHANE)

E-fuels, also referred to as synthetic fuels, are a type of drop-in replacement fuel. They are manufactured using carbon dioxide, together with hydrogen (electrolyzed water) obtained from low-carbon electricity sources such as wind, solar, and nuclear power. The carbon dioxide may be sourced from an industrial source or from direct air capture (DAC). Carbon monoxide may be used in addition to carbon dioxide. The products are low-carbon, drop-in renewable fuels. The new clean hydrogen (45V), enhanced CCUS (45Q), and CFPC (45Z) tax credits established with the IRA may provide additional incentives for these fuels subject to limitations on stacking these credits.

13.3.4 ALTERNATIVE ICE FUELS (HYDROGEN)

Hydrogen is typically considered a transportation fuel utilizing fuel cell technology. However, hydrogen can also be used to power an ICEV. A renewable hydrogen-ICEV coupling would offer a low-carbon, renewable ICEV option. Low-carbon hydrogen, including green hydrogen (produced via electrolysis using low-carbon power) and blue hydrogen (produced through reforming of natural gas coupled with CCUS), is eligible for additional incentives from the clean hydrogen (45V) and CCUS (45Q) provisions of the IRA. Importantly, the same fuel is not eligible to claim both the 45V and 45Q tax credits.

Expected Transition, Hurdles, and Consumer Acceptance of Identified Fuels

In this section, we explain the transition of all fuels and fuel technologies identified above from concept to practical application to achieve a measurable reduction in transportation carbon emissions from specific fuels coupled with specific vehicle technologies.

This will include an analysis of the specific hurdles (economic, technological, and consumer acceptance) for each fuel-vehicle pairing to get to meaningful market penetration, as well as the various ways to reduce the carbon intensity of petroleum gasoline and diesel. Petroleum gasoline and petroleum diesel were not included in the previous section as they are not low-carbon fuels but are instead the current conventional fuels which are to be displaced by lower carbon fuels. Petroleum gasoline and diesel will, however, be discussed in this section as they will remain a large part of the fuel mix as the energy transition proceeds. The discussion of petroleum fuels in this section will include measures which could reduce the petroleum fuels' carbon intensities. Measures to reduce carbon emissions from ICEVs via improved fuel economy will be addressed in the following section.

In general, there are three methods of reducing life cycle carbon emissions using gasoline and diesel vehicles: 1) reducing carbon emissions in the production and supply of petroleum gasoline and diesel fuels, 2) using blended or neat fuels with lower carbon intensities, and 3) vehicle improvements. We will discuss vehicle improvements below. In this section, we will focus on the opportunities to reduce the carbon emissions from fuels used in ICEVs, as well as the challenges.

14.1 PETROLEUM AND CURRENT DROP-IN FUELS FOR GASOLINE AND DIESEL ICEVs

In the near term, gasoline and diesel vehicles present the greatest opportunity for reducing carbon emissions in the U.S. since the fueling infrastructure currently exists and consumers continue to purchase gasoline- and diesel-powered ICEVs. Similar to the transition to reformulated gasoline three decades ago, when reductions in criteria emissions were gained in existing vehicles through modification of the fuels' composition, immediate carbon emissions reductions can be gained by reducing the carbon intensity of the fuel. In this section, we discuss the reduction in the carbon intensity of petroleum fuels along with the current drop-in fuels that can contribute to reducing the carbon emissions from gasoline and diesel ICEVs.

14.1.1 PETROLEUM GASOLINE

Petroleum gasoline is the most common transportation fuel in the U.S.—approximately 99% of the light-duty vehicles used by American families are powered by gasoline[176]—and improving the fuel efficiency of gasoline-powered vehicles has reduced carbon emissions over the past two decades by more than any other carbon-reduction method. Given that gasoline demand in the U.S. peaked in 2019 (i.e., demand has begun to decline), the existing petroleum infrastructure, described above, is sufficient to meet future supply needs. Consumer acceptance of gasoline is nearly universal, with the only major concerns being those of tailpipe carbon emissions and criteria pollutants. These concerns have been partially addressed by auto manufacturers and fuel suppliers meeting increasingly stringent fuel efficiency and pollution emission standards over the past few decades, and progress continues into the future.

According to the GREET model, approximately 22% of life cycle emissions from gasoline-powered vehicles are created in the upstream production of crude oil, transport of crude oil to refineries, the refining process, and transport of gasoline to market.[177] The opportunities for emissions reductions within these activities are significant. One primary way to reduce production, refining, and transportation carbon emissions is to reduce the carbon intensity of the energy used in the associated processes. Emissions from crude production come from the combustion of natural gas and distillates to generate steam and electricity. These emissions can be reduced by using renewable energy from solar and wind sources. Additionally, flaring and fugitive methane emissions contribute 13% of all GHG emissions from crude production and transport. These emissions sources are being reduced by regulations worldwide which should maintain or reduce carbon emissions from crude production and transport even as production shifts to more energy-intensive crude production.

Some very heavy crude oils require substantial amounts of energy to be extracted in usable form. For example, while the average carbon intensity of crude oil processed in California in 2021 was 12.80 g/MJ, the carbon intensities of individual crude oils varied from 1.59 g/MJ to 48.13 g/MJ.[178] The differences in the range of carbon intensities of individual crude oils can be extreme enough to change life cycle emissions of fuels produced by nearly 50%.[179] Refineries worldwide lack financial incentives to process lower carbon crude oils. California's LCFS regulation provides some incentives for crude producers to reduce carbon emissions while extracting crude oils with carbon capture and sequestration (CCS), but the reduced emissions from the crude production process simply generate LCFS credits for the producer without directly impacting the assessed CI of the gasoline and diesel produced by refiners using this crude.

Similarly, the carbon emissions required to refine gasoline from very heavy crude oils are much higher than for lighter crude oils because heavy crudes contain larger volumes of heavy gasoils and residues that require energy-intensive processes such as fluid catalytic cracking and delayed coking in order to be converted to gasoline. Since these heavy crudes are more difficult and costly to convert into light products, they are generally less expensive than lighter crudes. Hence, refineries that have the complexity to process these heavy crudes and can thus offset their higher capital and operating costs can often be more profitable than simpler refineries.

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[176] EIA / AEO 2022 Table 39.

[177] About 71% of the life-cycle carbon emissions of gasoline in the U.S. projected by the GREET model are in the combustion of gasoline. The rest are from the supply of crude, refining and supply of the gasoline to consumers.

[178] CARB / Calculation of 2021 Crude Average Carbon Intensity Values.

[179] While CARB does increase the LCFS CI reduction requirements in California when the pool of crudes used in-state increases from historical levels, this pooling does not provide direct incentives to reduce consumption of high CI crudes since the additional costs are shared by all fuel providers into the California market.

As discussed in the Life Cycle portion of this report, there are many ways that refineries can lower their GHG emissions. These include:

1. Using more-efficient equipment – The efficiency of refining equipment and energy efficiency have steadily improved over the past century, and continued improvements will be forthcoming as refiners continue to invest in, develop, and employ new technologies designed to lower GHG emissions.
2. Deploying carbon capture and sequestration – Incentives for CCS increase with CO_2 concentration in effluent streams and scale. Dozens of CCS investments are being developed throughout the U.S.—78 were announced between 2021 and 2022[180]—with several announced projects for aggregating CO_2 streams from ethanol plants for sequestration. The enhanced CCUS incentives included in the IRA are available to refiners deploying this technology.
3. Utilizing renewable or low-carbon hydrogen – Using RNG to produce refinery hydrogen is an alternative encouraged in California, but since it can also be used to directly fuel vehicles, as discussed previously, and decarbonize power generation, it is not clear if there will be sufficient supply to contribute to lowering gasoline fuel CI. Production of low-carbon hydrogen used in refining may be eligible for the clean hydrogen (45V) tax credit established with the IRA.
4. Switching to renewable feedstocks – We will discuss this option in detail in the sections on renewable gasoline and renewable diesel below. Fuels produced from renewable feedstocks which are co-processed with petroleum are not eligible for the CFPC (45Z) tax credit provision of the IRA.

Taken together, these four improvements are expected to enable continued reduction in carbon emissions from producing and delivering gasoline to consumers.

CONCLUSION: Transitioning to a reduced-carbon petroleum gasoline should be comparatively simple as the production capacity, logistics, fuel delivery, and vehicle technology exist. Since any change would be transparent to the consumer—barring probable fuel price increases to support carbon emissions reductions in crude production, transportation, and refinery operations—consumer acceptance would be high. The challenges to reducing the carbon intensity of crude oil and refined gasoline would fall on the upstream oil and gas production, tanker, and refining industries. As these are global industries, reducing carbon emissions would require widespread adoption to eliminate gas flaring; increasing the use of renewable energy in production, transportation, and refining; and improving energy efficiency in each area. These are the types of changes currently being pursued in the fuels industry and could quickly produce significant reductions at low to medium costs. The majority of economic projects required to make these changes could probably be developed in less than 10 years with incentives similar to those provided to renewable fuels producers. However, global initiatives would also likely be required to obtain the maximum benefits because of the global nature of the crude oil supply chain. Widespread adoption of environmental, social, and governance (ESG) measures by the oil and gas industry and marine industry would further reduce the carbon intensity of petroleum gasoline.

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[180] Akin / Notable US Carbon Capture and Storage Projects.

14.1.2 PETROLEUM DIESEL

Petroleum diesel is the second most common transportation fuel in the U.S. Like gasoline, it is an established fuel that has been used for over 100 years and is produced and supplied to all parts of the U.S. While gasoline is the dominant fuel in the light-duty vehicle fleet, diesel is the primary fuel for the medium- and heavy-duty vehicle fleets and railroad locomotives that are used to haul goods across the country. Diesel's high energy density combines with the high thermal efficiency and high torque produced from diesel engines to make it the preferred fuel for this segment of the transportation sector. It is also important to note that this segment is much more difficult to decarbonize by electrification—as opposed to other options—since new heavy-duty EVs need additional onboard battery storage to achieve the range required for long-haul trucking, and heavy-duty EVs cost two to three times as much as similar diesel models, compared to 20-30% more for light-duty vehicles.

The factors impacting ongoing use for diesel are similar to those relating to gasoline:

1. The existing infrastructure for diesel is sufficient to meet future supply needs,
2. Consumer acceptance of diesel is widespread with the only major concerns being those of tailpipe carbon emissions and criteria pollutants, and
3. Truck manufacturers must meet increasingly stringent fuel efficiency and pollution emission standards.

Reducing carbon emissions in the production and supply of diesel is similar to that of gasoline, except that significantly less carbon is emitted in the production of diesel than gasoline. While 22% of life cycle emissions for gasoline come from production and supply, only 16% of emissions from diesel come from these factors. This difference is due to the significant amounts of gasoline that are produced from cracking and coking operations, which require large amounts of energy. However, the same opportunities listed for gasoline—lower carbon crude oils, refinery efficiency, CCS, lower carbon hydrogen, and renewable feedstocks—can be used in principle for diesel production. How directly each of these applies to the diesel produced is estimated by models such as GREET.

CONCLUSION: Similar to petroleum gasoline, transitioning to a reduced carbon petroleum diesel may be possible as the production capacity, logistics, fuel delivery, and vehicle technology exist. Since any change would be transparent to the consumer—barring probable fuel price increases to support carbon emissions reductions in upstream crude production, transportation, and refinery operations—consumer acceptance would be high. The challenges to reducing the carbon intensity of crude oil would fall on the oil and gas production, tanker, and refining industries. As these are global industries, reducing carbon emissions would require widespread adoption to eliminate gas flaring; increasing the use of renewable energy in production, transportation, and refining; and improving energy efficiency in each area. To make these changes, strong global initiatives would likely be required, although domestic initiatives could be helpful. Widespread adoption of ESG measures by the energy and marine industries would further reduce the carbon intensity of petroleum diesel. As with gasoline, if the proper incentives were in place, most of the economic projects could be developed in the next 10 years at a low to medium cost compared with other alternatives.

14.1.3 ETHANOL (E10 AND E15 BLENDS)

Ethanol is a renewable alcohol fuel that can reduce oil dependence and carbon emissions. Most gasoline in the U.S. is E10, and all 2001 model year and newer cars are legally compatible with blends up to E15, although not all of these vehicles are warranted by their manufacturer for E15.[181,182] Acceptance of E10 is nearly universal in the U.S., and E15 should be similarly accepted by consumers. The infrastructure for E10 is ubiquitous and sufficient for future demand but will require some modifications to enable E15 to achieve the same level of acceptance. Terminals might require minor investments in pumps and/or tanks to offer E15 efficiently since it would increase blended ethanol volumes by 50% for a complete transition. In addition, even though new equipment in retail sites can be rated for up to E25, E40, or E85, this does not apply to all new equipment nor legacy equipment that may only be listed as compatible with blends up to E10. Similarly, while there is excess ethanol production capacity in the U.S., new capacity may need to be built if there were to be universal adoption of E15.

Here and below we will discuss the opportunities to reduce the overall carbon intensity of gasoline fuel through increasing the blend percentage of ethanol (E10 and E15 will be discussed in this section while blends beyond 15% will be discussed afterwards. Options for reducing the carbon intensity of ethanol itself will be discussed futher on.)

Although E15 was approved for use by EPA under a partial waiver of the Clean Air Act (CAA) in 2011, there have been hurdles to its use. One such hurdle was temporarily removed in 2022 via an emergency waiver from EPA granting E15 the same 1 psi RVP waiver that E10 enjoys during the summer months but which E15 had previously not had.[183] Without the RVP waiver applied, E15 would have to have a lower RVP than E10 during the summer months, and a different gasoline blendstock would be required for E15 than E10. This hurdle has limited E15 availability in the marketplace. Even with this waiver, E15 may be slow to develop since the temporary basis of the emergency waiver creates uncertainty about E15's future and therefore discourages investment. To eliminate this uncertainty, the CAA would need to be amended or a permanent E15 RVP waiver adopted by EPA.

A second, lesser hurdle for E15 is the nature of the EPA E15 waiver in 2011. In its waiver, EPA excluded approval for E15 use in motorcycles, vehicles with heavy-duty engines such as school buses and delivery trucks, off-road vehicles such as boats and snowmobiles, engines in off-road equipment such as chain saws and gasoline lawn mowers, and conventional vehicles older than model year 2001.[184] Because the E15 waiver does not cover all the same uses as E10, both fuels would need to be supplied to the marketplace separately.[185] For a fuel retailer, the choice might be selling E15 in place of an existing grade. Although the exclusion of E15 from some gasoline uses is not a high hurdle, it could slow E15 adoption.

On the consumer acceptance side, there is little change except that E15 would have about 2% less energy per gallon than E10. Although this is small, it generally takes a slight price discount for consumers to choose E15. Therefore, retailers currently offer E15 for $0.05-$0.10 per gallon less than E10. In addition, E15 has an octane rating higher than traditional regular grade E10, and consumers often think buying gasoline with a higher octane rating at a lower price is a competitive value.

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[181] Consumer Reports / Can Using Gas with 15 Percent Ethanol Damage Your Car?.

[182] DOE AFDC / E15.

[183] EPA / Re: August 30, 2022, E15 Reid Vapor Pressure Fuel Waiver.

[184] DOE AFDC / E15.

[185] EPA has approved E15 for use in light-duty conventional vehicles of model year 2001 and newer. E15 is still prohibited for use in motorcycles, non-road, and heavy-duty applications. As such, the volume excluded from E15 use is much smaller than the volume which is allowed.

While there are regulatory and consumer perception hurdles to widespread E15 adoption, ethanol has no economic hurdles to continue to be sold at 10% levels. Ethanol has at times been both more and less expensive on an energy basis than gasoline,[186] but it is subsidized by the RFS to ensure it will be continuously economical to fuel suppliers and consumers. E15 has minor economic hurdles for low levels of adoption in certain retail sites, but larger costs would be incurred to have it completely replace E10 in the market.

Ethanol could also reduce the carbon intensity of E10 and E15 by becoming lower in carbon intensity itself. Almost all the ethanol used in transportation fuels in the U.S. is produced from corn, and increasing the share of ethanol from sugarcane (SCE) that is used will decrease the average carbon intensity of ethanol. Increasing the share of SCE is challenging for several reasons, including:

1. **Most SCE is produced in Brazil, which uses ethanol in its transportation fleet and does not consistently have a surplus available to export.**
2. **Getting some of this SCE to the U.S. and away from Brazil would require increasing and prioritizing exports over domestic transportation in Brazil.**
3. **Brazilian ethanol production varies widely from year to year with rain and weather, and SCE production primarily occurs during the sugarcane harvest season, making production highly unratable.**
4. **The long transport distance from Brazil to much of the U.S. exposes the importer to price fluctuations which cannot readily be hedged.**

These factors, in addition to the high value of cane sugar as food , make a substantial increase in SCE use impractical.

There are three ways that are currently progressing to reduce the corn ethanol carbon intensity. The first two leverage the fact that a large percentage (33-50%) of corn ethanol's carbon intensity is related to corn production, primarily energy and fertilizers. Thus, the first way to reduce corn ethanol's carbon intensity is by continuing to increase corn

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[186] Ethanol is generally cheaper than gasoline on a volume basis, but it has only two-thirds the energy content of gasoline. As a result, it can price higher or lower than gasoline on an energy basis.

yield per acre without increasing the energy and fertilizer inputs.[187] A second way is by changing the agricultural practices of farming to reduce the carbon intensity of the corn used to produce ethanol.[188] These practices include no-till farming aimed at greater carbon and nutrient sequestration in the soil and reduced chemical fertilizer use. A third option for reducing the carbon intensity of ethanol is to capture the carbon dioxide produced from fermentation and sequester it in underground formations that would offset emissions when used in the vehicles.

As fermentation produces a highly concentrated stream of carbon dioxide, capturing this carbon dioxide from the atmosphere and permanently sequestering it underground could be credited to the carbon intensity of the ethanol.

CONCLUSION: The carbon intensity of corn ethanol has been decreasing and will continue to decrease as yields increase, agricultural practices are improved, and CCS is implemented on ethanol production facilities. Wider use of E15 will reduce the carbon intensity of gasoline. With the RFS in place, cost would be minimal unless there is wholesale replacement of E10. Logistics and fuel delivery impacts will be minimal, and the fuel is compatible with post-2001 vehicles. Thus, E15 is a viable means to reduce the carbon intensity of gasoline ICEVs. The challenges it faces are regulatory and legislative, which keep it from being a true replacement for E10 in most on-road ICEVs. If these challenges were addressed, a near-complete transition to E15 could be accomplished in as little as five years. Without significant regulatory and legislative efforts, this transition could take considerably longer.

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[187] Green Car Congress / Argonne study finds 23% reduction decrease in carbon intensity of ethanol from 2005 to 2019.

[188] DOE Office of Energy Efficiency & Renewable Energy / Ethanol vs. Petroleum-Based Fuel Carbon Emissions.

14.1.4 BIODIESEL (B5 AND B20)

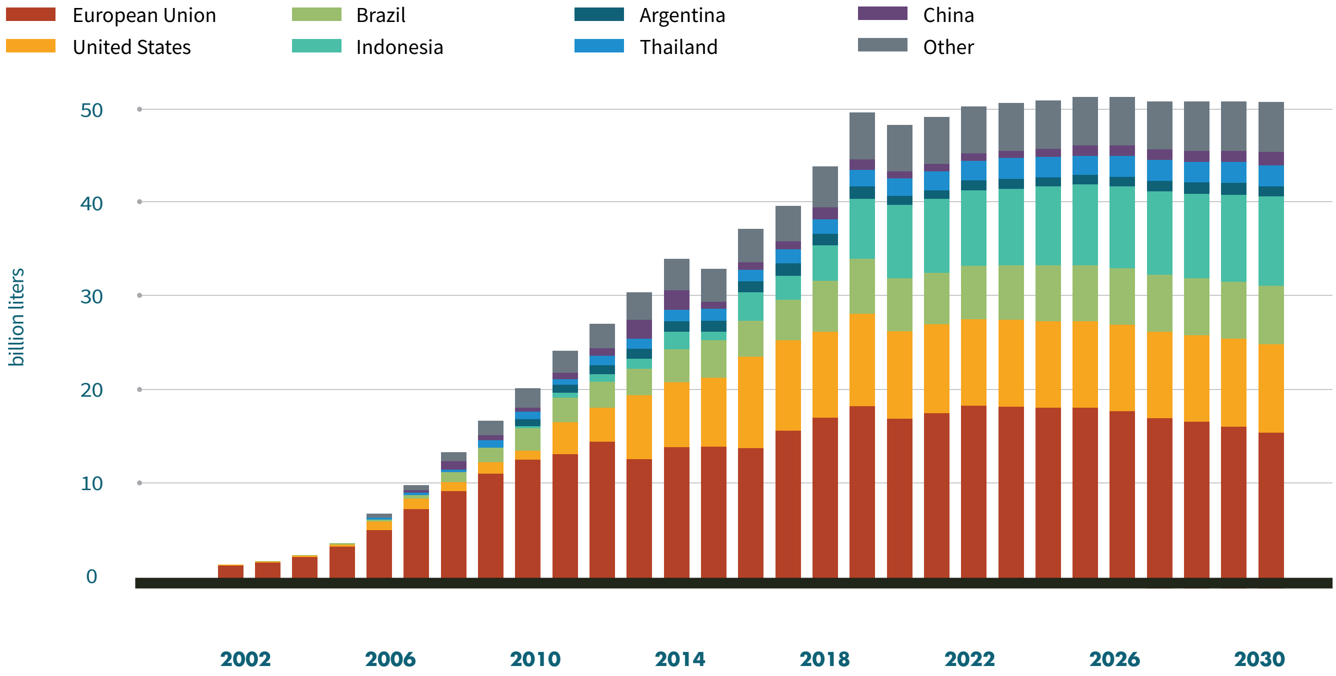
As noted in the Life Cycle section of this report, BD use in the U.S. peaked in 2021 and is not projected by the EIA to return to that level in the next 25 years because it is being displaced by RD. The disadvantages that BD has versus RD include:

1. **Production at smaller scale,**
2. **Owned by smaller, less financed companies,**
3. **Chemical dissimilarity to petroleum diesel, and**
4. **A 20% “blend wall” in existing diesel infrastructure due to poor cold flow properties and material compatibility concerns.**

Combined with the fact that BD and RD compete for the same feedstocks, these disadvantages have caused U.S. RD production to increase by over 500 million gallons and BD production to decrease by the same amount, respectively, between 2021 and 2022, and have led the EIA to not project growth for BD. In fact, if demand for gasoline and diesel declines significantly, sufficient shuttered refinery equipment might become available for conversion to RD production to displace BD beyond what is currently predicted by the EIA. EIA’s projection on BD and RD demand reflected in the 2022 AEO is discussed further in the Life Cycle section of this report.

Globally, BD has enjoyed widespread growth—the production technology is of low complexity and feedstock has been easily procured. The U.S. consumption of BD has been just a fraction of the global consumption. According to the Food and Agriculture Organization (FAO) of the United Nations, it is expected that global BD consumption will level off through the rest of this decade. This is shown in the global history and projection from FAO below.[189] (Figure 65)

FIGURE 65. DEVELOPMENT OF GLOBAL BIODIESEL CONSUMPTION



Source: OECD-FAO, OECD-FAO Agricultural Outlook, OECD Agriculture Statistics (database).

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[189] Organization for Economic Cooperation and Development (OECD) / OECD-FAO Agricultural Outlook 2023-2030, Section 9. Biofuels.

In the U.S., BD production capacity was 2,255 million gallons per year in 72 facilities at the beginning of 2022.[190] Most of these facilities are in the Midwest where much of the oilseed crops which comprise the bulk of BD feedstocks are grown. Domestic BD production capacity exceeds the domestic use of 1,710 million gallons in 2021.[191] Most BD moves from the production facility to terminals in the market via rail. Local markets can be supplied by tanker trucks and barging can be part of the delivery logistics. As mentioned above, BD may be transported in pipelines in up-to-B5 blends, but usually is not allowed at any concentration if the pipeline also carries jet fuel. BD may be blended to B99 at the production facility, enabling the production facility to capture the $1.00 per gallon biomass-based diesel blenders tax credit and separate the associated RFS RINs. BD is normally blended to its final concentration at the terminal or as the tanker truck is loaded for delivery to the retail station or customer.

BD is made up of mono-alkyl ester fatty acids which give it unique fuel properties such as poor cold flow, which can cause problems at low temperatures. BD is incompatible with jet fuel even at low concentrations and also reduces particulates but increases NOx emissions compared to petroleum diesel. Generally, BD is allowed up to B20 in diesel by vehicle manufacturers. Consumer acceptance of BD is generally good, and higher-level blends should find the same consumer acceptance.

CONCLUSION: BD has production capacity, logistics, and fuel delivery systems that could be used to increase its concentration in the diesel pool, thus lowering the carbon intensity of diesel fuel. It has some challenges because of its unique properties and economics that are apparent since the BD industry operates at 75% capacity. The most prevalent challenge for BD is RD, which uses the same limited feedstocks as BD and produces a product without the limitations of a mono-alkyl ester fatty acid. Without feedstock competition with RD, increasing BD blending to approach B20 in much of the U.S. could be accomplished in 5-10 years with exceptions made to allow B5 in colder climate locations. Since existing systems are mostly compatible with B20, the overall nonsubsidized cost is low to medium.

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[190] EIA / U.S. Biodiesel Plant Production Capacity.

[191] EIA / 2021 Supply and Disposition.

14.1.5 RENEWABLE DIESEL

Unlike BD, discussed above, RD is composed of hydrocarbon molecules, as is petroleum diesel. Thus, the properties of RD meet all the specifications of diesel. Other than potential labeling requirements, RD can be blended with petroleum diesel and/or BD in any proportion. The ability to replace BD and diesel with no changes to vehicles or fuel infrastructure is the basis for expected ongoing growth in RD production and usage. The technology is well-developed, and very well regarded in the marketplace, and RD may capture a premium retail price compared to diesel fuel due to its low-carbon nature and high-cetane properties even though it has slightly less energy per gallon.

As of January 2023, there are 14 RD production facilities with a total capacity of 2,381 million gallons per year.[192] Three of those production facilities are petroleum refineries that produce RD by co-processing RD feedstocks along with petroleum diesel. Most of the capacity is located on the U.S. Gulf Coast. Additionally, a large volume of RD is imported to the West Coast from one of the first large RD production facilities located in Singapore.

RD production capacity is growing rapidly, with dozens of projects being developed in the U.S Gulf Coast, California, Western U.S., Canada, Europe, and Singapore that will triple current production capacity over the next two to three years. A good portion of this new capacity will target the European market. Notably, two of the existing production facilities are repurposed petroleum refineries, and two new projects are very large-scale conversions of petroleum refineries in California. The development of these projects suggests that if sufficient feedstock can be found, growth in RD production could be greater than what is discussed in the Life Cycle section of this report. Supporting this hypothesis is the strong growth of RD to 37% of California's diesel pool in the second quarter of 2022. This trend shows no signs of receding. In fact, declining petroleum gasoline and diesel demand could create additional opportunities to repurpose refineries to produce RD.

To date, because of the LCFS, a large majority of the domestic RD use has been in California. With much of the RD production capacity either inland in the West or on the Gulf Coast, RD is delivered by rail tank cars, or by water and/or truck or pipeline to the terminals in the marketplace despite high transportation costs. Since RD is almost identical to petroleum diesel in composition, it can be blended at the refineries or terminals and sold as R100/R99. RD can be shipped in the pipeline system; in blends with petroleum diesel, however, it is limited to 5% due to labeling requirements. A challenge for RD produced outside of California is that, as California’s diesel becomes primarily RD, additional markets will have to be developed, preferably local to the production facilities or markets that are served by pipelines from the Gulf Coast. The addition of LCFS-style programs in Oregon, Washington, and British Columbia will provide some of the incentives to use RD in those markets. According to the Transportation Energy Institute, an increasing number of publicly traded companies have begun sourcing RD for use outside of LCFS states to improve their ESG emissions reporting.

CONCLUSION: RD is compatible with the existing logistics, fuel delivery, and vehicle technology systems that are used for diesel fuel. It has very good customer acceptance in any blend. The only challenges to RD are the FTC labeling requirements for biomass-based diesel. RD is a fast-growing method of decarbonizing the fleet of diesel vehicles and is likely the greatest way to reduce carbon emissions in the heavy-duty fleet over the next 10 years. While it is considerably more expensive than petroleum diesel, the economics for RD growth is positive with

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[192] Stillwater analysis of publicly available information.

the current set of regulatory subsidies in place, and the limit on its growth over this timeframe is more likely to be feedstock availability rather than capital availability. If the agricultural and waste fats, oils, and grease sector of the U.S. economy can increase feedstock collection and production sufficiently, RD will make reductions of 50% to 70% in carbon emissions in the overall U.S. heavy-duty transport sector in the next 15 years.

14.1.6 FT DIESEL (CTL AND GTL)

Production of fuels via Fischer-Tropsch (FT) was mainly developed by Germany during the Second World War and by the South African Company SASOL two decades later. Historically, feedstocks used to produce the syngas that is reacted to FT product were coal and natural gas. Today, FT diesel is primarily produced from natural gas-derived synthesis gas using the FT reaction. These natural gas-to-liquid (GTL) production facilities are located in Malaysia, Qatar, Nigeria, and South Africa. There are also coal-to-liquid (CTL) facilities that produce FT diesel in South Africa. The FT diesel produced is used locally and in Europe. FT diesel is a high-quality, high-cetane drop-in fuel. However, since GTL diesel is made from fossil natural gas, it nonrenewable and has a high carbon intensity (over 100 g/MJ).[193]

Although the FT diesel produced to date does not contribute to the reduction of carbon emissions, the history of FT illustrates some of the primary challenges of utilizing FT processes to produce diesel and other fuels from low-carbon renewable feedstocks. The FT reaction is a polymerization technology converting a carbon monoxide and hydrogen syngas into a waxy liquid product of straight-chain normal paraffins. The product is further upgraded to fuels such as diesel via hydrocracking and isomerization, which are commercial refinery processes.

For over 50 years, there has been significant ongoing interest in FT technology as a way to utilize coal and stranded natural gas reserves. In spite of all these efforts to commercialize FT technology, the challenge has been and continues to be an acceptable capital cost to produce fuels that achieve reliable, scalable operations.[194]

For FT technology to contribute to decarbonization, feedstocks other than coal and natural gas will need to be used since the CI of FT diesel produced from both coal and natural gas is higher than that of petroleum diesel.[195] RNG is a possible feedstock, but competition for its use with other applications is likely to be intense. Cellulosic feedstocks that are nonfood based and include crop residues, wood residues, dedicated energy crops, and industrial and other wastes are also possible. None of these have yet been proven at commercial scales.

CONCLUSION: The FT process produces fuels that are compatible with the existing logistics, fuel delivery, and vehicle technology systems that are used for diesel fuel. The properties are very similar to RD, and if made with biomass would have the same FTC labeling requirements as biomass-based diesel. The challenge for FT is cost and economics. FT technology has long been used to generate liquid fuels from coal and gas, but this pathway has never been as economical as petroleum fuels. Furthermore, when used with coal and fossil natural gas as feedstocks, FT does not help to decarbonize transport fuels—in fact, it increases the carbon intensity of fuels

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[193] Argonne National Lab / Life Cycle Analysis of Electrofuels: Fischer-Tropsch Fuel Production from Hydrogen and Corn Ethanol Byproduct CO_2.

[194] Most of the existing GTL facilities also produce a significant portion of their output as very high valued specialty oils and waxes.

[195] Argonne National Lab / Life Cycle Analysis of Electrofuels: Fischer-Tropsch Fuel Production from Hydrogen and Corn Ethanol Byproduct CO_2.

ICEV improvements can complement ZEV deployment.

A portfolio approach will maximize the reductions in on-road transportation carbon emissions in both the near and long term.

compared to petroleum diesel. Accordingly, FT diesel from natural gas (GTL) and coal (CTL) will not be discussed further in this report. Low-carbon FT diesel from biomass-to-liquid (BTL) sources will be discussed below.

14.1.7 RENEWABLE GASOLINE

As mentioned above, RG is produced as a by-product of RD production. Utilizing new technologies, RG can also be produced from feedstocks other than those used for RD and BD production and in different existing refinery units.[196, 197, 198, 199, 200] The naphtha stream produced as a by-product of RD production typically has very low octane and can be processed in a catalytic reformer and/or isomerization unit to increase its octane and improve other blending properties. Since it is produced as a by-product in the production of RD and comes from the same feedstocks, RG is a low-carbon renewable fuel. Given that RG is a by-product, the volume of RG currently being produced is much smaller than the volume of RD currently being produced. Some refiners are trying to figure out how to dramatically increase their ability to process renewable feedstocks to produce RG in existing refinery equipment without large capital investment,[201] but it has not yet been done at scale.

Since RG is completely compatible with the existing gasoline production and delivery infrastructure, there should be few obstacles in these parts of the fuel value chain that prevent adoption at scale.

RG would likely have the same wide-scale acceptance as RD since their principles of production and use are very similar. It has a CI 60% below that of gasoline, so it could contribute carbon reductions to the enormous existing gasoline vehicle fleet and would be supplied through the existing gasoline supply infrastructure. Although it would be more expensive to produce than petroleum gasoline, like RD compared to petroleum diesel, the existing incentives would likely be sufficient to justify large-scale production. The two key obstacles to RG becoming material are lack of technology proven at scale and competition for feedstocks with RD in a feedstock-limited environment.

CONCLUSION: RG is compatible with the existing logistics, fuel delivery, and vehicle technology systems that are used for gasoline. It has very good customer acceptance in any blend. If RG can be produced economically and at scale it could be the fastest method of decarbonizing the light-duty ICEV fleet. The economics for RG are enhanced with the current set of regulatory subsidies in place. The greatest challenge for RG is developing an economic and scalable production technology beyond that used for RD. Overall, modest volumes of RG would reduce the carbon emissions of the gasoline ICEVs utilizing the fuel by 50-70% and can be produced at moderate cost over the next 5-15 years when producing RD. Much larger volumes would be needed to displace most petroleum gasoline, and this would require commercialization of other RG production technologies.

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[196] Virent / Renewable Gasoline.

[197] Neste / Neste is testing renewable gasoline in Sweden for possible commercialization internationally.

[198] Government Fleet / What is Renewable Gasoline?.

[199] Green Car Congress / Bosch, Shell, and Volkswagen develop renewable gasoline with 20% lower CO_2; rollout of Blue Gasoline this year.

[200] Reuters / EXCLUSIVE Exxon, Chevron look to make renewable fuels without costly refinery upgrades – sources.

[201] Reuters / EXCLUSIVE Exxon, Chevron look to make renewable fuels without costly refinery upgrades – sources.

14.2 CURRENTLY AVAILABLE ALTERNATIVE FUELS FOR GASOLINE AND DIESEL – ICE-AFVs

In this section, we cover alternative fuels that are not currently being used in existing gasoline or diesel ICEVs as they require vehicles specifically designed for that fuel (i.e., AFVs). These vehicles have modified fuel receiving, storage, engine control, and materials that are suited for these alternative (i.e., non-gasoline or non-diesel) fuels. Typically, an alternative fuel and its corresponding vehicle are inseparable—the fuel can only be used in one type of vehicle and that vehicle can only run on that specific type of fuel. Most AFVs are part of centrally fueled fleets, which minimizes the challenge of minimal retail fueling availability. Since these fuels require vehicles specifically designed for them, an inherent challenge to increasing their use is increasing the size of the fleet of vehicles that use the fuel. These alternative fuels and vehicles include RNG and renewable propane, as well as higher blends of ethanol and BD in the gasoline and diesel pools, respectively.

14.2.1 RENEWABLE NATURAL GAS

According to the GREET model, some RNG has the lowest CIs of any fuel. RNG can be produced from landfills, digestion of wastewater sludge, food scraps, agricultural waste, and livestock manure. RNG produced from swine manure has a CI of -338 g/MJ, which reduces carbon emissions by 527% versus fossil natural gas. RNG from dairy manure, food scraps, and other organic waste also has very low CIs, which create enormous economic incentives for production to be placed in states with LCFS programs. The very low (and sometimes negative) CI values are thanks to the fuel being credited for reducing methane emissions (“methane has 80 times the warming power of CO_2 over the first 20 years after it reaches the atmosphere”) that would otherwise occur and being cleaned up so that it can be used in place of fossil natural gas.[202] Natural gas is used in vehicles in the form of CNG and LNG; combined, these transport fuels made up less than 0.1% of the total natural gas used in the U.S.[203] RNG generates RINs, and in California and Oregon, generates so much value by generating LCFS credits that over 95% of the CNG and LNG used in these states is RNG. The two states represent 55% of the RNG used for transportation in the U.S.

In 2022, 360 million GGE of RNG were used as a transportation fuel in a NGV fleet of over 175,000 vehicles.[204] Fueling of these vehicles is supported by 1,740 CNG and LNG fueling stations. Not all the CNG and LNG used is RNG; much of the U.S. volume is fossil natural gas. The growth of RNG by feedstock is shown in Figure 66.

The challenge to increasing RNG use is the limited number of NGVs (compared to the total vehicle fleet), the comparatively small scale of RNG production, and the limited fuel dispensing system for CNG and LNG. Specifically, the fleet of 175,000 NGVs is dwarfed compared to about 276 million total registered vehicles; there are about 130 billion gallons of gasoline used each year in the U.S. compared to the 360 million gallons of RNG; and there are 145,000 gasoline retail outlets in the country compared to 1,740 natural gas fueling sites. The logistics to deliver RNG to market, however, are available since the U.S. natural gas grid delivers natural gas nationwide.

Because of the additional costs of NGVs and fueling sites to support them, NGVs have been primarily used for high-use urban services such as transit buses, shuttle buses, refuse trucks, delivery vehicles, etc.

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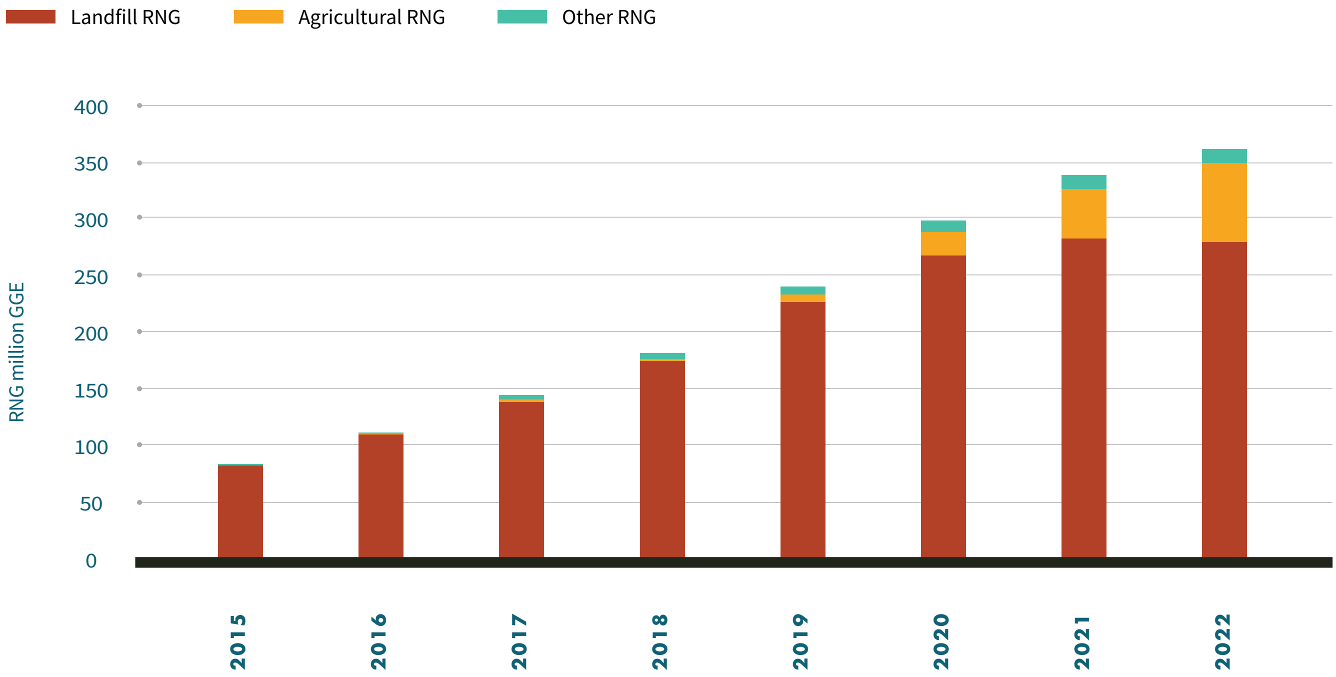
[202] Environmental Defense Fund / Methane: A crucial opportunity in the climate fight.

[203] EIA / Natural Gas.

[204] NGV America / Vehicles for Every Route.

FIGURE 66. U.S. RNG PRODUCTION FOR TRANSPORTATION



Source: Stillwater analysis and Renewable Natural Gas Database, Argonne National Laboratory

The NGV fleet could grow rapidly if heavy-duty NGV applications become more widely accepted.

Increasing the total production capacity of RNG is challenging because each production site has a small production volume relative to the scale of other biofuel production facilities. One advantage that RNG can have over other biofuels, however, is the fact that it uses waste feedstocks that otherwise would contribute methane and CO_2 emissions if left to break down naturally. Methane has 16 times the GHG impact as CO_2, so use of the feedstock to produce RNG has great leverage in reducing the carbon intensity of ICEVs.

CONCLUSION: RNG can use the existing national natural gas grid to reach markets. Growth in RNG use as a transportation fuel, however, will be limited to the size of the NGV fleet and the availability of fuel dispensing system for NGVs.[205] Hence, the challenges for RNG are growing the NGV fleet and fueling sites. For customers who have elected to purchase an NGV, acceptance of RNG versus fossil natural gas should be high as there should be no noticeable change for the customer. RNG has an extremely high leverage on the carbon intensity of the ICEV fleet since it can have carbon intensities that are very low (even negative) due to elimination of methane emissions from RNG feedstocks. However, prospects for wide-scale adoption to displace the existing vehicle fleet are small since it is not compatible with the existing fueling system and delivery logistics, requiring investment in new vehicles and fuel delivery in addition to production. Used in its existing transportation niche, RNG will continue to provide more than 100% carbon reduction.

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[205] Note that RNG could be used to replace fossil natural gas and reduce GHG emissions anywhere that natural gas is used in the economy, not just for transportation purposes. As such, the total potential uses for RNG are not limited to the NGV fleet.

14.2.2 RENEWABLE PROPANE

RP (also known as biopropane) is a nonfossil fuel that is produced from 100% renewable raw materials. It must be used in a vehicle dedicated to propane fuel or that can receive, store, and use propane as an optional fuel. RP is produced as a by-product of RD production at about 5% of the RD volume and has the same chemical structure and physical properties as conventional propane. Because it is produced from renewable feedstocks, RP has a CI of about 30 g/MJ versus 80 g/MJ for fossil propane, which is a carbon reduction of more than 60%.[206] Only some of the RP being produced is captured to be delivered to market because most of it is consumed to provide energy and/or produce hydrogen at RD production facilities, thus lowering the CI of the produced RD and eliminating the need for equipment and logistics to transfer the relatively small stream of product to market.[207]

While much more RP could be captured, segregated, and moved to market, propane use in the transportation sector is relatively small. There are only 60,000 on-road LPG vehicles in the U.S., and many are used in fleet applications.[208] Since this makes up only 0.02% of the 276 million registered vehicles in the U.S., major growth of RP will be limited by the growth of the LPG-ICEV fleet. If this fleet grows, another limit could be the limited production of RP since its yield is relatively fixed as it is linked to RD production capacity. Logistics will have to be developed to facilitate transfer of RP from the production facilities to the fuel delivery sites. Unlike many other alternative fuels, however, RP can utilize the same fueling equipment as conventional propane, like household tanks, portable propane tanks, etc.

CONCLUSION: RP for use in ICEVs can use the existing LPG fueling network, but that may be its sole advantage. The challenge for additional use is the size of the LPG-ICEV fleet; if that grows rapidly the remaining challenge is to develop technology and production facilities to provide RP volumes beyond what is produced at RD plants. For customers who have elected to purchase an LPG-ICEV, acceptance of RP versus fossil propane should be high as there should be no noticeable change for the customer. Since production as an RD by-product is growing rapidly, supplying this niche could be accomplished in the next five years—the period of time required for infrastructure improvements—at a similar low to medium cost to produce RD. However, similar to RNG vehicles, increasing scale to displace gasoline and diesel vehicles is not practical in the long run.

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[206] Roush Clean Tech / Renewable Propane: The Near-Zero Solution.

[207] National Propane Gas Association (NPGA) / The Big Question for Renewable Propane: Can it Scale?.

[208] DOE AFDC / Propane Vehicles.

14.2.3 HIGHER ALCOHOL BLENDS OF ETHANOL (E15+ TO E85)

In this section, we discuss ethanol blends of greater than 15% (E15). We divide this discussion into two sections: high-level blends which include E85 used in FFVs, and mid-ethanol blends from 16% to 50%. These higher ethanol blends have the potential to significantly reduce the amount of carbon emissions from gasoline vehicles by displacing a larger portion of petroleum gasoline. Unlike lower blends like E10 and E15, however, these fuels have considerably greater obstacles to overcome before achieving widespread use. The primary obstacle is that the vast majority of existing vehicles are compatible with ethanol blends up to E15 but are not compatible with higher ethanol blend levels. Higher alcohol blends are compatible with the existing ethanol production and logistics system, but modifications would be required to handle the increased volume. The primary challenge for implementation of higher alcohol blends is downstream of the logistics system, specifically at retail sites where additional underground storage tanks, upgraded piping, and upgraded dispensers may be required.

E85 and Flexible-Fueled Vehicles

E85, also known as flex fuel, is a bit of a misnomer as it does not contain 85% ethanol; it contains 51% to 83% ethanol depending on geography and season.[209] The balance of the fuel is gasoline or could be a low-octane hydrocarbon, as the ethanol portion has a very high octane rating. FFVs have material compatibility with high alcohol blends and can operate on fuels with any level of ethanol up to 83%, hence the usage of "flexible" in the name. E85 is normally produced in the tanker truck or as the tanker truck is loaded and delivered to the retail site. The retail site's tanks and equipment must have material compatibility with the high ethanol content. At the retail site, the fuel is normally dispensed in a dedicated dispenser. At some sites, the ethanol portion could be delivered directly, and blender pumps—dispensers that draw and blend fuel from two tanks—can be used to blend the E85 from the ethanol and gasoline on-site.

As of this writing, there are about 21 million FFVs in the U.S. which are capable of handling gasoline blends up to 83% ethanol (E85). Of the over 115,000 gas stations in the U.S., only 2.5% (3,900) carry flex fuel. This is, in large part, because most of the gasoline fueling infrastructure has been designed to handle blends of ethanol up to 15% but not higher blends. This particular fleet arose as automakers were given credits toward meeting corporate average fuel efficiency (CAFE) standards by FFVs.[210] The rules for calculating fuel efficiency

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[209] DOE AFDC / E85 (Flex Fuel).

[210] Flexible fuel vehicles (FFVs) are defined as cars that are capable of operating on any blend of gasoline and ethanol up to 83%.

for FFVs were so favorable[211] that automakers found FFV production to be an efficient way to meet CAFE standards rather than improving the fuel efficiency of their entire fleet. Hence, FFV production grew dramatically. Eventually the CAFE rules were changed such that most FFV production was discontinued. Today, about 7% of the over 280 million registered vehicles in the U.S. can use blends up to E85, and only three manufacturers—Chevrolet, GMC, and Ford—continue to produce FFVs in limited quantities.[212] This means that the number of FFVs in use has begun to decline, reducing the incentive to expand the fueling infrastructure.

The additional cost of producing an FFV[213] is low and was reported to be about $200 in 2011.[214] Today, the costs are likely higher but remain nominal. The challenge to E85 use is the cost of adding E85 to existing retail sites to make the fuel more widely available. In a study by the National Renewable Fuel Laboratory[215] performed 15 years ago, the total average cost was found to be about $20,000 to convert existing equipment and $70,000 to install new equipment, but some estimates were almost twice as high.

Another challenge is that consumer acceptance of E85 has been low, primarily because of the lower energy content per gallon, which reduces the vehicle's range,[216] and the limited availability of E85 fueling sites. Furthermore, most FFV drivers are unaware of their vehicle's capability. While manufacturers received CAFE credits for production, they and their dealers had no obligation to promote consumption of E85. When the CAFE credit was changed to be conditional on FFV use of E85, most manufacturers ceased production of FFVs. According to EIA, about 400 million gallons of E85 were dispensed into the 21 million FFVs in the U.S. last year—that's less than 20 gallons of E85 per FFV per year.

CONCLUSION: E85 and FFVs can significantly reduce carbon intensity through the higher proportion of ethanol. E85 shares much of the production and logistics systems with conventional E10 gasoline; aside from modifying for additional volume, few challenges are posed in these areas. There are challenges in the fuel dispensing, vehicle production, and consumer acceptance areas. Retail sites that offer E85 need to be expanded significantly at potentially high costs. Incentives for FFVs will need to be implemented so that a greater proportion of vehicles could be classified as FFVs. Lastly, consumer awareness and acceptance of E85 must be improved such that consumers use E85 when available. This may require pricing E85 at a discount over gasoline to overcome customer concerns. Converting the current light-duty fleet to FFVs fueled with E85 would require changing incentives for automakers, 30 years or more to turn over the fleet, a significant expansion of ethanol production, and resolution of consumer awareness and acceptance issues to enable a 45% reduction in carbon emissions. Given these challenges, E85 should be viewed as one solution in a larger portfolio of options for decarbonizing ICEV fuels.

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[211] Energy Institute at HAAS / Automakers Complain, but CAFE Loopholes Make Standards Easier to Meet.

[212] Better Fuel for Minnesota / 2021 Flex Fuel Vehicles.

[213] There are also associated costs with certifying the vehicle to meet emissions standards on various levels of ethanol blend. This certification is done on a model-by-model basis but adds cost.

[214] Consumer Reports / Ethanol (E85) fuel alternative.

[215] National Renewable Energy Laboratory (NREL) / Cost of Adding E85 Fueling Capability to Existing Gasoline Stations: NREL Survey and Literature Search.

[216] DOE Office of Energy Efficiency & Renewable Energy / Ethanol.

Intermediate Alcohol Blends

Intermediate alcohol blends—E25, E30, E40[217]— have been investigated as fuels to increase the renewable content of gasoline, similar to E85. Unlike E85 and FFVs, however, these mid-alcohol blends would produce higher octane fuels that potentially could improve mpg in higher compression ICEVs. These intermediate alcohol blends would face the same challenges as E85, with the additional challenge of developing and growing a new ICEV fleet. Although an intermediate ethanol blend could improve mpg, the addition of a new fuel and a new ICEV technology to the marketplace would make the fuel dispensing and vehicle landscape more complex. An intermediate ethanol blend would probably not provide the carbon reduction of E85 used in an FFV since E85 has a much higher content of renewable ethanol.

CONCLUSION: It is difficult to envision an intermediate ethanol blend as a viable alternative to the established E85 and FFV fuel-vehicle combination to reduce carbon emissions from ICEVs.

14.2.4 HIGHER BLENDS OF BIODIESEL (B20+)

BD is an established low-carbon fuel for use in diesel ICEVs—with blends of 5% or up to 20% as described above. Higher blend levels of BD could further reduce the carbon emissions from diesel ICEVs, but there are some significant hurdles to overcome, including the development of an ASTM fuel specification standard for higher blends of BD. Most existing diesel vehicles have material compatibility issues at concentrations over 20%, and in some cases even at 5%, based on manufacturer representations. In some vehicles, BD-compatible material for certain parts (such as hoses and gaskets) have allowed B100 to be used in some engines built since 1994. In higher BD blends, the poor cold flow properties associated with BD are intensified, presenting a challenge for the current fleet.

There are additional challenges for the usage of high BD blends, as B100 has a solvent effect. On initial use, it can clean a vehicle's fuel system and release deposits accumulated from petroleum diesel use. The release of these deposits may initially clog filters and require frequent filter replacement in the first few tanks of high-level blends.[218]

On the plus side, the existing production and logistics and a portion of the fuel dispensing systems may be compatible with higher level BD blends.

CONCLUSION: BD can utilize existing production capacity, logistics, and fuel dispensing systems to increase its concentration in diesel fuel to higher level blends, thus lowering the carbon intensity of diesel fuel. There may be some challenges in material compatibility of the existing vehicle fleet; resolving this will likely require future vehicle production to be manufactured for compatibility with higher BD blends. This would mean that it would take 30 years or more to turn over the existing fleet to achieve a 40-60% reduction in carbon emissions. Like B5 and B20, the most prevalent challenge for BD is RD, which uses the same limited feedstocks as BD but produces a product without the same limitations.

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[217] DOE AFDC / Ethanol Blends.

[218] DOE AFDC / Biodiesel Blends.

14.3 POTENTIAL DROP-IN AND ALTERNATIVE FUELS FOR GASOLINE AND DIESEL ICEVs AND ICE-AFVs

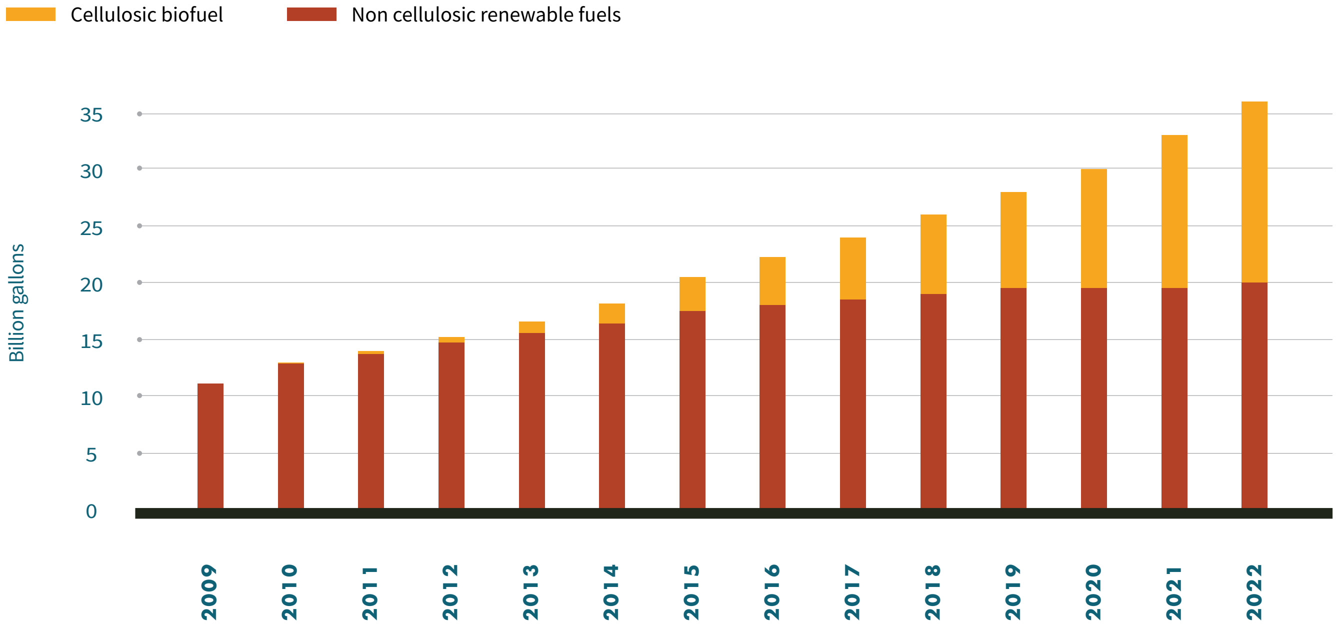
In this section, we discuss the renewable and low-carbon ICEV fuels which are still in various stages of development and are not yet commercialized. Implementation of these fuels may not require a change to the fuel logistics, fuel delivery, or vehicle technology if they are drop-in fuels. If the fuels are not compatible with existing logistics, fuel delivery, and current vehicle technology, however, changes will be required to use these fuels. The potential future low-carbon fuels discussed in this section do not require feedstocks that are also part of the food supply. As such, these fuels avoid the food versus fuel debate altogether.

14.3.1 CELLULOSIC FUELS

Cellulosic fuels are derived from cellulosic feedstocks that are nonfood based and include crop residues, wood residues and biomass, dedicated energy crops, and industrial and other wastes. These feedstocks are composed of cellulose, hemicellulose, and lignin that are converted to fuels. The RFS, as expanded by the Energy Independence and Security Act of 2007 (EISA), set high expectations for the development of a cellulosic fuels industry as a replacement for petroleum fuels. Figure 67 illustrates the RFS targets for cellulosic fuels and non-cellulosic fuels under the RFS.

Only about 4% of the volume of cellulosic fuels called for under the RFS in 2022 was produced. Of that volume, more than 99.7% was in the form of RNG. The inability to meet the RFS cellulosic targets illustrates the major challenge to cellulosic fuels, breaking down cellulose into sugars or organic molecules that can be converted to ethanol or converted to other fuels. The primary obstacle has been economics, as costly enzymes and/or chemicals are required to break down the cellulose, making it uneconomical to produce these fuels with the current level of RFS incentive and the $1.01/gallon cellulosic biofuels production tax credit. Overcoming the challenges of this step is the key to widespread production of cellulosic biofuels outside of pyrolysis or FT production.

FIGURE 67. CELLULOSIC BIOFUEL AND NON-CELLULOSIC RENEWABLE FUELS UNDER THE RFS



Source: Stillwater analysis and Title II, Subtitle A, Energy Independence and Security Act of 2007, PL 110-140, December 19, 2007

Cellulosic Ethanol

Cellulosic ethanol is currently being produced in limited quantities in ethanol plants. Cellulase enzymes are used to convert the cellulose in the kernel fiber to sugars that are then fermented to ethanol. According to the life cycle analysis report submitted as part of the LCFS Tier 2 pathway application for POET Biorefining – Big Stone:

> *Kernel fiber represents the most readily accessible cellulosic biofuel feedstock and holds the potential to provide over 1.8 billion gallons of cellulosic ethanol annually. Because the kernel fiber is a feedstock that is already being delivered commensurate with starch to the existing grain biofuel production facilities, kernel fiber ethanol production also represents the fastest route to commercialization for cellulosic biofuels.*[219]

The volume of cellulosic ethanol potentially produced via this route is significant—1.8 billion gallons of ethanol represents about 10% of the current U.S. ethanol production capacity. Conversion of kernel fiber has advantages over other cellulosic ethanol routes as the feedstock is already at the ethanol production facility, synergistically shares utilities, and utilizes the same equipment as corn starch ethanol.

CONCLUSION: The challenge to expanding the volume of cellulosic ethanol so that it could be used to reduce the carbon intensity of ethanol blended into gasoline is the development of economically viable production from other cellulosic feedstocks. Despite the significant incentives provided by the RFS and LCFS, these have been slow to develop. The true obstacle for cellulosic ethanol is cost, and developing technologies that are competitive could take 30 years or more. If this economic obstacle could be overcome, however, cellulosic ethanol could replace or supplement starch-based ethanol as a lower carbon fuel in the gasoline pool or to supply E85 to FFVs. The challenges to blends above E10 were discussed in the sections covering E15, intermediate ethanol blends, and E85.

Cellulosic Diesel

Cellulosic diesel could be produced in several ways, including via pyrolysis or FT or in a process similar to the production of cellulosic ethanol, which adds further processing to form hydrocarbon molecules in the diesel fuel range. This cellulosic diesel route has not developed because of the high costs of the conversion processes. The challenges to cellulosic diesel are the same as those faced by cellulosic ethanol. The advantages are the same as RD since the fuel is compatible at all blend levels.

CONCLUSION: Cellulosic diesel has great potential to reduce the carbon intensity of ICEV fuels. The primary challenge is development of the processes that can produce cellulosic diesel economically. If that happens, the production is easily compatible with the current logistics, fuel delivery, and ICEV technology, resulting in reduced carbon intensity. However, developing this technology could take 30 years or more.

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[219] POET Biorefining – Big Stone / Low Carbon Fuel Standard Tier 2 Pathway Application No. B0174.

14.3.2 REPURPOSING REFINERIES FOR RENEWABLES PRODUCTION

We discussed the carbon intensity of petroleum fuels above relative to the carbon intensity of the crude delivered to refineries. In the GREET model, 29% and 17% of life cycle carbon emissions for gasoline and diesel, respectively, are from crude oil production and delivery, the refining process, and product delivery; the rest is from tailpipe emissions. The refining process itself contributes a relatively small portion to the product's carbon emissions, but refineries could produce a lower carbon fuel if a renewable feedstock were used. With a renewable feedstock, the carbon intensity of the fuel would be dependent on the carbon intensity of the feedstock.

Refining technology and equipment are very similar to that used in the production of renewable fuels. Many existing or planned RD facilities repurpose hydrotreating and hydrocracking units within petroleum refineries. These RD operations use the same fats, oils, and grease feedstocks that stand-alone RD and BD facilities use. One advantage of an existing refinery is that it would have the infrastructure required to support a renewable fuels operation: tankage, receiving facilities, product delivery facilities, pipeline connections, utilities, and such.

Using existing refineries would be a logical way to convert the material produced by pyrolysis or other renewable conversion process that does not produce a finished fuel suitable for direct use into a final product. In this way, a repurposed refinery would become the finishing step, using its cracking and upgrading processes in the renewable fuel chain and reducing the cost of implementing the supply of renewable fuel to the market. While this is happening for RD production, it has not yet happened for FT, pyrolysis, or cellulosic fuels because the costs of these technologies are still too high to allow the production of the intermediates that can be processed in refineries. However, if production technology breakthroughs lower the costs of these fuel components, existing refineries have equipment that could efficiently produce the finished products that could be used to power the existing fleet of ICEVs.

CONCLUSION: Refineries can be great assets to convert low-carbon renewable liquid feedstocks that are produced by primary renewable conversion processes. Once the low-carbon feedstock production is established, repurposing of refineries to low-carbon ICEV fuel production could occur within a short time of between 5 and 10 years, depending on how closely the low-carbon feedstock aligns with current refinery streams.

14.3.3 PYROLYSIS FUELS (GASOLINE, DIESEL, PROPANE, AND METHANE)

There are two primary routes for producing transportation fuels from biomass and waste: pyrolysis and gasification. Each is discussed separately as the differences in production present different challenges to commercialization. Feedstock challenges are similar for the two routes. Gasification (BTL) was discussed above; this section covers pyrolysis.

Pyrolysis fuels can be generated from biomass or waste stream feedstocks by heating in the absence of oxygen to temperatures that cause the thermo-decomposition of the feedstock (around 500°C and above). Pyrolysis of biomass produces three products: liquid bio-oil, solid biochar, and gaseous syngas. Under conditions optimized for liquid, bio-oil yields of 60-70 wt% can be achieved from a typical biomass feedstock, with 15-25 wt% yields of biochar. The remaining 10-15 wt% is a syngas mixture of carbon dioxide, carbon monoxide, hydrogen, and light hydrocarbons.[220] Fast pyrolysis has the most promise for the pyrolysis-to-fuel pathway as it has high liquid yields.

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[220] U.S. Department of Agriculture Biomass Pyrolysis Research at the Eastern Regional Research Center / What is Pyrolysis?.

The primary pathway envisioned for pyrolysis fuels is for the bio-oil to be upgraded to a bio-crude or biointermediate that can be processed to transportation fuels in existing refineries. To achieve this, a major technical challenge with the quality and characteristics of bio-oil from pyrolysis must be overcome. Pyrolysis bio-oil is a mixture of hundreds of oxygenated organic compounds (carboxylic acids, ketones, aldehydes, furans, sugars) and water that is very different than the hydrocarbons and oxygenated compounds found in current fuels. Because it is so highly oxygenated, the raw bio-oil's fuel value (energy content) is only 50-70% of petroleum fuel's. Bio-oil is also acidic (pH 2-3), unstable, and corrosive, which presents challenges in subsequent processing as well as transportation, piping, and storage.[221]

Bio-oil's composition and acidity are major challenges to producing a stable and upgradable version that can be processed further into transportation fuels. Development of a stabilization technology to assist in producing an upgradable bio-oil has been a major challenge to commercialization of pyrolysis as a renewable fuel pathway.[222] Usually the technology for this first step involves the addition of hydrogen.

If commercial stabilization technology can be established and sufficient pyrolysis and stabilization technology capacity is installed, pyrolysis might become a major supply source of feedstock for existing refineries, reducing the carbon intensity of the fuels they produce. If biocrude and biointermediate can fully replace crude oil, then existing petroleum refineries would be able to produce renewable fuels. With this pathway, the low-carbon products would be nearly identical to today's conventional fuel and should be true drop-in fuels. As such, pyrolysis fuels are compatible with the current logistics, fuel delivery, and vehicle technology. Because the switch from petroleum fuels to pyrolysis can be done without changes downstream of fuel production, consumer acceptance should be high.

There is much current interest in pyrolysis as a means to recycle waste plastics. Pyrolysis of plastics is nearly identical to pyrolysis of biomass, but the resulting liquid product has fewer undesirable characteristics since the feedstock contains less oxygenated material. Thus, the liquid is easier to stabilize to a product suitable for refinery processing. Depending on how the life cycle of the feedstock is determined, fuels from pyrolysis of plastics might be considered a low-carbon fuel.[223] The same characteristics downstream of the production facility would apply.

There are a few small-scale pyrolysis production facilities operating with renewable feedstocks. These facilities often produce a bio-oil that is used in electricity production or heating. Two such facilities are Ensyn in Canada and Empyro in the Netherlands.

CONCLUSION: Pyrolysis holds promise to convert renewable or waste feedstocks into liquids that can be further upgraded to low-carbon gasoline and diesel for use in ICEVs. To date, however, this has not been done at scale, perhaps reflecting that economics are not favorable. If these processes become economical, and true drop-in fuels are produced either directly from the biofuels facility or indirectly through a repurposed petroleum refinery, the production can easily fit within the current logistics, fuel delivery, and ICEV system, resulting in reduced carbon intensity.

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[221] These comments are general as exact chemical composition of bio-oil and its properties are dependent on the pyrolysis feedstock and the pyrolysis conditions.

[222] Biofuels Digest / The Pyromaniax, Class of 2015: The Top 10 Pyrolysis projects in renewable fuels.

[223] Note that pyrolysis of waste plastics would not qualify for RINs under the RFS under the current law.

14.3.4 FT DIESEL (BTL)

As discussed above, fuels can be produced via FT synthesis from many feedstocks. The technology can also be used to convert agricultural residues, wood waste, and municipal solid waste (MSW) into fuels, primarily diesel. As a drop-in fuel like RD, FT diesel has the potential to substantially decarbonize the difficult-to-electrify heavy-duty fleet. The fuel would use existing fuel supply logistics, existing fuel delivery, and current vehicle technology; be readily acceptable to the public; and have the major advantage of a potentially enormous supply of feedstocks if conversion of the waste feedstocks could be done economically.

The primary difference between biomass-to-liquid (BTL) and gas-to-liquid (GTL) or coal-to-liquid (CTL) production of FT diesel is the feedstock and syngas production technology. There are two routes to low-CI FT diesel: the primary method is from biomass and the second is from RNG.

FT diesel from RNG is essentially GTL producing a low-carbon product. This pathway has two primary challenges. The first is that its feedstock (RNG) is already a low-carbon ICEV fuel, and the energy loss in the conversion to a liquid diesel greatly favors using the feedstock itself to fuel vehicles.[224] Secondly, to achieve scale for a GTL plant, large quantities of feedstock are required, as it takes approximately 10,000 standard cubic feet of RNG to produce one barrel of FT diesel.

The first step in the BTL process—biomass partial oxidation or pyrolysis gasification—produces syngas for the FT reaction step. This is virtually identical to the third step in the processes for GTL or CTL. This gasification step is where either oxygen is used to partially combust the feedstock at high temperatures (~1100°C) or external heat is used to decompose the feedstock into primarily carbon monoxide and hydrogen. Other products are carbon dioxide, ash, oils, and tars.

The primary technical challenges for BTL diesel are dealing with the by-product tars and oils and the high capital cost per unit of production for the syngas production and FT synthesis. A secondary challenge, especially using MSW as a feedstock, is the wide range of potential contaminants and its inherent variability.

The firm which has achieved the greatest progress to date towards commercial operation is Fulcrum Bioenergy, which recently achieved commercial operation of the gasifier unit at their Sierra BioFuels Plant in Reno, Nevada, utilizing MSW feedstocks.[225] While this is an essential milestone, this is only the first step in the process as they will also need to achieve commercial operation on their FT process unit (which converts syngas from the gasifier to FT syncrude) and upgrading units (which convert the FT syncrude to salable products) in order to produce diesel fuel. The plant is rated for 11 million gallons of renewable, low-carbon transportation fuels annually.

If Fulcrum or other firms developing this technology are successful at achieving reliable commercial and profitable operations at an acceptable cost

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[224] Ultimately, RNG usage as a transport fuel is limited by the population of NGVs. With that market in the U.S. nearing RNG saturation, there is potential opportunity for RNG to spill over into competing RNG uses.

[225] Fulcrum BioEnergy / Fulcrum BioEnergy Successfully Starts Operations of its Sierra BioFuels Plant.

and scale, the potential production of BTL diesel will be well beyond BD and RD potential given the constraints on the supply of fats, oils, and greases for feedstock, which are expected to limit growth of BD and RD. Incentives provided by the RFS, IRA, and LCFS programs will play a significant role in bridging the cost spread between BTL diesel and petroleum diesel. As BTL diesel has the potential to be a truly drop-in fuel which can be used in blends of up to 100%, it will be possible to displace a very large fraction of petroleum diesel demand over the time required as production capacity grows.

CONCLUSION: FT diesel produced from biomass (BTL) holds promise to convert renewable feedstocks into liquids that can be further upgraded to low-carbon gasoline and diesel for use in ICEVs. If the BTL process becomes economical, the drop-in fuels that are produced, either directly from the biofuels facility or indirectly through a repurposed refinery, can easily fit within the current logistics, fuel delivery, and ICEV technology, resulting in reduced carbon intensity. Since the technology is not yet economical, the costs are very high and the time required to both develop and implement is unknown but will be quite long. Potential carbon reductions could also vary significantly depending on the technology and feedstocks used. Fuels produced from most biomass would likely reduce carbon emissions by 25-75%, but fuels produced from RNG would likely reduce carbon by more than 100%.

14.3.5 E-FUELS (GASOLINE, DIESEL, PROPANE, AND METHANE)

E-fuels are synthetic fuels produced from renewable energy instead of renewable feedstocks. The potential for e-fuels is limited by the ability to generate renewable energy and use it in the production of fuels. The production and use of e-fuels somewhat mimics the carbon cycle, as e-fuels are synthetically produced from CO_2 (preferably from DAC) and hydrogen from water using renewable energy, and the use of the e-fuel returns the CO_2 and water to the environment. Because the energy is renewably sourced and the CO_2 is removed from the atmosphere (or from a CO_2 emitting source), the resulting fuel's carbon intensity is very low— as low as zero if the energy used is generated from solar, wind, nuclear, or hydro. Depending on the specific fuel products synthesized, e-fuels can be drop-in fuels or may be fuels that require specific logistics, fuel delivery, and vehicle technology.

One e-fuel production facility has recently begun operation in Chile. Located in Punta Arenas, the plant uses wind-generated electricity as its energy input and DAC for CO_2. The Haru Oni project is the world's first integrated, commercial, industrial-scale plant for making synthetic climate-neutral fuels.[226,227,228,229] It was developed by HIF with technology and engineering support from various providers, including cofounder and product offtaker Porsche. The plant includes a 3.4 MW wind turbine that generates the power for a proton exchange membrane (PEM) electrolysis unit to produce hydrogen from water and a dry amine solid state sorbent to capture CO_2 from the air. The CO_2 and hydrogen are converted to methanol in a synthesis reactor, and the final step is conversion of the methanol via the methanol-to-gasoline process. In all, the power generated by the wind turbine

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[226] HIF Global / Haru Oni Demonstration Plant.

[227] Automotive Logistics / Porsche Haru Oni synthetic fuel plant begins production.

[228] HIF Global.

[229] Siemens Energy / Haru Oni: Base camp of the future.

is converted to 750,000 liters (195,000 gallons) of methanol per year, part of which is converted to 130,000 liters (34,000 gallons) of synthetic gasoline per year via a methanol-to-gasoline (MTG) process. With this production scheme, the gasoline produced is a drop-in fuel which can utilize existing logistics, fuel dispensing systems, and current vehicle technology. The fuel would also be carbon neutral.

The process sequence used at Haru Oni is one of several that are conceptually possible for producing e-fuels. Other process sequences that might be used to produce e-fuels have a similar front end; that is, production of renewable power and capture of CO_2 via DAC or from an emitting source. At this point, some potential e-fuel routes are:

1. **E-gasoline via conversion of CO_2 and hydrogen produced from electrolysis of water to methanol and conversion of the methanol to gasoline via the MTG process.**
2. **FT diesel via conversion of CO_2 to carbon monoxide via a reverse water-gas shift reaction, combining with hydrogen from electrolysis of water, and then to a FT reactor and product finishing unit to produce e-FT diesel.**
3. **RNG via hydrogenation of the CO_2 with hydrogen produced through electrolysis of water. This will produce a carbon-neutral RNG that can be used in NGVs.**
4. **E-gasoline and e-diesel via conversion of CO_2 and hydrogen to ethylene and polymerization of the ethylene to gasoline or diesel.**
5. **E-ethanol via conversion of CO_2 and hydrogen to ethylene and hydration of the ethylene with water to form e-ethanol.**

Note that each of these e-fuel routes generates building-block carbon containing molecules (CO, methanol, ethylene) as a process step that is further processed to produce the higher carbon molecules that comprise the fuels. Since it is possible to produce almost any carbon-containing building-block molecule with power and CO_2, there are probably other possible e-fuel routes in addition to those listed.

There are challenges to e-fuels in both the technological and economic dimensions. For the technology, moving from the concept stage to the actual production stage is just in its infancy. Production of e-fuels will need to achieve sustained and safe operation producing on-specification e-fuels. The steps involved with e-fuels are, for the most part, proven at commercial scale, but some steps (such as FT and MTG) are not widely practiced. The probable major challenge that e-fuels must surmount is the economic one—either high capital costs or low-margin economics. The low-margin economics are enhanced by current subsidies and may be further enhanced by additional subsidies. An additional challenge may be the efficiency of converting renewable power to liquid fuels since the prime energy feedstock that is used, renewable energy, will also be in demand to decarbonize the electricity grid.

CONCLUSION: As e-fuels are just in their infancy and there are multiple pathways, each with different challenges and economics (and variable future subsidies), the assessment of e-fuels can only be conceptual at this time. Perhaps in several years a clearer picture will evolve. Notwithstanding this uncertainty in concept, e-fuels present an almost ideal way to decarbonize the ICEV fleet, as e-fuels are carbon neutral while also compatible with logistics, fuel delivery, and vehicle technology. E-fuels are valuable in the transition as they can be used as a drop-in fuel along with all the other liquid drop-in fuels previously discussed.

14.3.6 HYDROGEN

Hydrogen for ICEVs would be available from the same sources used for fuel cell electric vehicles (FCEVs). The hydrogen for FCEV is envisioned to be from electrolysis of water using renewable power. Carbon-negative, as determined by CARB in the LCFS program, transportation hydrogen is currently being produced in California. Hydrogen-fueled ICEVs would use the same production, logistics, and fueling infrastructure as hydrogen supplied to FCEVs.

Hydrogen ICEVs would require engine modifications to operate on hydrogen, and the vehicle will need to have a fuel receiving and storage system designed for hydrogen. The hydrogen ICEV is a slightly modified version of the traditional gasoline ICEV. These hydrogen engines burn fuel in the same manner that gasoline engines do; the main difference is the exhaust product. Gasoline combustion results in emissions of mostly carbon dioxide and water, while the main exhaust product of hydrogen combustion is water vapor.

The biggest challenge to hydrogen ICEVs may be the perception that they are not as environmentally friendly as other other types of ZEVs. The other challenge is that using hydrogen as an ICEV fuel requires a vehicle designed for hydrogen, and the range of such vehicles may be small since the space required to store liquid hydrogen is much greater than that for gasoline.

CONCLUSION: Although hydrogen ICEVs are viable and can share the same production, logistics, and fuel delivery systems as FCEVs, the most probable continued vehicular use of hydrogen will be FCEVs.

Options for ICEV Improvements

The transportation carbon emissions from ICEVs might be reduced in four primary ways:

1. **Use lower carbon fuels as discussed in the sections above,**
2. **Improve vehicle fuel efficiency,**
3. **Reduce use of vehicles, and**
4. **Capture CO_2 from vehicle exhaust.**

Of these four methods, the last two are not included as part of this analysis since reducing use of vehicles is not a technical issue but a social engineering one, and capturing CO_2 onboard the vehicle is a nonstarter.[230] In this section, we discuss efforts and methods to improve the efficiency of ICEVs that result in improved fuel economy, thus reducing transportation carbon emissions without reducing usage (at constant fuel carbon intensity).

15.1 IMPROVED FUEL ECONOMY

Improving fuel efficiency has historically been the most significant way to reduce carbon emissions from gasoline- and diesel-powered vehicles. EPA rates average mpg for all new vehicles using predetermined driving conditions to provide consumers with reasonable estimates of how much fuel will be required for everyday service.[231] This rating is an estimate of the combined impacts of engine efficiency, vehicle weight, use of hybrid technology, and recovering energy from braking using hybrid technology.

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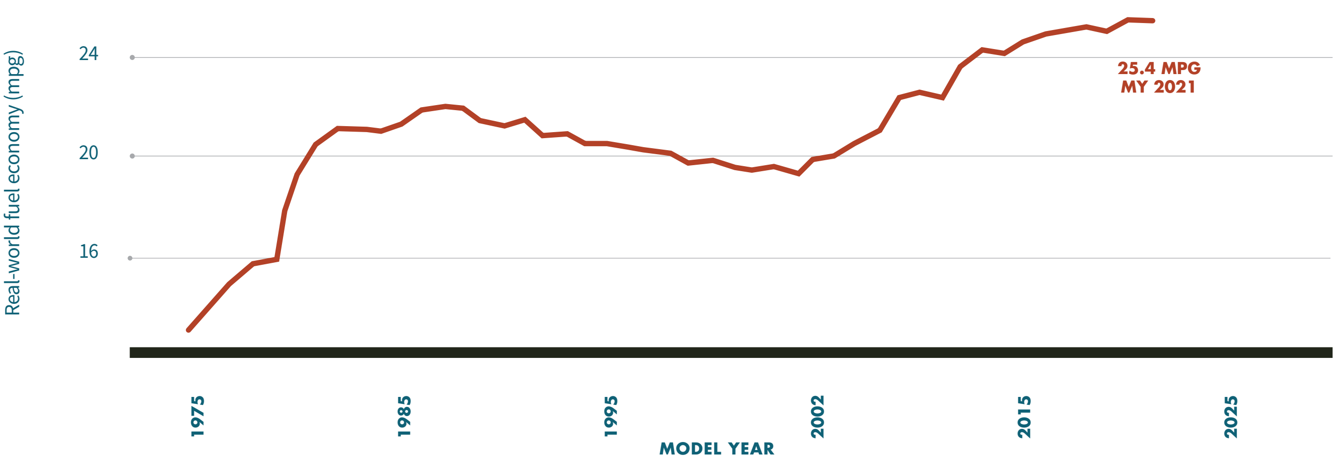
[230] Adding the equipment to each vehicle to capture and store CO_2 from the tailpipe and recover for sequestering or use would be very costly and much less economic that other ways of CO_2 capture. Vehicle technology challenges include the fact that the CO_2 would add a significant amount of weight compared to the gasoline used; per EIA, a gallon of gasoline produces 19.37 pounds of CO_2 compared to gasoline which produces about 6 pounds per gallon. In addition, CO_2 would need to be stored as a liquid, requiring compression, liquification, and pressurized storage onboard the vehicle; this increases the weight and complexity of the vehicle. This mode of CO_2 capture would be far less cost effective than capture from other CO_2 emission sources or from direct air capture.

[231] DOE Office of Energy Efficiency & Renewable Energy / FuelEconomy.gov.

Historical improvement in average fuel economy of light-duty vehicles has been over 70% in the last 50 years, as shown in Figure 68 below. Efficiency advancements have enabled this improvement despite the large growth in average vehicle weight (due in part to more and larger light-duty trucks in the vehicle population).

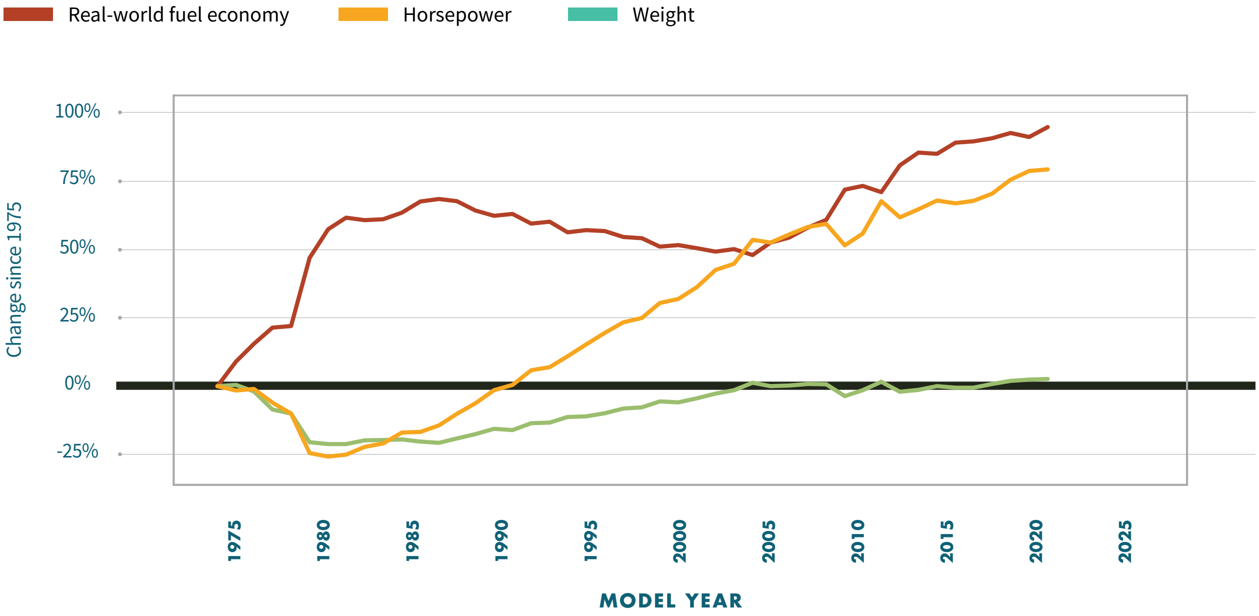
Figure 69 below shows the simultaneous increases in mpg, engine horsepower, and vehicle weight in the U.S. between 1975 and 2021.

FIGURE 68. ACTUAL LIGHT-DUTY VEHICLE FUEL ECONOMY IMPROVEMENT IN THE U.S.



Source: The 2022 EPA Automotive Trends Report

FIGURE 69. LIGHT-DUTY VEHICLE FUEL ECONOMY, HORSEPOWER, AND WEIGHT CHANGES OVER TIME



Source: The 2022 EPA Automotive Trends Report

These improvements are forecasted to continue. In its 2022 AEO Reference Case, EIA forecasts continuing improvements in light-duty vehicle fuel economies, as shown in Table 15 below. [232]

TABLE 15. KEY VEHICLE MODELS USED TO QUANTIFY VEHICLE TECHNOLOGY EMISSION DIFFERENCES

	2021 MPG (GREET)	2021 MPG (2022 AEO)	2035 MPG (2022 AEO)
FCEV (mpge)	61.48	52.95	51.62
BEV (mpge)	87.42	95.75	100.04
Gasoline	30.08	35.29	37.03
Gasoline Hybrid	36.47	50.64	52.70

Source: 2022 GREET, 2022 AEO Reference Case Fuel Economy

Similar approaches can be used to improve the fuel economy of diesel-fueled ICEVs, which are the primary type of heavy-duty vehicles: improving engine efficiency, lowering vehicle weight, and recovering energy from braking using hybrid technology. By design, diesel engines are more efficient than gasoline engines because they operate at much higher compression ratios. Modern turbo-diesel engines also use electronically controlled common-rail fuel injection as well as other techniques to increase efficiency. Engines in large diesel trucks, buses, and newer diesel cars can achieve peak efficiencies around 45%, but the maximum efficiency of the current engine technology could be increased to about 60% if cost were not a constraint.[233] This could potentially increase commercial vehicle fuel economy by over 40%, or nearly double the fuel economy of passenger vehicles. Commercially achievable engine efficiencies are constrained not only by basic chemistry and physics but also by factors such as cost, consumer driving needs and comfort, need for reliability and durability, and environmental regulations. Practical efficiencies will depend heavily on the targeted transportation sector since fuel use has the largest impact on commercial truck operating cost.

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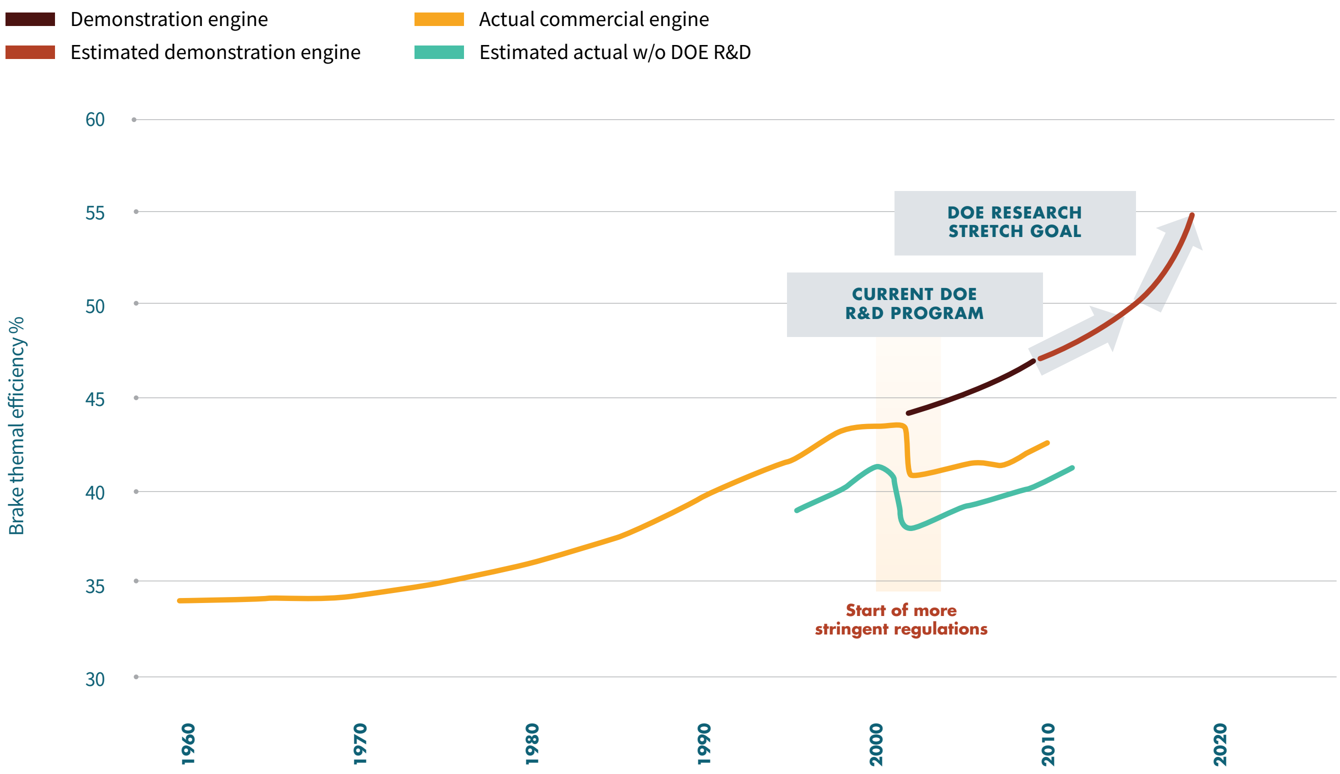
[232] Because EVs do not use fuel, their fuel economy is represented as miles per gallon equivalent (MPGe). This is similar to MPG but represents the number of miles the vehicle can go using a quantity of fuel with the same energy content as a gallon of gasoline. One gallon of gasoline has the energy equivalent of 33.7 kWh of electricity.

[233] Caton, Jerald A. / Maximum efficiencies for internal combustion engines: Thermodynamic limitations.

Historical diesel engine efficiency gains over time are shown in Figure 70 below.[234]

FIGURE 70. HISTORICAL PROGRESS IN HEAVY-DUTY ENGINE EFFICIENCY



Source: U.S. DOE, Quadrennial Technology Review 2015, Chapter 8, Advancing Clean Transportation and Vehicle Systems and Technologies

Since most of the diesel consumed is used to move freight, reducing the weight of the vehicles is necessarily a secondary consideration. (Vehicle strength to safely carry heavy loads is the primary consideration.) However, hybrid technology is an excellent fit for diesel buses used for mass transit in large cities. Recovering the energy used in braking for buses that frequently stop to pick up passengers has been shown to increase fuel efficiency by 45%.[235]

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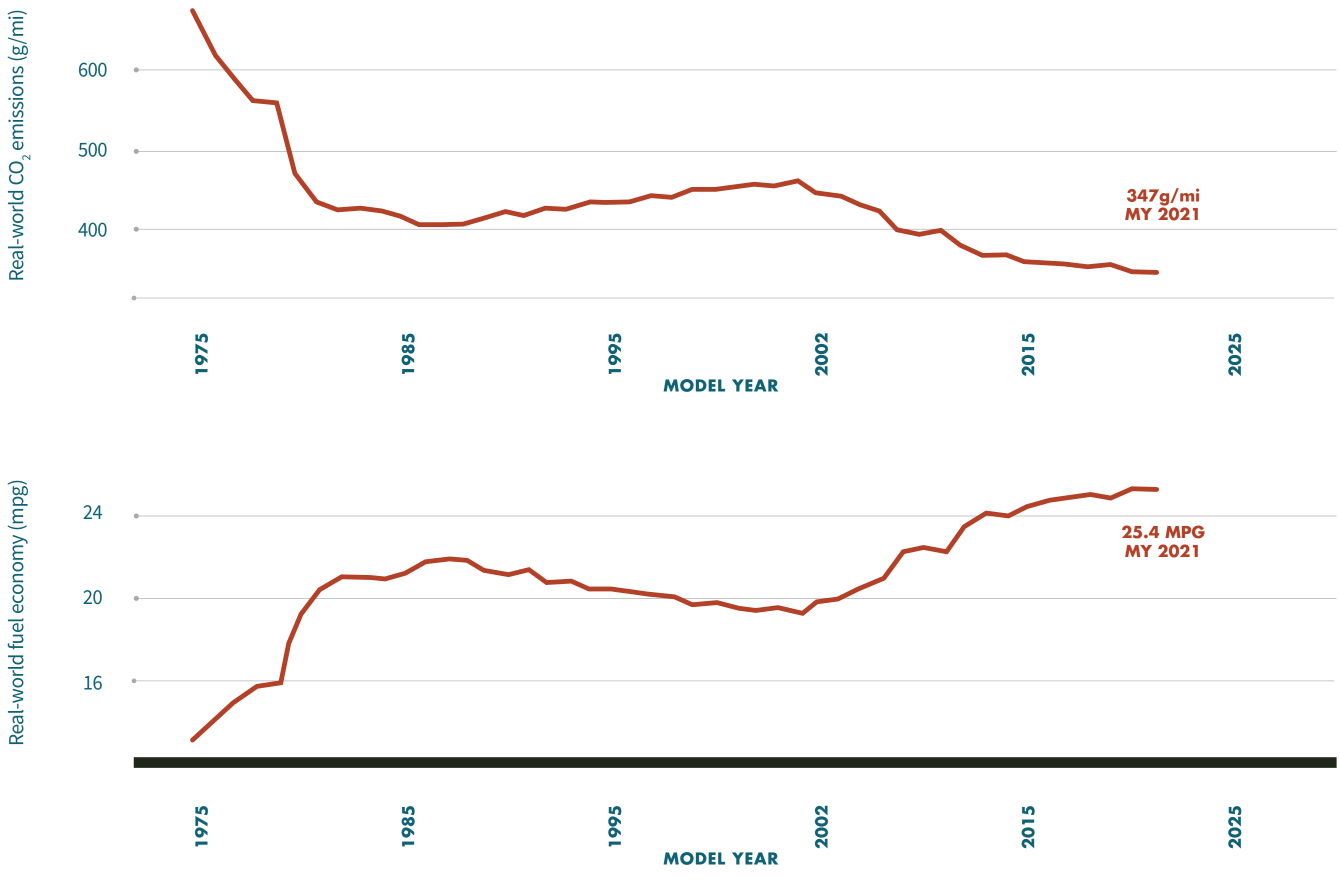
[234] DOE / Quadrennial Technology Review 2015, Chapter 8: Advancing Clean Transportation and Vehicle Systems and Technologies.

[235] The New York Times / As Hybrid Buses Get Cheaper, Cities Fill Their Fleets.

FIGURE 71. REAL-WORLD CO_2 EMISSIONS AND FUEL ECONOMY



Source: Highlights of the Automotive Trends Report | US EPA

The advancements in efficiency have been reflected in the new-vehicle estimated real-world CO_2 emissions by model year. Figure 71[236] is from EPA's Highlights of the Automotive Trends Report. It shows the improvement in CO_2 emissions per mile from the 1975 model year through 2021.

CONCLUSION: The potential impacts of engine efficiency improvements alone can potentially increase passenger vehicle fuel economy by 35% to 50% and commercial vehicle fuel economy by 30%, with accompanying carbon emissions reductions. An average of more than 16 million passenger vehicles with advanced combustion engines are sold each year; they offer tremendous potential to improve the fuel economy of the vehicle fleet as less-efficient vehicles are replaced and retired. Fuel economy improvements offer direct cost savings to the consumer and do not require any changes to consumer driving behavior or limit mobility. The recently revised corporate average fuel economy (CAFE) standards and the upcoming more stringent emissions regulations (e.g., EPA Tier 3, CARB LEV III)[237] are expected to motivate accelerating deployment of engine technologies that will improve engine efficiency to increase vehicle fuel economy.

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[236] EPA / Highlights of the Automotive Trends Report.

[237] U.S. Department of Transportation (DOT) National Highway Traffic Safety Administration (NHTSA) / Corporate Average Fuel Economy.

15.1.1 GASOLINE HYBRIDS

Widespread adoption of hybrid technology has offered a major improvement to the carbon emissions of the ICEV fleet in the U.S. Hybrid vehicles are powered by an ICE engine and one or more electric motors which use energy stored in batteries. There are two primary types of hybrids:[238]

1. **Conventional hybrid vehicles (HEVs)** – An HEV is a type of hybrid vehicle that combines a conventional internal combustion engine system with an electric propulsion system. These vehicles cannot be plugged in to charge the battery. The battery is charged by the ICE and through regenerative braking. The extra power provided by the electric motor can potentially allow for a smaller engine, and the battery can also power auxiliary loads and reduce engine idling when stopped. Together, these features result in better fuel economy without sacrificing performance.

2. **Plug-in hybrid electric vehicle (PHEVs)** – These vehicles are a sort of crossover between an HEV and an EV. Generally, these vehicles operate as EVs when their batteries are charged by plugging in and they are operating within the range provided by their batteries. Once they've exhausted their batteries' range, PHEVs operate as a HEVs. Note: PHEVs can be considered EVs when operating strictly on the battery charge stored from external power sources, but the following comments and discussion related to HEVs apply to PHEVs that are beyond their range or are operating with depleted battery charge.

HEVs have a sizable efficiency advantage over conventional ICEVs. References indicate that HEVs typically get at least 25% better fuel economy than their standard ICEV counterparts.[239] The primary reason for the hybrid's improved fuel economy is regenerative braking during the city driving cycle.[240] Regenerative braking uses the electric motors as generators to recharge the batteries during braking. In a conventional ICEV, this energy is absorbed by the brake pads and dissipated as heat into the environment.

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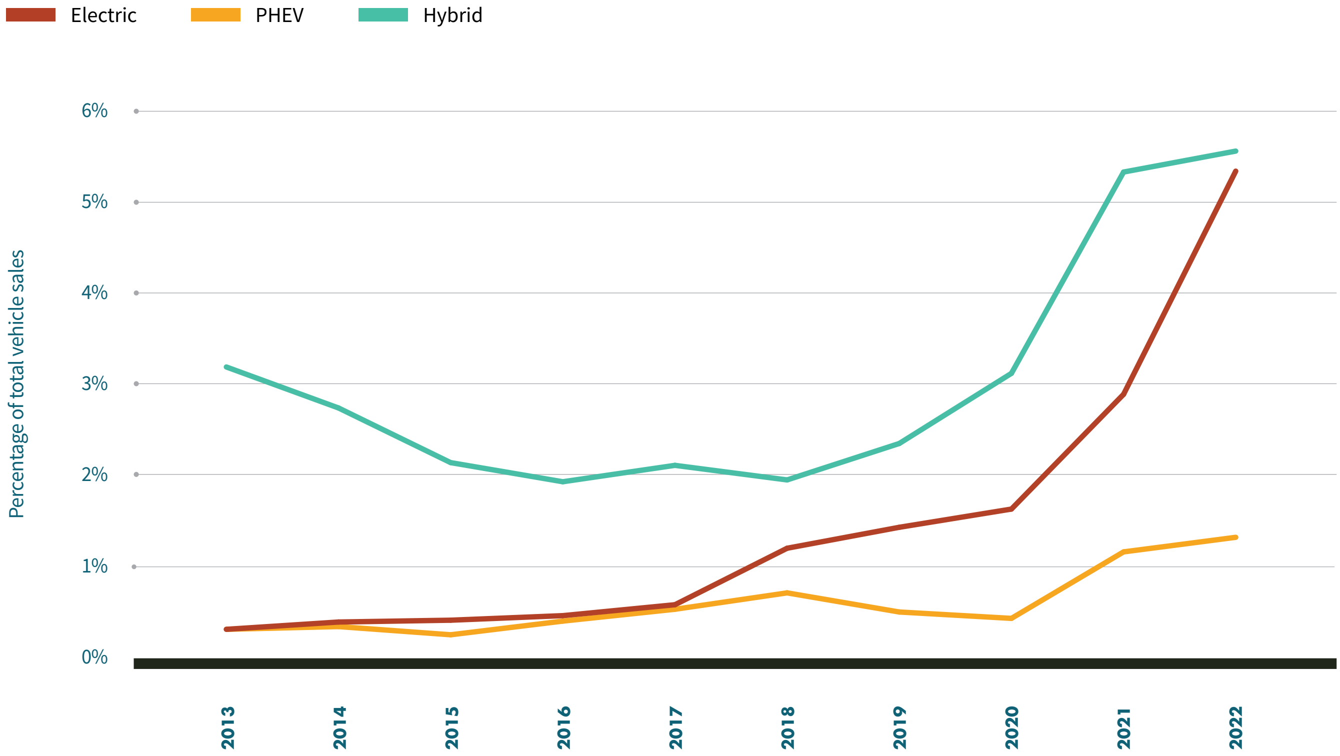
[238] Progressive / What's the difference between a hybrid and a plug-in hybrid car?.

[239] CarsDirect / Fuel Economy Comparison: Hybrid vs Diesel vs Gas.

[240] The impact of regenerative braking is small during highway driving where braking is limited.

Hybrids have higher initial costs, but this is typically offset by lower operating costs in the first few years.[241] The attractiveness of lower fuel costs and environmental concerns have driven sales of hybrids in recent years, as shown in Figure 72[242] below, and hybrid technology has been a significant factor in improving fuel efficiency and reducing carbon emissions from gasoline ICEVs.

FIGURE 72. EV AND HYBRID SHARE OF LIGHT-DUTY VEHICLE SALES



Source: Wards Intelligence

15.1.2 DIESEL HYBRIDS

A diesel-electric hybrid is a vehicle that is powered by both a diesel engine and an electric motor. Trains have relied on this technology for decades. Production of on-road diesel-electric hybrid vehicles so far has been limited to urban transit bus fleets. Urban bus fleets are ideal for this application since regenerative braking's largest contribution to efficiency is in the urban driving cycle with frequent stops and starts. The main challenge is that diesel-electric hybrid vehicles are expensive to produce.

15.1.3 HYBRID IMPROVEMENTS

Gasoline and diesel hybrids can benefit from the same improvements in engine efficiencies discussed earlier by incorporating those technologies in their ICE motor. As noted, hybrid technology may offer an efficiency advantage over ICEVs only if the hybrid technology is designed to allow the ICEV to operate in its most efficient range.

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[241] Consumer Reports / Regardless of Gas Prices, Some Hybrids Pay for Themselves Immediately.

[242] EIA / Electric vehicles and hybrids surpass 10% of U.S. light-duty vehicle sales.

One potential improvement to hybrid vehicles is a switch from batteries and motors to a hydraulic system called the hydraulic hybrid:

> *The U.S. EPA worked together with various partners to develop a unique hybrid, high-efficiency vehicle that uses hydraulic fluid to store and provide energy to power the car. The technology dramatically improves the fuel economy of sport utility vehicles and light trucks. The hybrid system uses hydraulic pumps and hydraulic storage tanks to store energy in the place of electric motors and batteries used in electric hybrid vehicles. In laboratory tests conducted in partnership with UPS, the hydraulic hybrid showed a fuel economy of 60 to 70% over a conventional truck engine.*[243]

CONCLUSION: Hybrid vehicles offer a major step up in efficiency over conventional ICEVs in most driving conditions except highway driving. These vehicles are compatible with existing fuels and future low-carbon versions of these fuels. Adding the plug-in feature of the PHEV allows a vehicle to use electricity or gasoline/ diesel depending on the range required. The disadvantage of hybrid and PHEV vehicles is the higher initial cost. Because this technology is in place now, is growing in popularity, and is compatible with current and future fuels, hybrids and PHEVs can be a key component to reduce the carbon emissions from ICEVs.

15.1.4 OTHER FUEL ECONOMY IMPROVEMENTS

Because of the current regulatory emphasis on ZEVs (e.g., EVs and FCEVs), a number of automakers have indicated that they are ceasing development of new ICE motors. Despite this change in emphasis, some automakers are continuing programs to increase the efficiency of their ICEV platforms.

Engine efficiency refers to an engine's ability to transform the available energy from its fuel into useful work. The modern gasoline combustion engine operates at an average of roughly 20-30% engine efficiency.[244] With the low engine efficiency of current gasoline engines, there is opportunity to increase that efficiency which would lead to direct decreases in carbon emissions. Improvements in ICE efficiency enable improvements in fuel economy either directly or when employed as the motor in hybrid vehicles.

Mazda has introduced a gasoline engine technology "that uses the principle of homogeneous charge compression ignition, or HCCI, which has been a holy grail for engine designers for decades."[245] Called SKYACTIV-X,[246] Mazda's technology employs both spark and compression ignition technology, and Mazda claims that the engine improves fuel efficiency up to 20-30% over their standard gasoline engine.

Nissan is working on an engine with 50% thermal efficiency[247] that is designed to operate within a very narrow range of speed and load. Nissan is developing this engine as a generator for hybrid vehicle use, where only an electric motor drives the wheels, with no mechanical connection between the engine and the wheels. The ICE generates energy to charge a battery, and that battery powers the motor. Nissan was able to achieve 50% thermal efficiency in testing by essentially tuning the engine to operate within a very specific range of speed and load. Because the engine doesn't drive the wheels,

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[243] EarthEasy / Hybrid Car Outlook and Other Future Technologies.

[244] WikiMotors.Com / What is Engine Efficiency?.

[245] Motor Authority / 2020 Mazda 3 prototype first drive: Can spark-less engines ignite our passions?.

[246] Mazda / SKYACTIV-X: a revolutionary new combustion engine.

[247] Road & Track / Nissan Says It's Working on an Engine With 50-Percent Thermal Efficiency.

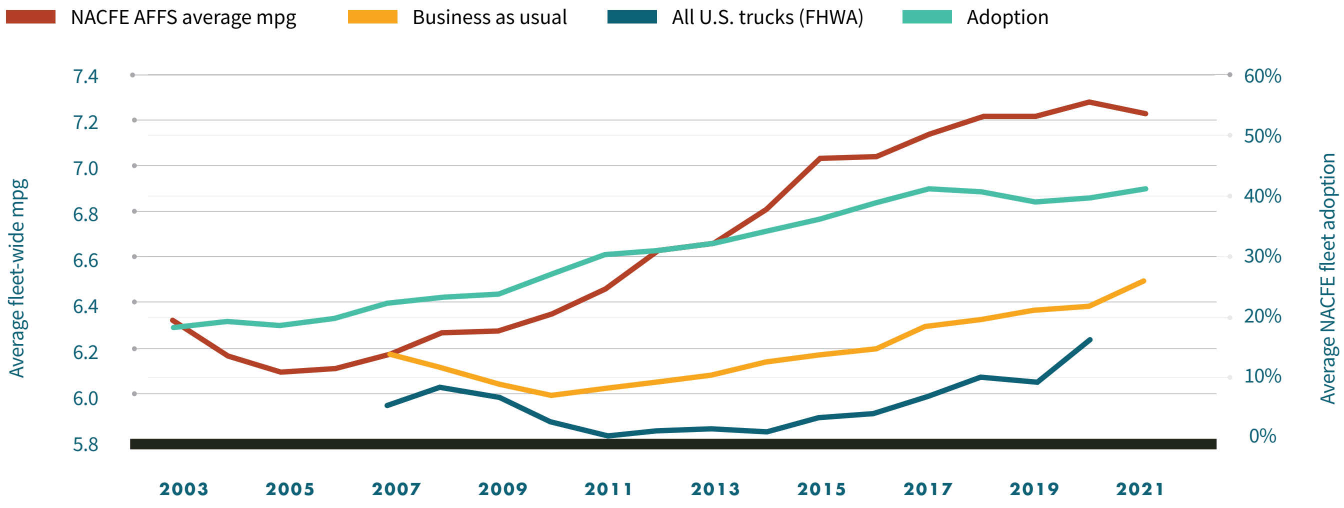
it doesn't have to work with the wide parameters demanded by varying road and driving conditions.

For HDVs, where diesel ICEVs prevail, engine efficiency is higher. Compared to gasoline-fueled ICEVs (which have an engine efficiency of 20-30%), diesel-fueled ICEVs have a higher engine efficiency of 42%.[248,249] In the past decade, the efficiency of diesel engines has increased, advancing from mechanically controlled systems with zero sensors to electronically controlled engines and aftertreatment systems with 30-plus sensors to monitor and control engine operation. In the 1980s, fuel injection pressures were in the 2000-3000 PSI range, whereas today's diesel engines develop injection pressures in the 30,000-40,000 PSI range.[250] Higher pressures increase the fuel atomization and thus improve combustion efficiency.

Another efficiency improvement has been engine downspeeding. By reducing engine operating speeds, there is reduced internal friction, resulting in increased fuel economy and improved fuel consumption. For instance, with a typical line-haul truck operating at normal highway speeds, for each 100 RPM drop in engine speed, fuel economy is improved by approximately 1%.[251]

In addition to engine efficiency, other improvements to HD trucks can greatly improve fuel economy. The North American Council for Freight Efficiency (NACFE)[252] has assembled 86 currently available technologies for lowering fuel consumption in heavy-duty trucks. These technologies are in seven technology groupings: power train, chassis, tires and wheels, tractor aero, trailer aero, idle reduction, and practices. Data from reporting companies take into account the miles per gallon and the percent of the available technologies in these groupings that are implemented. Figure 73 illustrates the trend of mpg for these fleets, the U.S. average as depicted by Federal Highway Administration mpg data, the percent adoption of the available technologies, and the estimated mpg without the available technologies.

FIGURE 73. AVERAGE FLEET-WIDE FUEL ECONOMY OVER TIME



Source: NACFE, 2022 Annual Fleet Fuel Study, December 2022

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[248] Large low speed two-stroke marine engines used in marine applications have efficiencies up to 55%.

[249] Stillwater analysis of California Air Resources Board New Vehicle and Engine Certification Compression-Ignition and Heavy-Duty Engines and Vehicles (2010-2018 model years).

[250] Fleet Equipment / The advancements of diesel technology.

[251] Fleet Equipment / The advancements of diesel technology.

[252] The North American Council for Freight Efficiency (NACFE) works to drive the development and adoption of efficiency enhancing, environmentally beneficial, and cost-effective technologies, services and methodologies in the North American freight industry.

Ranking of Options

In the previous sections, we have provided a foundational understanding of current ICEV fuel production, delivery and fueling logistics, and vehicle landscape. Building on that foundation, we then outlined the fuels that have potential to reduce the carbon intensity of ICEVs. We also discussed each fuel's potential to contribute to a lower carbon ICEV fleet. Finally, we offered an overview of the potential to improve the fuel efficiency of ICEVs.

In this section, we pull together all the information from previous four sections in a systematic fashion that allows us to rank the options for decarbonizing ICEVs using factors we identified as key in the prior sections. Since the error bar of knowledge is small for current fuels and very large for aspirational fuels, only a qualitative ranking can be made. We have made this assessment for various combinations of vehicles and fuels in an effort to determine which pathways are most likely, in our current judgment, to prove beneficial in the short and long runs. Some fuel options to reduce ICEV carbon emissions which are compatible with current ICEVs can be implemented in a short (less than five-year) timeframe given the proper incentives, while others, where technology is established or near established, could be available in the mid-term (5 to 15 years). The longer term (greater than 15 years) options face significant technological or developmental challenges before they could be widely commercialized.

We also note here that different applications have different solutions. For example, hybrid technology adds enormous value to a city bus with frequent stops but much less for a truck doing long-haul deliveries. It is also worth noting that electrification faces more challenges in the heavy-duty sector than in the light-duty sector, so alternative biofueled technologies may have a particularly meaningful impact in the heavy-duty fleet.

16.1 METHODOLOGY

For each fuel and technology discussed above, we have evaluated technical feasibility, preferred options in the short versus long term, consumer acceptance, infrastructure and delivery needs, and potential cost to reduce emissions. We qualitatively assessed these to provide an overall picture of the chances of success for various combinations of vehicles and fuels.

We identified the fuels and corresponding ICEV technology paired for analysis and judged each of them using the following criteria:

- **Status/Potential of Fuel Production** – Status, potential, or requirement to capture the indicated carbon-reduction benefits.
- **Compatibility with Current Fuel Delivery Logistics** – Here, we answer the question: Is the fuel compatible with current logistics systems for delivery to marketplace or is a new logistics system required?
- **Compatibility with Current Dispensing System** – Here, we answer the question: Is the fuel compatible with current llast-mile fuel-to-vehicle delivery systems? If a new fuel dispensing system is required, the answer here is “no.”
- **Consumer Acceptance** – Here, we answer the question: Will the fuel, dispensing experience, and requisite ICEV be easily accepted by the consumer?
- **Shortest Time to Full Maturity** – This is our qualitative assessment of how soon each fuel and corresponding vehicle technology could realize their potential as a decarbonizing option for ICEVs. We have grouped these fuels into four categories: current, near-term, mid-term, and long-term. Current options are already at maturity. Near-term options have potential to be fully mature within five years. Mid-term options would require at least 5 to 15 years to reach full maturity, and long-term options would require more than 15 years.
- **Relative Unsubsidized Cost of Transition** – The qualitative cost of transition expressed without subsidy. Note that the current low-carbon fuels are economical with subsidies (RPS, LCFS, CFPC, BTC, etc.) and mandates.
- **Carbon Emissions Reduction versus Current Fleet and Fuels** – An estimated potential carbon emissions reduction of the fuel-vehicle pairing compared to the current fleet of ICEV gasoline and diesel vehicles fueled with E10 gasoline or petroleum diesel.

16.2 QUALITATIVE COMPARISONS OF ALTERNATIVES

Table 16 shows our qualitative analysis of options to reduce carbon emissions in the on-road sector as described in this report. We begin with the current fuels then move to the most common alternatives and progress through the potential future fuels being developed. Each alternative option is compared to a baseline of the current fleet of ICEVs fueled with E10 gasoline or petroleum diesel.

Given the length of time and investment required to convert the on-road fleet to ZEVs, it is both cost-effective and compelling to do what is possible to decarbonize ICEVs in the nearer term as they will be on the road for at least the next few decades. Based on this study and the comparison of alternatives discussed, in this last section we propose a list that prioritizes actions to optimize the carbon reduction potential of the ICEV fleet based on the parameters evaluated. These parameters include potential fleet carbon reductions, ease of economic and consumer acceptance, technical viability, costs, and timing. We have ranked these actions into three tiers in order of priority based on these parameters, which are designed to maximize carbon reduction of the ICE transportation fleet in both the short and long term.

The first-tier options in Table 17[253] are those opportunities that seem obvious based on feasibility and relatively low cost-to-benefit ratios. The second-tier options are opportunities that need more time to develop, and the third-tier options require a significant breakthrough to become practical alternatives. The first four columns of Table 17 mirror Table 16. The Potential Impact column in Table 17 lists our qualitative assessment of the possible impact of each option, taking into account the portion of the pool that could feasibly be satisfied by each fuel-vehicle pairing and the carbon reduction achievable. Lastly, all of these options require government incentives or initiatives—some existing, some modified, and some new—to come to fruition. In the Initiatives Required column, we identify incentives or market shifts which might help each option reach its potential.

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[253] Renewable Diesel (RD) at 100% by volume (R100) can be placed into a vehicle without issue, but the Biomass-Based Diesel Blenders Tax Credit (BTC) requires blending of RD with petroleum diesel in order to generate the credit. As such, essentially all RD in the market is blended with at least a small amount of petroleum diesel.

TABLE 16. COMPARISON OF ALTERNATIVES TO DECARBONIZE ICEVs

OPTION	PAIRED VEHICLE TECH-NOLOGY	STATUS/ POTENTIAL OF FUEL PRODUCTION	COMPATIBLE WITH CURRENT FUEL DELIVERY LOGISTICS?	COMPATIBLE WITH CURRENT FUEL DISPENSING SYSTEM?	CONSUMER ACCEPTANCE	SHORTEST TIME TO FULL MATURITY	RELATIVE UNSUBSIDIZED COST OF TRANSITION	CARBON EMISSIONS REDUCTION VS. CURRENT FLEET & FUELS
Current ULSD & E10 Gasoline	Current Gas ICEV	Current	Yes	Yes	Yes	Current	None	base
Reduced CI Gasoline & Diesel	Current Gas ICEVs	Current	Yes	Yes	Yes	Mid-Term	Low-Med	5-15%
Ethanol (E15)	Current Gas ICEV	50% ethanol increase	Yes, mostly	Yes	Yes	Near-Term	Low	3%
Ethanol (E15)	Plug-in Hybrids (PHEVs)	50% ethanol increase	Yes	Yes	Yes	Mid-Term	Low-Med	20%
Biodiesel (B5)	Current Diesel ICEV	Requires ~100% increase over current production	Yes	Yes	Yes	Near-Term	Low-Med	<5%
Biodiesel (B20)	Current Diesel ICEV	Requires ~700% increase over current production	Yes, mostly	Yes	Except in colder regions	Mid-Term	Med	5-15%
Renewable Diesel (R99)	Current Diesel ICEV	Requires 20x increase over current production	Yes	Yes	Yes	Mid-Term	Low-Med	50-70%
Renewable Diesel (R99)	Plug-in Hybrids (PHEVs)	Requires 20x increase over current production	Yes	Yes	Yes	Mid-Term	Med	55-85%
Renewable Gasoline (RG)	Current Gas ICEV	Niche fuel, scaling challenges w/o cellulosic, pyrolysis, BTL, or e-fuels breakthrough	Yes	Yes	Yes	Mid-Term	Med	50-70%
Renewable Natural Gas (RNG)	NGV	Small	No	No	Risks	Near-Term	Med	100+%
Renewable Propane (RP)	LPG ICEV	Small	No	No	Likely	Near-Term	Low-Med	60-70%
Ethanol (Intermediate Blends	Dedicated Vehicle	3-4x increase over current production	Yes	No	Likely	Long-Term	Med	20-30%
Ethanol (E85)	FFV	500% ethanol increase	No	Yes	Maybe	Long-Term	Med	25%
Biodiesel (B20+)	Current Diesel ICEV	400-2000% increase	No	No	Maybe	Long-Term	Med-High	40-60%
Cellulosic Ethanol	Current Gas ICEVs	Tiny with high potential	Yes	Yes	Yes	Long-Term	Very High	5-10%
Cellulosic Diesel	Current Diesel ICEVs	Tiny with high potential	Yes	Yes	Yes	Long-Term	Very High	60-90%
Pyrolysis Fuels	Current Gas & Diesel ICEVs	technology not yet commercialized; sizeable potential	Yes	Yes	Likely	Long-Term	Very High	0-60%
FT Diesel (BTL)	Current Diesel ICEVs	Tiny with high potential	Yes	Yes	Likely	Long-Term	Very High	20-100+%
E-Fuels	Current Gas & Diesel ICEVs	High potential technology not yet commercialized	Yes	Yes	Yes	Long-Term	Very High?	40-100%
Hydrogen (H_2)	H_2 ICEV	FT of RNG	No	No	Challenged	Long-Term	Very High	60-100%+
ICEV Improvements	NA	NA	Yes	Yes	Yes	Contin-uous	Low	20-50%

TABLE 17. TIERED ICEV CARBON-REDUCTION POTENTIAL OF ALTERNATIVE OPTIONS (Table ES-1 in Executive Summary)

TIER	OPTION	PAIRED VEHICLE TECHNOLOGY	CARBON REDUCTION VS. CURRENT FLEET & FUELS	POTENTIAL IMPACT	REGULATORY	MARKETPLACE
0	Current ULSD & E10 Gasoline	Current Gas ICEV	base	N/A	N/A	N/A
1	Biodiesel (B5)	Current Diesel ICEV	<5%	small	N/A	Increased feedstock generation
1	Ethanol (E15)	Current Gas ICEV	3%	small	Wider EPA approval	Infrastructure build-out
1	Renewable Gasoline (RG)	Current Gas ICEV	50-70%	small	Continuation/expansion of existing regulatory incentives	Scalability of production
1	Renewable Natural Gas (RNG)	NGV	100+%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Renewable Propane (RP)	LPG ICEV	60-70%	small	Continuation/expansion of existing regulatory incentives	Conversion of vehicles and fueling infrastructure
1	Reduced CI Gasoline & Diesel	Current ICEVs	5-15%	small to medium	Strengthened regulations on upstream flaring and methane emissions; continued move to renewable marine fuels; continued regulatory incentives for CCUS and use of renewable energy at refineries	Refinery investment in CCUS and usage of renewable energy
1	Ethanol (E15)	Hybrids (HEV & PHEV)	20%	small to medium	E15 approval and increased incentives for hybrid expanded vehicle purchases	Conversion to hybrid vehicle fleet and expansion of E15 infrastructure
1	Biodiesel (B20)	Current Diesel ICEV	5-15%	small to medium	N/A	Increased feedstock generation
1	Ethanol (E85)	FFV	15-25%	small to medium	Increased incentives for FFV production and purchase (adjustments to CAFE) and potential aftermarket equipment certification program for FFV conversions	Fueling infrastructure expansion and increased vehicle and fuel availability
1	Renewable Diesel (R99)[3]	Current Diesel ICEV	50-70%	medium	Continuation/expansion of existing regulatory incentives	Increased feedstock generation
1	Renewable Diesel (R99)	Hybrids (HEV & PHEV)	55-85%	medium	Increased incentives for hybrid vehicles	Conversion to hybrid vehicle fleet and increased feedstock generation
2	Ethanol (Intermediate Blends)	Dedicated Vehicle	5-15%	small	New incentives for development of dedicated intermediate-ethanol-blend vehicle production	Expanded compatible fuel infrastructure
2	Biodiesel (B20+)	Current Diesel ICEV	40-60%	small	Establish ASTM standards	OEM warranty, expanded fueling infrastructure, and increased feedstock generation
2	ICEV Improvements	NA (current fuels)	20-50%	medium	Technology-neutral testing and CAFE standards	Broad OEM roll-out
2/3	Hydrogen (H_2)	H_2 ICEV	60-100%+	small	Substantial financial incentives	Build-out of hydrogen production hubs, expansion of dedicated fueling infrastructure, conversion of vehicle fleet to H_2
3	Cellulosic Ethanol (E10)	Current Gas ICEVs	5-10%	small	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Cellulosic Diesel	Current Diesel ICEVs	60-90%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	FT Diesel (BTL)	Current Diesel ICEVs	20-100+%	medium	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	Pyrolysis Fuels	Current Gas & Diesel ICEVs	0-60%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost
3	E-Fuels	Current Gas & Diesel ICEVs	40-100%	large	Substantial financial incentives for fuel and technology development	Technological breakthrough to reduce production cost

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254 Renewable Diesel (RD) at 100% by volume (R100) can be placed into a vehicle without issue, but the Biomass-Based Diesel Blenders Tax Credit (BTC) requires blending of RD with petroleum diesel in order to generate the credit. As such, essentially all RD in the market is blended with at least a small amount of petroleum diesel.

16.3 CONCLUSION

Decarbonizing the on-road transportation sector does not have a one-size-fits-all solution. The mounting public policy shift toward ZEVs (i.e., PHEVs, EVs, and FCEVs) has much promise to decarbonize the sector. However, mandates to eliminate ICEVs entirely and in the timeframe envisioned for the transition to ZEVs might well prove aspirational. ZEV technologies and fueling systems face challenges that must be overcome. Fuel production, delivery infrastructure, fuel storage to address the diurnal cycle, battery material availability, fueling site expansion, and vehicle and battery production are all significant challenges for a full transition to ZEVs. The need to address these challenges makes the ZEV solution to carbon emissions a long-term one. Since fleet turnover is slow, ICEVs will comprise a significant portion of the fleet well into the future, and deployment of carbon reduction options for ICEVs can provide partial solutions in the near and mid-term.

This study illustrates how carbon emissions from the current fleet of ICEVs can be reduced and how the future ICEV fleet could have a smaller carbon footprint with new renewable fuels production and ICEV technologies. Many near-term options for reducing the carbon intensity of ICEV fuels will have near-term reductions in carbon emissions since those ICE fuels will be used in the current fleet of ICEVs. As with the development and introduction of reformulated gasoline (RFG)[255]—gasoline specifically designed to reduce criteria pollutants when used—and its acceptance as a fuel,[256] which immediately reduced emissions across the ICEV fleet, reducing the carbon intensity of ICEV fuels today would further reduce emissions of the existing fleet that uses that fuel.

Just as there are viability and timing uncertainties for ZEVs, there are varying degrees of viability and timing uncertainties in each of the options for decarbonizing ICEVs. Given these uncertainties and the fact that some of these alternatives are highly aspirational, a portfolio approach to ICEV decarbonization is advisable. It is also advisable to cast a wide net when it comes to new vehicle technologies around which there is also uncertainty, especially regarding timing. Such an approach could maximize the reductions in on-road transportation carbon emissions in both the near and long term. A portfolio approach for ICE fuels and future vehicle technologies will result in both ICEVs' (near-term) and ZEVs' (longer term) roles in minimizing transportation carbon emissions being realized.

To fully and effectively execute a portfolio approach to fleet decarbonization in both the near and long term, a comprehensive cost-benefit analysis of all options using existing and projected technologies and the risks involved should be undertaken. Such an analysis would determine the most cost-effective way to decarbonize in the shortest timeframe practical. This effort should incorporate unbiased estimates of costs, timing, degrees of carbon reduction, and risks in timing and execution. With the results of a cost-benefit analysis available, incentives could be aligned with the data to finance multiple parallel paths simultaneously in order to achieve the most emissions reductions practical over the short and long term.

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[255] Los Angeles Times / Arco to Introduce Low-Emission Gas to Replace Leaded Regular on Sept 1.

[256] EPA / Gasoline Standards – Reformulated Gasoline.

APPENDIXES

APPENDIX A

Next Generation Cover Crop Feedstocks For Biomass-Based Diesel

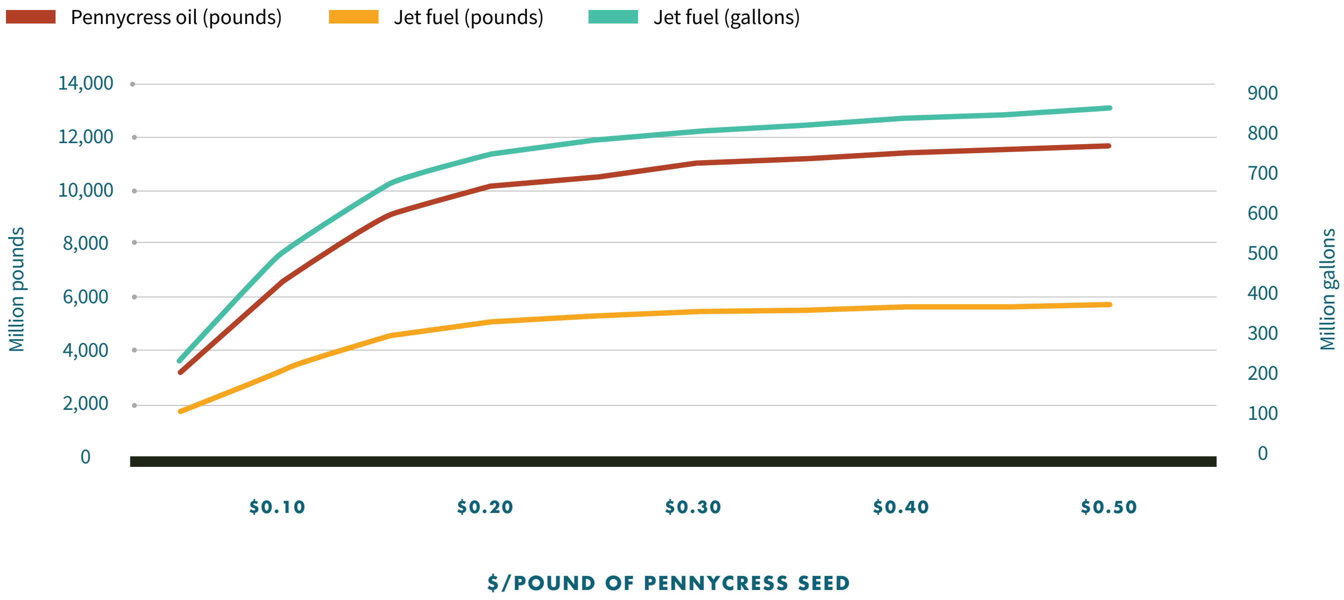
PENNYCRESS

Pennycress can yield about 1,500 pounds of seed per acre, and this is being improved to reach 2,000 to 2,200 pounds per acre. It is estimated that with these improved yields, CoverCress crop planted on half of the rotational hectares in the U.S. Midwest corn belt could produce 1.1 billion gallons of oil and 7 million metric tons of edible seed meal annually. In partnership with Bunge and Chevron, CoverCress Inc. (CCI) is going to scale up production of CoverCress that Bunge will process at its soybean processing plants in Destrehan, Louisiana, and Cairo, Illinois.[257] Chevron will have the purchase rights for the oil to use as a renewable feedstock. CCI plans to plant pennycress on 10,000 acres in south-central Illinois and portions of Missouri.

There is not yet an established market for pennycress, and commercial scale production has not yet been established. Cover crop adoption in the U.S. has been slow, and cover crops have been adopted on only about 4% of cropland acres in Illinois, Indiana, and Iowa; farmers are planting them on a small number of acres. Whether adoption of pennycress as a cover crop and feedstock for biomass-based diesel develops will depend on its profitability.

As shown in Figure AA-1, a modeling simulation conducted by Markel et al.[258] using the POLYSYS model over the 2016-2039 period showed

FIGURE AA-1. AVERAGE ESTIMATED PENNYCRESS AND SAF PRODUCTION (2016-2039)



Source: Markel et al., Potential for Pennycress to Support a Renewable Jet Fuel Industry.

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[257] CoverCress / Our Story.

[258] Markel, Evan, B. C. English, C. Hellwinckel, and R. J. Menard / Potential for Pennycress to Support a Renewable Jet Fuel Industry.

that if pennycress seed received a price of $0.20 per pound, it would be profitable enough to encourage sufficient feedstock production to produce 800 million gallons of SAF per year in addition to producing RD, naphtha, and LPG as by-products. At this price, there would be 22.1 million acres planted annually, with a national average yield of 1,193 pounds per acre.

Markel et al.[259] find that at a price greater than $0.80 per pound, pennycress production can begin to produce substantial supply of SAF. Breakeven price of pennycress depends on its yield and is estimated to range between $0.06 and $0.12 per pound with yields ranging from 800 to 1,600 pounds per acre. At $0.20 per pound, the addition of pennycress to the corn-soybean rotation is likely to increase profitability of corn and soybean production and can be expected to increase total harvested crop acreage of corn and soybeans by 3% and 5%, respectively, over the baseline scenario. This will increase corn and soybean production and reduce prices by 9% and 1%, respectively. Despite this, it would increase net returns to land. At the $0.20 per pound price of pennycress, Markel et al. estimate that 26.3 billion pounds of pennycress could be produced and converted to 723 million gallons of SAF and 533 million gallons of other fuels.

CARINATA

Alam and Dwivedi[260] examines the production potential of carinata in Georgia, Alabama, and Florida based on water storage, soil organic carbon, root zone depth, and land availability and estimates the portion of U.S. jet fuel demand which could be replaced by potential carinata-derived fuel. They find that 3.3 million total acres of land across Georgia (2.25 million acres), Florida (0.24 million acres), and Alabama (0.82 million acres) is suitable for growing carinata, with 56% of this land

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[259] Markel, Evan, B. C. English, C. Hellwinckel, and R. J. Menard / Potential for Pennycress to Support a Renewable Jet Fuel Industry.

[260] Alam, Asiful and P. Dwivedi / Modeling site suitability and production potential of carinata-based sustainable jet fuel in the southeastern United States.

being moderately suitable and 37% being highly suitable. The moderately and highly suitable sites for carinata in Georgia were located in the southern and northern part of the state, respectively. Most sites in Alabama that were highly suitable for growing carinata were located in the southern and northern part of the state, while Florida had a range of low suitable sites spread across the state. Alam and Dwivedi also find that 2.34 million metric tons of carinata could be produced across these states at 5% risk level, based on riskiness of frost damage and land availability and that 92% of this can be potentially sourced from Georgia alone. They also estimate that 325 million gallons of carinata-SAF could be produced from this level of carinata production, which could displace 2.4% of total jet fuel consumed in the U.S. in 2021. With a 20% risk level and assuming a high yield scenario, 2.3% of annual jet fuel consumption in the U.S. could be displaced by carinata produced in these three states. In June 2022, EPA also approved the pathway for conversion of carinata to be compliant with the RFS for biomass-based diesel.

Alam et al.[261] estimate the breakeven price of aviation fuel from carinata in the southeastern U.S. They find that without including coproduct credits or renewable identification number (RIN) credits, carinata-based SAF was more expensive than conventional aviation fuel. The cost of producing carinata-based fuel ranged between $3.20 and $4.80 per gallon and was higher than the cost of conventional aviation fuel of $1.90 per gallon. After including coproduct credits and RIN credits, however, these costs would range between $0.45 to $2.50 per gallon; this variability in costs was driven by variability in the assumed variable costs, coproduct credit, and RIN credit. The addition of the CFPC could make carinata-based fuel competitive with conventional aviation fuel.

CAMELINA

Under dryland conditions (i.e., without irrigation) in Montana, camelina is expected to yield 1,800 to 2,000 pounds of seed per acre (lb/acre) in areas with 16 to 18 inches of rainfall. Yield is 900 to 1,700 lb/acre with 13 to 15 inches of rainfall. With irrigation, seed yields of 2,400 lb/acre have been reported.[262] The cost of producing camelina biofuel in Oregon is estimated to be $7 per gallon. At a BD wholesale price of $2.50 per gallon and even after including coproduct credit, government subsidies are critical for camelina biofuel to break even. The small producer tax credit, the Oregon renewable fuels tax credit, and the Oregon Business Energy Tax Credit can lead to a revenue greater than the cost of producing BD. Oregon's Willamette Valley is estimated to have the potential to produce camelina in about 52,520 acres and to provide an oil yield of 4.3 million gallons a year.

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[261] Alam, Asiful, M. F. Hossain Masum, and P. Dwivedi / Break-even price and carbon emissions of carinata-based sustainable aviation fuel production in the Southeastern United States.

[262] Ehrensing, D.T. and S.O. Guy / Camelina.

APPENDIX B

Cellulosic Biomass Feedstocks for Biofuels

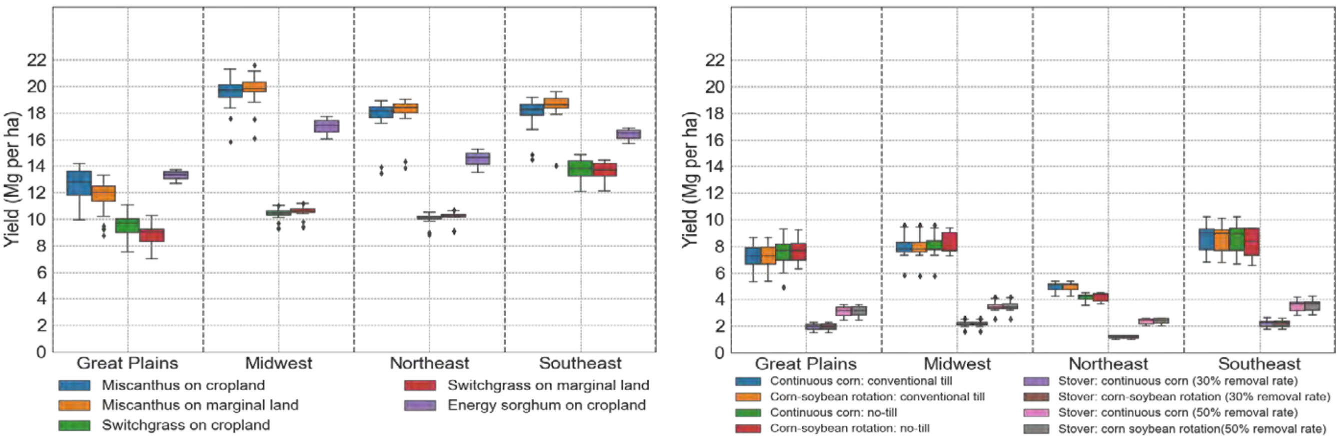
AGRICULTURAL RESIDUES

Agricultural residues for biofuel production come mainly from conventional crops, particularly corn and wheat, but can also be obtained from barley, oats, and sorghum. The yield of the crop residue is related to the corresponding grain yield. In the case of corn, a grain-to-residue ratio of 1:1 for dry matter of crop grain to dry matter of crop residues (with 15% moisture) is typically assumed. Only a fraction of the biomass is harvested to preserve soil organic matter and protect soil from wind and water erosion. Recommended stover removal rates depend on soil characteristics, climate, management practices (tillage), and other factors that determine the loss of soil organic matter and runoff. A larger percentage of stover can be removed with no-till crop production than with conventional till. Corn stover yields are about two metric tons per hectare with the highest yields in the Midwest, as shown in Figure AB-1.[263]

MISCANTHUS AND SWITCHGRASS

Two perennial crops, switchgrass (*Panicum viragatum*) and miscanthus (*Miscanthus giganteus*), have been identified as among the best choices for low-input and high dry matter yield per acre in the U.S. There has been field research on switchgrass in the U.S. since 1991, but research on miscanthus in the U.S. wasn't initiated until 2002 at the University of Illinois Urbana-Champaign. Switchgrass is a warm season perennial grass with a stand life of 10 years or more where production in year one is a fraction of the production achieved during the remaining production years. There are several varieties of switchgrass including the Cave-in-Rock cultivar (an upland variety well-suited for the upper Midwest) and Alamo and Kenlow (lowland varieties most suited for the southern U.S.). Miscanthus is a perennial rhizomatous grass; the miscanthus

FIGURE AB-1. VARIATION IN YIELD ACROSS BIOMASS FEEDSTOCKS AND REGIONS



Source: Lee et al. (in review)

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[263] Lee, Yuanyao, M. Khanna, and L. Chen / Quantifying Uncertainties in Greenhouse Gas Savings and Mitigation Costs with Cellulosic Biofuels (manuscript, under review).

variety considered for biofuels is the sterile hybrid genotype *Miscanthus* × *giganteus*. It is non-native to the U.S. and has a productive life of about 15 years; it has an establishment period of approximately three years during which yields are typically lower than the maximum. These grasses provide a number of ecosystem services, such as high rates of soil carbon sequestration and low nutrient runoff.

Recent studies indicate that yields of these perennial grasses vary across varieties, location, and age of the crop.[264] Miscanthus yield is substantially higher than that of switchgrass; miscanthus yield increases with age until about eight years or so and then declines, while switchgrass yields peak at six years of age.[265] Miscanthus is most productive in the Midwest, with average yields as high as 20 metric tons per hectare while switchgrass is most productive in the Southeast, with average yields of about 14 metric tons per hectare, as shown in Figure AB-1.

BIOMASS SORGHUM

Biomass sorghum is a high-yielding annual crop that is drought tolerant and can produce more biomass in water-limited environments than similar annual crops such as corn. It is more productive than corn due to a longer growing season and lower sensitivity to heat. Its yield is similar to that of miscanthus (16 to 18 metric tons per hectare), but it requires more nitrogen and other inputs than miscanthus and does not have the same benefits in terms of soil carbon sequestration.

ENERGY CANE

Energy cane is another perennial but with a shorter life span than miscanthus and switchgrass; it is similar to sugarcane. It is a tropical grass with high-yield potential across the Gulf of Mexico. It is a low-sugar, high-cellulose variety of sugarcane that can be established, managed, and harvested using existing sugarcane industry equipment.

WOODY CROPS

In addition to these herbaceous sources of biomass, there are two short rotation woody crops—hybrid poplar and willow—that are also considered to have potential for biofuel production. Willow is commercialized in the Northeast and in the Great Lakes region. Current research suggests that coppiced willow production[266] is the most efficient means of producing biomass from willow, with harvests occurring every four years to keep biomass growth at its most efficient. Since willow is harvested by coppicing, no replanting is necessary. Poplar can be grown in Michigan, Minnesota, Wisconsin, the Northwest, the Mississippi Delta, and other regions. It has a long establishment period, and the first harvest is likely to be in the eighth year. It is then replanted for a second harvest eight years later. Land preparation is the same as for willow, and the poplar cuttings are planted with the same equipment. Willow yield can be 10 dry metric tons per hectare per year over a 12-year period. Poplar yield is eight dry metric tons per hectare per year.[267]

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[264] Zhang, Na, B.P. Sharma, and M. Khanna / Determining spatially varying profit-maximizing management practices for miscanthus and switchgrass production in the rainfed United States.

[265] Zhang, Na, B.P. Sharma, and M. Khanna / Determining spatially varying profit-maximizing management practices for miscanthus and switchgrass production in the rainfed United States.

[266] Coppicing is a traditional method of woodland management which utilizes the capacity of many species of trees to put out new shoots from their stump or roots if cut down. In a coppiced wood, young tree stems are repeatedly cut down to near ground level, resulting in a stool. In theory, coppicing allows for indefinite harvesting of wood without the need to replant.

[267] Kells, Bradley J. and S. M. Swinton / Profitability of Cellulosic Biomass Production in the Northern Great Lakes Region.

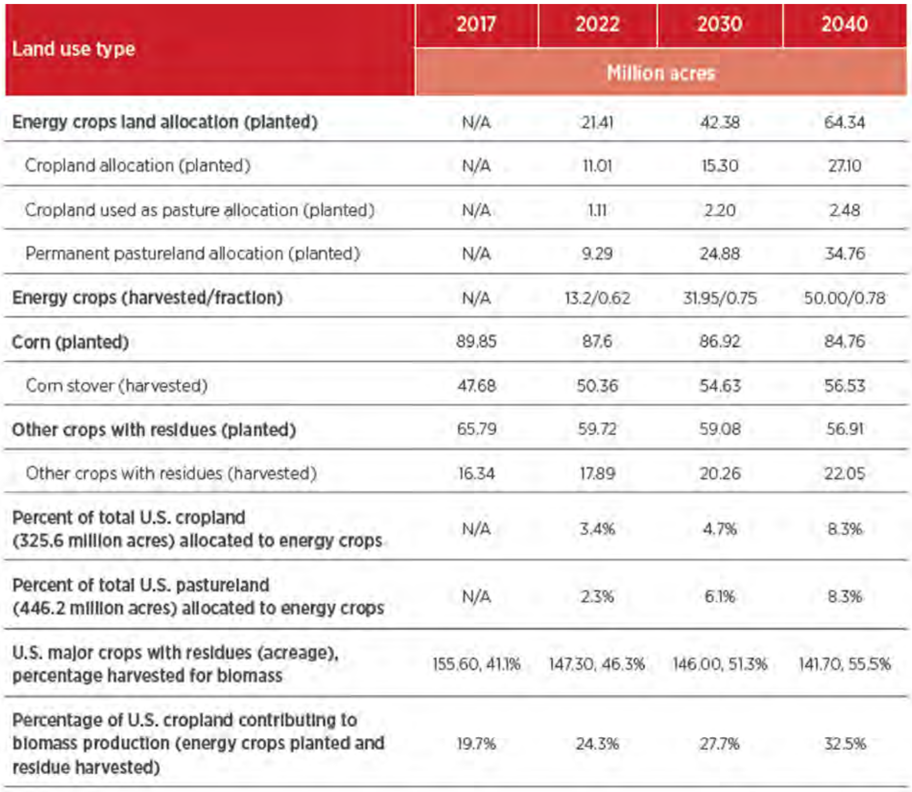
PROJECTED SUPPLY OF CELLULOSIC BIOFUEL FEEDSTOCKS

The DOE conducted a study of the potential supply of biomass feedstocks over the 2015-2030 period. The study, referred to as the 2016 Billion-Ton Report,[268] considered two scenarios—a base-case scenario with a 1% annual increase in yield of energy crops and a high-yield scenario with a 2% annual yield increase. They considered farmgate prices of biomass, ranging from \$40 per dry U.S. ton to \$100 per dry ton with long-term contracts for energy crops beginning in 2019. The results of this study are displayed in Table AB-1 and Figure AB-2.

In the base-case scenario, crop residue production commences at a farmgate price of \$40 per dry ton. Total supply of biomass would reach 59 million tons with both residues and energy crops in 2030 and 108 million tons in 2040. Of this, 79% of the supply is from residues in 2030 and 54% in 2040. Herbaceous energy crop production grows in later years (11% in 2030, 31% in 2040) as these crops reach maturity along with woody energy crops (11% in 2030 and 15% in 2040). At this low biomass price, switchgrass is the primary herbaceous energy crop that is produced, and there is some production of miscanthus, which is a higher cost crop. In this scenario, there is less than one million tons of energy sorghum by 2040. Woody energy crops contribute about half the total energy crop production in 2030 but decrease to 32% of energy crop production by 2040 as switchgrass production increases.

At a farmgate price of \$60 per ton, biomass supply is 388 million tons of residues and energy crops in 2030 and 588 million tons in 2040. At this price point, 49% of total supply is available from herbaceous energy crops in 2030, which increases to 58% by 2040.

TABLE AB-1. PROJECTED LAND ALLOCATION FOR BIOMASS PRODUCTION AT BIOMASS PRICE OF \$60 PER TON



Land use type	2017	2022	2030	2040
	Million acres			
Energy crops land allocation (planted)	N/A	21.41	42.38	64.34
Cropland allocation (planted)	N/A	11.01	15.30	27.10
Cropland used as pasture allocation (planted)	N/A	1.11	2.20	2.48
Permanent pastureland allocation (planted)	N/A	9.29	24.88	34.76
Energy crops (harvested/fraction)	N/A	13.2/0.62	31.95/0.75	50.00/0.78
Corn (planted)	89.85	87.6	86.92	84.76
Corn stover (harvested)	47.68	50.36	54.63	56.53
Other crops with residues (planted)	65.79	59.72	59.08	56.91
Other crops with residues (harvested)	16.34	17.89	20.26	22.05
Percent of total U.S. cropland (325.6 million acres) allocated to energy crops	N/A	3.4%	4.7%	8.3%
Percent of total U.S. pastureland (446.2 million acres) allocated to energy crops	N/A	2.3%	6.1%	8.3%
U.S. major crops with residues (acreage), percentage harvested for biomass	155.60, 41.1%	147.30, 46.3%	146.00, 51.3%	141.70, 55.5%
Percentage of U.S. cropland contributing to biomass production (energy crops planted and residue harvested)	19.7%	24.3%	27.7%	32.5%

Source: EIA. 2016 Billion-Ton Report

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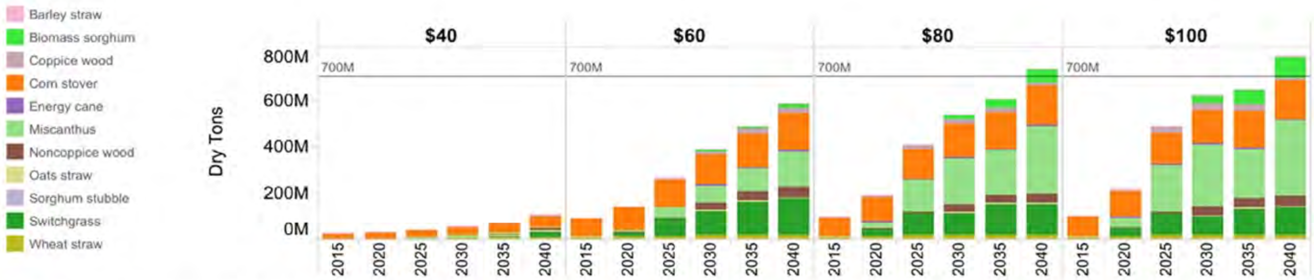
[268] DOE Office of Energy Efficiency & Renewable Energy / 2016 Billion-Ton Report.

Another 13% is available from woody energy crops in 2030, which decreases to 12% in 2040. Increasing the farmgate price to $80 leads to biomass supply from energy crops and residues of 537 and 734 million tons in 2030 and 2040, respectively. Of this supply, 60% in 2030 and 67% in 2040 is from herbaceous energy crops, while woody energy crops are limited to 10% of the market in 2030 and 8% in 2040, and residues make up the rest.

In the high-yield scenario, energy crop production commences at the $40 per ton farmgate price of biomass. At the $80 per ton price, total production reaches 1.07 billion tons in 2040 and 20% (214 million tons) of this is from residues. In the high-yield scenario, miscanthus is the dominant source of biomass, followed by corn stover, switchgrass, and sorghum.

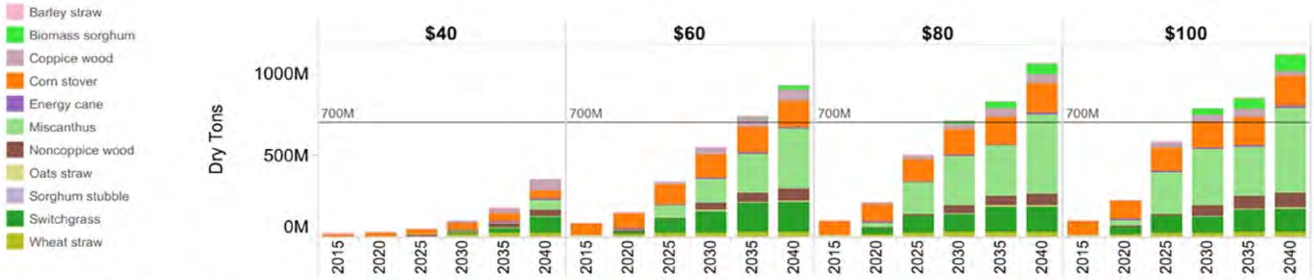
FIGURE AB-2. BIOMASS SUPPLY FROM ALTERNATIVE BIOMASS SCENARIOS

A. Low yield growth (1% per year) increase scenario



Please cite as: U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651.

B. High yield growth (2%) increase scenario



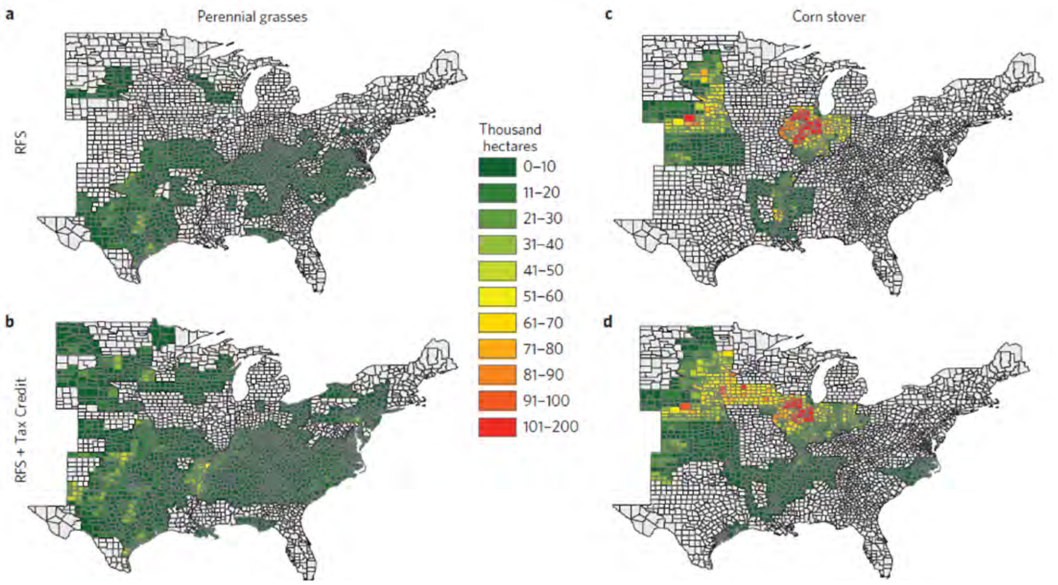
Please cite as: U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p. doi: 10.2172/1271651.

FEEDSTOCK PRODUCTION TO MEET A CELLULOSIC BIOFUEL MANDATE

The RFS had set a target of a maximum of 15 billion gallons of corn ethanol and at least 16 billion gallons of cellulosic biofuels to be achieved by 2022. Hudiburg et al.[269] examine the feedstocks and acreage that will be needed to achieve these targets. They also examine the implications of providing a tax credit for cellulosic biofuel production on the incentives to produce cellulosic biofuels and land use. They find that under the corn ethanol mandate, land under corn would increase and that some of this increase would be met by reducing land under other crops. A little less than half of the 16-billion-gallon mandate could be met by available corn stover that can be sustainably harvested, and the rest would be met by energy crops. While much of the energy crop production is likely to occur on marginal land in the rainfed region (east of the 100th meridian) that is of low quality and not in crop production, some cropland would also be converted to energy crop production. Miscanthus and switchgrass would meet a significant part of the cellulosic biofuel mandate. The provision of a tax credit of $1 per gallon of cellulosic biofuels would increase the land under energy crops and corn stover harvest.

More specifically, compared to a no-policy scenario i.e., (no biofuel policy), the policy scenarios increased land allocated to energy crops by 4.2 and 12.0 million hectares for the RFS and RFS plus tax credit, respectively. Of this, 3.9 and 10 million hectares were converted to perennial grasses (3.0 marginal land and 0.9 cropland; Figure AB-3a), while 7.5 million hectares of current cropland were transferred to corn for grain and ethanol, and 3.4 million hectares of grazing (marginal) and forest land were converted to cropland. In the RFS plus tax credit scenario, about 10 million hectares of cropland were converted to perennial grasses (Figure AB-3a) and corn ethanol land was reduced compared to no policy. Some grazing and forest land (3.6 million hectares) was converted to food and feed crop production to compensate for the cropland converted to energy crops.

FIGURE AB-3. LAND ALLOCATION FOR ENERGY CROPS AND CORN STOVER UNDER THE RFS AND CELLULOSIC BIOFUEL TAX CREDIT POLICY SCENARIOS



Note: In thousand hectares for the RFS (a, c) and RFS + Tax Credit (b, d) scenarios, for perennial grasses (a, b) and corn stover removals (c, d). Corn stover removals are 30% if the baseline system is conventional till and 50% if the baseline system is no-till.

Source: Hudiburg et al. (2016)

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[269] Hudiburg, Tara W. et al / Impacts of 32-billion-gallon bioenergy landscape on land and fossil fuel use in the US.

APPENDIX C

Additional Insights Concerning Risks and Uncertainties Affecting Cellulosic Feedstock Production

MARGINAL LAND

While there are several different definitions of marginal land—based on its soil quality and soil fertility or based on its land use (idle/abandoned)—the economic definition is land that is earning close to zero returns from crop production and is therefore at the border of crop and non-crop use. This economically marginal land is expected to have a lower land cost of conversion to energy crops and therefore be more likely to convert to producing energy crops as compared to cropland that is earning a positive return. Jiang et al.[270] use high-resolution satellite data on land use change to infer that land that is frequently transitioning between crop and non-crop is economically marginal land. They show that the amount of land that can be classified as marginal with confidence is relatively small and there is a substantial amount of land that can only be classified as marginal with uncertainty. Specifically, they find that the amount of land that can be classified as marginal with confidence versus with uncertainty is 10.2 and 58.4 million hectares, respectively, and mainly located along the 100th meridian. A small portion of this marginal land (1.4–2.2 million hectares with confidence and 14.8–19.4 million hectares with uncertainty) is in the rainfed region and not in crop production and is thus suitable for producing energy crops without diverting land from food crops in 2016. The availability of this land and the costs of converting land to energy crop production can significantly affect biomass supply and costs. As shown in Figure 51 in the report body, in general, the average breakeven price of miscanthus and switchgrass is about twice as high on cropland as on marginal land, suggesting that it would be economically rational for landowners to prefer growing these crops on their available marginal land.

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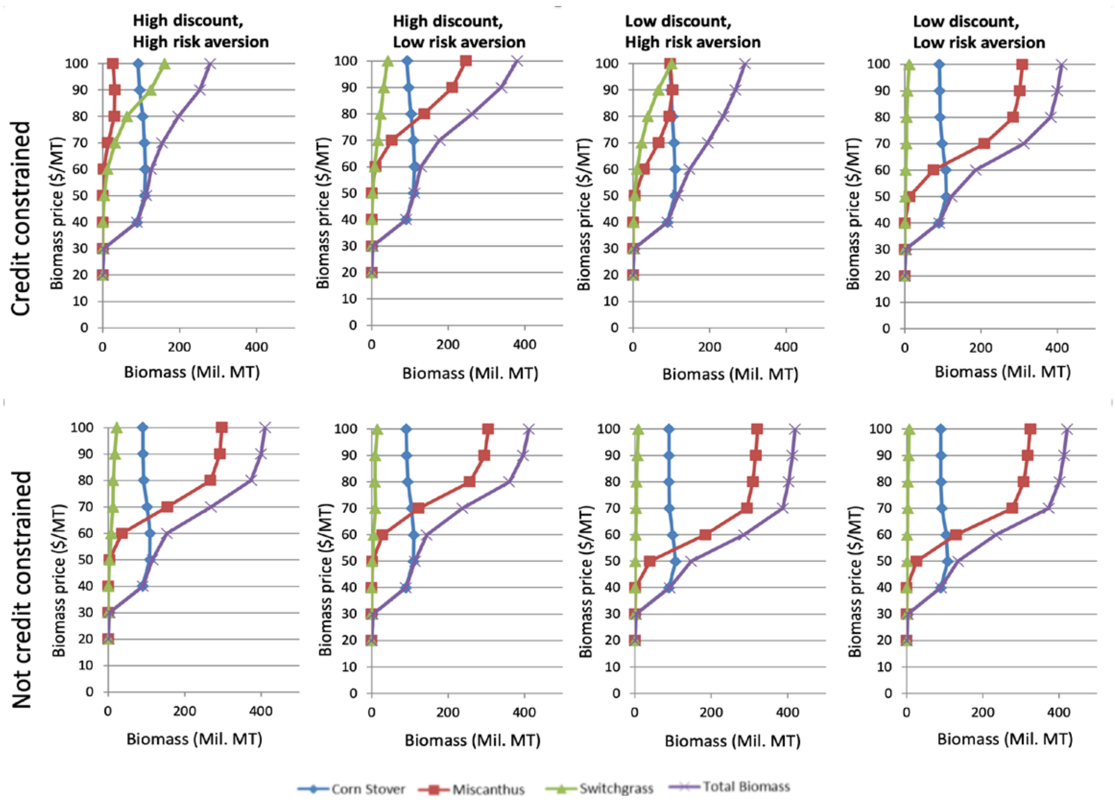
[270] Jiang, Chongya, K. Guan, M. Khanna, L. Chen, and J. Peng / Assessing Marginal Land Availability Based on Land Use Change Information in the Contiguous United States.

RISKS AND UPFRONT COSTS OF PRODUCING ENERGY CROPS

The risks and returns from energy crops vary spatially and, in some places, may be higher than those from conventional crops, while in other places they may be lower. Miao and Khanna[271] find that in large areas of the lower Midwest and the South, the riskiness of miscanthus yield is lower than that of corn. In contrast, the yield risk of switchgrass is typically larger than that of corn in much of the rainfed region except for some areas in the southern Great Plains and Northeast. These yields of miscanthus and switchgrass were simulated under 30 different weather conditions and the average yield and yield variability. Higher riskiness of a crop will raise the breakeven price that a risk-averse farmer would require in order to give up the existing use of the land. Figure AC-1 shows the impact of yield risks on the breakeven cost of energy crops on cropland and marginal land in the rainfed region of the U.S.

Since the yield of miscanthus is substantially higher than that of switchgrass, the breakeven price of miscanthus is typically lower than that of switchgrass across all regions. Miao and Khanna estimate that in the absence of risk considerations, the breakeven price of miscanthus grown on cropland is $84 per metric ton on average while that of switchgrass is $124 per metric ton. The corresponding values for breakeven prices on marginal land for miscanthus and switchgrass are $42 per ton and $50 per ton, respectively.

FIGURE AC-1. SUPPLY CURVES OF CORN STOVER, MISCANTHUS, SWITCHGRASS, AND TOTAL BIOMASS UNDER ALTERNATIVE SCENARIOS



Source: Miao and Khanna (2014)

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[271] Piao, Ruiqing and M. Khanna / Are Bioenergy Crops Riskier than Corn? Implications for Biomass Price.

The breakeven prices of energy crops vary significantly across regions and even within a region. They are low in areas where energy crop yields are high and where the opportunity costs of converting land to produce them are low. Opportunity cost is the foregone returns from the best alternative use of the land; in the case of cropland this could be the returns from producing corn and soybeans on that land. As shown in Figure 51 in the body of the report, the breakeven prices for both miscanthus and switchgrass grown on cropland are low in the Southeast because corn yields in this region are the lowest and the energy grass yields are relatively high. Breakeven prices for energy crops grown on cropland or marginal land are highest in the northern Great Plains because energy crop yields are low in this area.

Figures 51(d) and 51(h) in the body of the report show variability in the risk premium for miscanthus and switchgrass grown on cropland across the rainfed region, respectively. The risk premium varies considerably across regions and was found to be lowest in the Southeast and highest in the Great Plains. On average, Miao and Khanna found that the risk premium required to induce landowners to convert cropland to switchgrass could increase its breakeven price by 15.6% compared to that required under perfect certainty; the corresponding increase in the breakeven price of miscanthus would be by 7.6%. They also found that the risk premium for these crops is lower if they are grown on marginal land. The lower risk premium on marginal land is, in part, due to the low opportunity costs of growing energy crops on marginal land which require relatively low breakeven prices of energy crops and lower riskiness of those returns.

EFFECT OF RISK AND TIME PREFERENCES OF FARMERS ON BIOMASS FEEDSTOCK SUPPLY

Miao and Khanna show that high discount rate, high risk aversion, and credit constraint significantly discourage miscanthus production due to its long establishment period and high establishment cost. For example, under the high discount, high risk aversion, and credit constraint scenario, the average annual production of miscanthus under $100/MT price is about 27 million metric tons. However, under the low discount, low risk aversion, and no credit constraint scenario, the annual miscanthus production in a mature year at the same price is about 325 million metric tons (see the last graph on the lower panel of Figure AC-1). By comparing graphs in the upper panel with those in the lower panel in Figure AC-1, Miao and Khanna find that everything else equal, relaxing the credit constraint increases miscanthus production substantially and results in biomass supply from miscanthus overtaking that from corn stover at a price between $50 and $70/MT. In contrast, relaxing the credit constraint reduces switchgrass production because it makes miscanthus preferable due to the relatively higher yield of miscanthus. When farmers are credit constrained, a decrease in risk aversion or discount rate increases miscanthus production substantially more than when farmers are not credit constrained. This indicates that the availability of a loan that enables the farmer to smooth net returns over a perennial crop's life span mitigates the effect of the farmer's risk and time preference on perennial energy crop production.

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The Transportation Energy Institute, founded by NACS in 2013, is a 501(c)(4) nonprofit research-oriented think tank dedicated to evaluating the market issues related to vehicles and the fuels that power them. By bringing together diverse stakeholders of the transportation and fuels markets, the Institute helps to identify opportunities and challenges associated with new technologies and to facilitate industry coordination to help ensure that consumers derive the greatest benefit.

The Transportation Energy Institute commissions and publishes comprehensive, fact-based research projects that address the interests of the affected stakeholders. Such publications will help to inform both business owners considering long-term investment decisions and policymakers considering legislation and regulations affecting the market. Research is independent and unbiased, designed to answer questions, not advocate a specific outcome. Participants in the Transportation Energy Institute are dedicated to promoting facts and providing decision makers with the most credible information possible so that the market can deliver the best in vehicle and fueling options to the consumer.

For more about the Fuels Institute, visit transportationenergy.org

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