Life Cycle Associates

GHG Emissions Reductions due to the RFS2- A 2022 update

LCA.6145.238.2023
February 14, 2023

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ACKNOWLEDGEMENT

Life Cycle Associates, LLC performed this study under contract to the Renewable Fuels Association. Scott Richman was the project manager.

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Recommended Citation: Unnasch. S., D. Parida, and B. D. Healy (2023). GHG Reductions from the RFS2 – A 2022 Update. Life Cycle Associates Report LCA. LCA.6145.238.2023 Prepared for Renewable Fuels Association.

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Terms and Abbreviations

ANL	Argonne National Laboratory
ARB	California Air Resources Board
Btu	British thermal unit
BD	Biodiesel
CARB	California Air Resources Board
CI	Carbon Intensity
CNG	Compressed Natural Gas
CRF	Corn Replacement Feed
LNG	Liquefied Natural Gas
DGS	Distillers Grains with Solubles
DDGS	Dry Distillers Grains with Solubles
EPA	Environmental Protection Agency
EIA	Energy Information Agency
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse gas
GREET	Greenhouse gas, Regulated Emissions and Energy Use in Transportation (Argonne National Laboratory's well-to-wheels model)
kWh	kilowatt-hour
LCA	Life cycle assessment
LCFS	Low Carbon Fuel Standard
LHV	Lower heating value
MGY	Million gallons per year
MJ	Mega joule
mmBtu	Million Btu
RFS	Renewable Fuel Standard (U.S.)
NERD	Non-Ester Renewable Diesel
Tg	Terra gram (10^{12}g)
TTW	Tank-to-wheels
UCO	Used Cooking Oils
U.S.	United States
VOC	Volatile Organic Compound
WDGS	Wet Distillers Grains with Solubles
WTT	Well-to-tank
WTW	Well-to-wheels

Executive Summary

The RFS2 has resulted in aggregate GHG emissions reductions from the use of biofuels, which exceed the original projections from the final Rule for the first 15 years of its implementation. The RFS2 has resulted in significant GHG reductions, with cumulative CO_2 savings of 1,212 million metric tonnes over the period of implementation to date.

The GHG reductions are due to the greater than expected savings from ethanol and other biofuels, including continuous technology investments reducing the carbon intensity (CI) for corn ethanol. Further savings resulted from higher uptake of corn fiber ethanol, increases in low CI Renewable Natural Gas (RNG), and growth in Non-Ester Renewable Diesel (NERD). 2022 has seen annual emissions savings exceed pre-COVID levels as fuel demand nearly recovered and technology investments expanded. These emissions savings occur even though cellulosic biofuels have not met the RFS2 production targets.

In addition, EPA underestimated the petroleum baseline in the Rule. Studies by Life Cycle Associates and the Carnegie Institute have shown that the GHG emissions from U.S. petroleum are higher than the EPA calculated in 2005 (Boland, 2014; Gordon, 2012, 2015). This study calculates the annual U.S. petroleum GHG intensity based on the changing trends in feedstock availability over time and determines the GHG savings calculated from the aggregate mix of renewable fuels. The GHG intensity for each category of ethanol plant and biodiesel feedstock is estimated for the resource mix over the past 15 years and combined to determine an aggregate estimate. Figure 1 shows the total emissions reductions from the RFS2 compared with the GHG reductions projected from the rule. Introducing E15 would result in greater GHG reductions. Scenarios for E15 (5% to 75% mix) in gasoline are also shown for the year 2025.

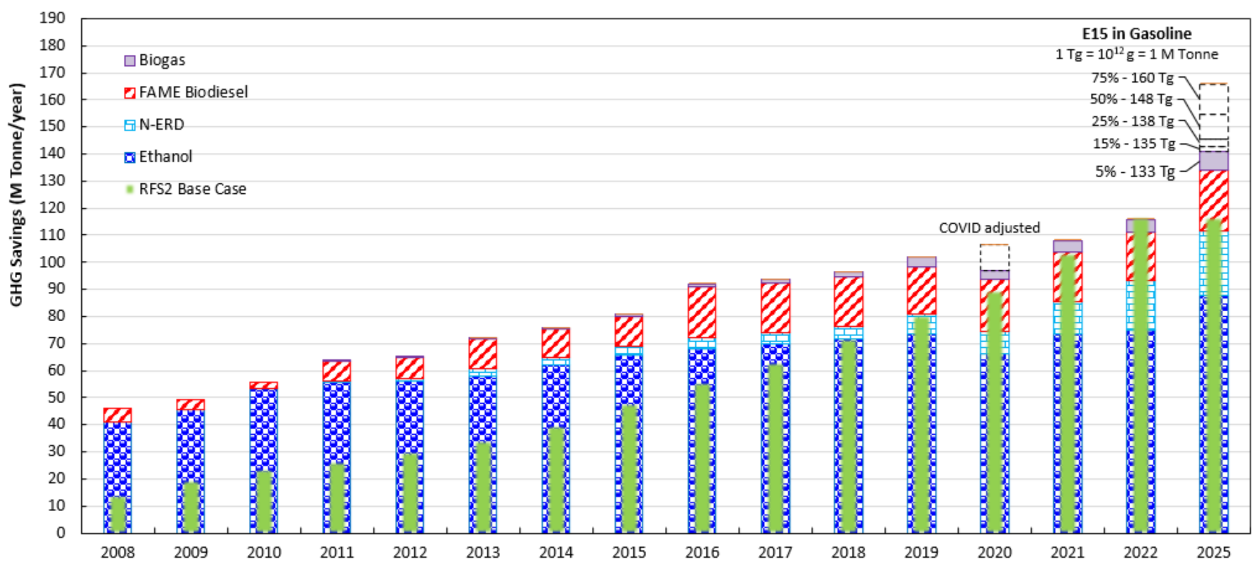

Figure 1. GHG Emissions Reductions due to the RFS2.

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1. Introduction

This study builds upon the 2014 Carbon Intensity of Marginal Petroleum and Corn Ethanol Fuels report and subsequent updates (Boland, 2014) (Boland 2015, Unnasch 2019)) released by Life Cycle Associates under contract to the Renewable Fuels Association. The Marginal Emissions report examined the trends in the greenhouse gas (GHG) emissions, termed Carbon Intensity (CI) of U.S. petroleum and corn ethanol transportation fuels. The CI is measured in grams of carbon dioxide emitted per megajoule of fuel (g CO_2 e/MJ). This work includes all renewable fuels sold under the RFS2 and their corresponding CI values.

The U.S. Renewable Fuel Standard (RFS2) requires the addition of 36 billion gallons of renewable transportation fuels to the U.S. slate by 2022. The RFS2 established mandatory GHG emission thresholds for renewable fuel categories based on reductions from an established 2005 petroleum baseline. Within the total volume requirement, RFS2 establishes separate annual volumes for cellulosic biofuels, biomass-based diesel, advanced biofuels, and renewable fuels. Figure 2 illustrates the RFS2 volume requirements per fuel category. To comply with the standard, obligated parties must sell their annual share (as calculated by EPA) within each category.

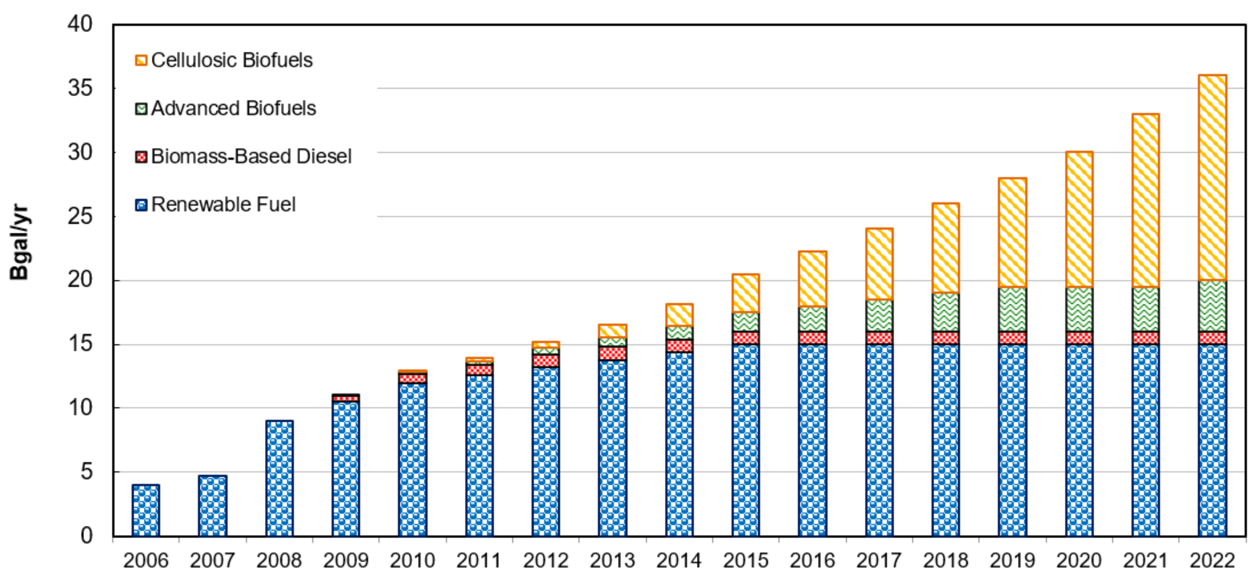

Figure 2. RFS2 renewable fuel volume requirements for the United States.

The 2005 petroleum baseline developed by EPA is based on the aggregate emissions from the production of petroleum fuels consumed in the U.S. during 2005. The methodology and assumptions for the petroleum baseline are contained in the EPA Regulatory Impact Analysis (EPA, 2010). The baseline remains constant throughout the statutory timeframe of the RFS2 (2005 to 2022). However, the mix of crude slates used to develop the baseline has changed since 2005, and the advent of new crude extraction and processing technologies has raised the aggregate CI of petroleum fuels above the 2005 baseline. Furthermore, the baseline refining emissions were underestimated and have since been revised in LCA models (ANL, 2014; El-houjeiri, 2012). The 2014 Marginal Emissions study (Boland, 2014) re-examines the mix of crude slates and U.S. consumption trends to develop the annual aggregate U.S. petroleum CI. The annual aggregate CI provides a more accurate estimate of the aggregate U.S. petroleum CI.

Figure 3 shows the weighted carbon intensities of petroleum fuels consumed in the U.S. alongside the EPA 2005 baseline. This revised estimate results in an aggregate petroleum CI that is higher than the 2005 EPA average gasoline baseline of 93.08 g CO_2 e/MJ. The median CI of aggregate U.S. petroleum gasoline is 96.8 g CO_2 e/MJ.

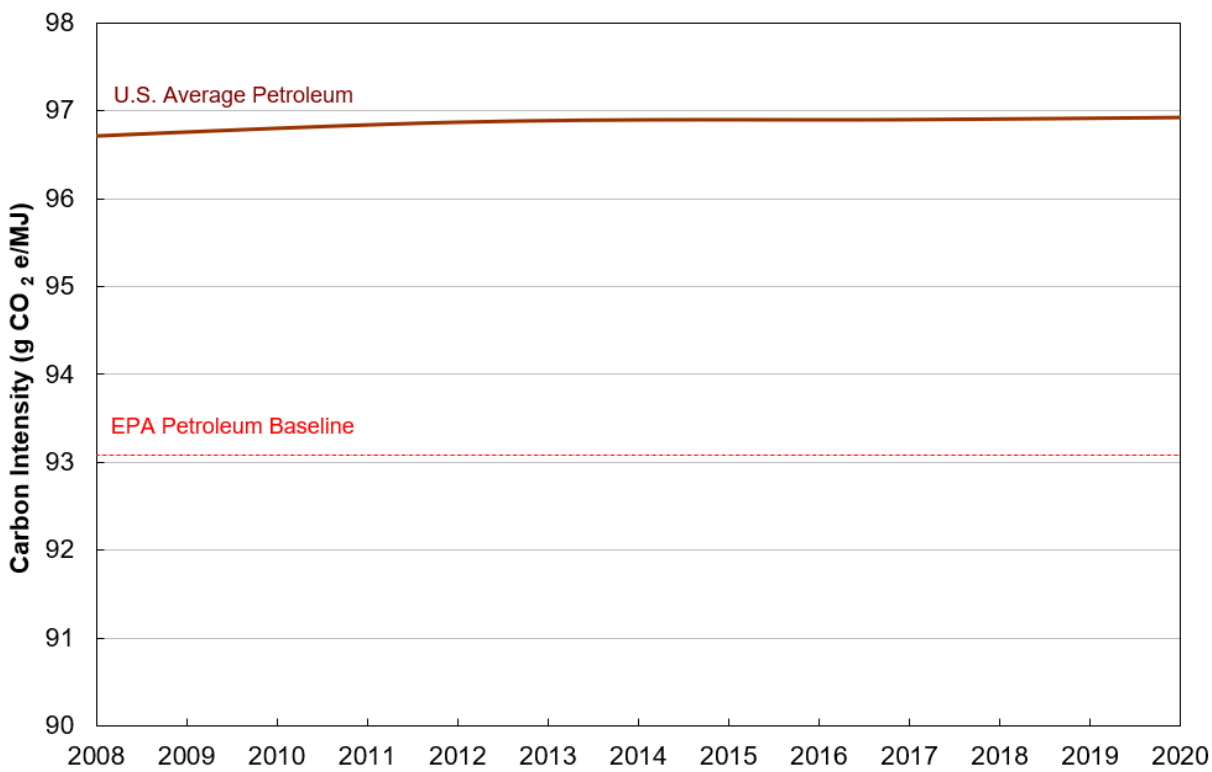

Figure 3. Weighted carbon intensity (g CO_2 e/MJ) of petroleum fuels consumed in the U.S.

1.1 RFS Renewable Fuel Categories, Production Volumes and RINS Generated

Table 1 shows the U.S. renewable fuel categories, the fuel type and the typical feedstocks used to produce each fuel. Also shown is the RIN D Code. The RIN code is the Renewable Identification Number (RIN), used to track fuel production and sales. Each type of renewable fuel generates a RIN when produced. Each D code applies to a specific RIN category.

EPA reports fuels sold by D-code type, which are further categorized as shown in Table 1. EIA reports the types of feedstocks used in biodiesel production.[1] This study matched the fuel/feedstock combinations with fuel volumes. Some fuel categories achieve GHG reductions that are consistent with the 50% and 60% GHG reductions in the RFS2, while other fuels such as corn oil biodiesel achieve even lower GHG reductions than the RFS requirements. The CI for each feedstock and fuel is matching in the following analysis.

Table 1. U.S. Renewable Fuel Categories, Fuel Type, Feedstock Source and RIN D-Code

RIN code	Fuel Category	Fuel Type	Feedstock
D6	Renewable Fuel	Ethanol	Corn, Grain Sorghum
D6	Renewable Fuel	Biodiesel	Palm Oil
D6	Renewable Fuel	NERD[a] (EV 1.7)	Palm Oil
D5	Advanced Biofuel	Ethanol	Grain Sorghum, Sugarcane, Beverage Waste
D5	Advanced Biofuel	Biogas	Landfill, Wastewater Treatment
D5	Advanced Biofuel	NERD (EV 1.6)	Tallow, Used Cooking Oils, Soybean, Distillers' Corn & Sorghum Oil, Food Waste
D5	Advanced Biofuel	NERD (EV 1.7)	Tallow, Used Cooking Oils, Soybean, Distillers' corn & sorghum oil, Food waste
D5	Advanced Biofuel	Bio-Naphtha	Used Cooking Oils, Distillers' Corn & Sorghum Oil
D4	Biomass-Based Diesel	Biodiesel	Soybean, Canola/Rapeseed, Tallow, Distillers' Corn & Sorghum Oil
D4	Biomass-Based Diesel	NERD (EV 1.5)	Tallow, Soybean, Distillers' Corn & Sorghum Oil
D4	Biomass-Based Diesel	NERD (EV 1.6)	Tallow, Soybean, Distillers' Corn & Sorghum Oil
D4	Biomass-Based Diesel	NERD (EV 1.7)	Tallow, Soybean, Distillers' Corn & Sorghum Oil
D3	Cellulosic Biofuel	Ethanol	Corn Kernel Fiber, Biomass Stover
D3	Cellulosic Biofuel	RCNG	Landfill, Wastewater Treatment, Animal Waste
D3	Cellulosic Biofuel	RLNG	Landfill, Wastewater Treatment, Animal Waste
D3	Cellulosic Biofuel	Renewable Gasoline	Forest Waste, Crop Residue, Food Waste
D7	Cellulosic Diesel	NERD (EV 1.7)	Forest Waste, Crop Residue, Food Waste

[a]NERD = Non-Ester Renewable Diesel

Table 2 shows the U.S. renewable fuel volumes generated (million gallons of fuel) from 2008 - 2022 (i.e., the period of RFS2 implementation). The study also evaluates the effect of the RFS extended through 2022 and estimates the fuel volumes for 2025.

[1] EPA categorizes renewable diesel by equivalence value EV. The equivalence value represents the ratio of heating value of a biofuel to the heating value of a gallon of denatured ethanol. NERD EVs may vary with data submitted by different fuel developers with petitions to EPA.

The GHG emissions for each category of fuel in Table 2 are calculated based on estimates of the composite carbon intensity (CI) for each of the fuels. The CI varies among all of the fuel technologies. Grain-based ethanol production uses a range of process fuels. Ethanol plants also produce distillers' grains, corn oil, and other food and feed products. Ethanol also is a higher-octane blending component which reduces the GHG emissions associated with crude oil refining.

Note that the RIN data is categorized by the Equivalence Value (EV) which corresponds to the different in energy content of diesel, naphtha, and jet fuel relative to ethanol which are typically associated with the production of non-ester renewable diesel (NERD) fuels as well as pyrolysis-based fuels. Biodiesel and NERD also use a range of feedstocks including vegetable oils and waste oils. The CI depends on the mix of these feedstocks.

Many sources of biogas generate RINs under the RFS including landfills as well as food waste and manure anaerobic digesters. The latter source of renewable natural gas (RNG) result in the avoidance of methane emissions, which further reduce GHG emissions. RNG is a feedstock for compressed natural gas (CNG) and liquefied natural gas (LNG) as well as a process fuel for some ethanol plants.

Table 2. U.S. Renewable Fuel Volumes used in Transportation

D	Fuel Type	Fuel Volumes (Million Gallons) [a]									
		2008	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**	**2021**	**2022**	**2025**[b]
6	Ethanol	9,309	13,298	12,987	14,022	14,725	14,967	12,777	13,984	14,248	15,544
6	Biodiesel	0	0	1	53	113	0	0	0	0	0
6	NERD (EV 1.7)	0	0	0	151	166	107	76	79	75	95
5	Ethanol	530	16	603	90	61	102	209	86	109	120
5	Biogas	0	0	3	20	0	1	0	0	0	10
5	NERD (EV 1.6)	0	5	2	0	0	0	0	0	0	0
5	NERD (EV 1.7)	0	3	10	9	5	24	51	62	73	110
5	Bio-Naphtha	0	0	0	12	18	21	19	19	62	98
4	Biodiesel	678	343	1,056	1,436	2,194	2,030	2,034	1,913	1,859	1,900
4	NERD (EV 1.5)	0	0	1	0	0	0	0	0	0	0
4	NERD (EV 1.6)	0	0	9	7	0	0	3	19	60	82
4	NERD (EV 1.7)	0	1	80	320	421	485	839	1,156	1,691	2,300
3	Ethanol[c]	0	0	0	1	4	8	82	141	160	172
3	RCNG	0	0	0	15	117	222	412	483	525	740
3	RLNG	0	0	0	17	72	83	92	84	83	165
3	Renewable Gasoline	0	0	0	0	0	0	0	0	0	0
7	NERD (EV 1.7)	0	0	0	0	1	0	0	0	0	0
	Anhydrous Ethanol	9,642	13,047	13,318	13,831	14,494	14,776	12,807	13,926	14,228	15,613
	Denaturant	197	266	272	282	296	302	261	284	290	319
	FAME Biodiesel	678	343	1,057	1,501	2,325	2,052	2,053	1,932	1,921	2,298
	Total N-E RD	0	9	103	488	591	615	969	1,316	1,899	2,387
	Total Biogas	0	0	3	53	189	304	504	567	607	915
	Total	**10,517**	**13,665**	**14,753**	**16,155**	**17,895**	**18,049**	**16,594**	**18,025**	**18,945**	**21,532**

[a] Fuel volumes correspond to total net generation EPA RIN data divided by the fuel's equivalence factor. Fuel volume is derived from the RIN generation data provided by EMTS. *except for the year 2025

[b] 2025 fuel volumes follow trends from LCFS states, where most of the low carbon fuels are marketed

[c] D3 ethanol from corn fiber. Data from CARBs LCFS transaction volume. CARB recognizes D3 ethanol but EPA does not. D3 ethanol volume has been subtracted out from D6 ethanol volumes from EPA RIN data to avoid double counting.

2. Land Use Change

The Land Use Change (LUC) reflects the net change in carbon stocks associated with expansion of crop production as well as indirect effects that are induced by the demand for feedstocks. LUC is an important, but controversial, element of a biofuel's life cycle impact, including the direct emissions associated with land conversion to agricultural fields and indirect emissions associated with economic impacts induced by the change to land use.

EPA, ARB and ANL have developed estimates for LUC estimates from biofuels production. These are summarized in Table 3. The development of LUC estimates is discussed in detail in the 2014 Marginal Emissions report (Boland, 2014). This analysis uses the best estimate for each biofuel category shown here to calculate the total emissions from the production of that biofuel.

Table 3. LUC Emissions Estimates from Biofuels

Policy	**Corn EtOH**	**Sorghum Ethanol**	**Corn Stover**	**Sugarcane Ethanol**	**Soybean BD/RD**	**Canola BD/RD**	**Palm BD**	**Tallow BD/RD**	**Corn BD**
					LUC (g CO_2e/MJ)				
2009 ARB	30	n/a	0	46	62	31	n/a	0	0
2010 EPA	28	13.1	-1.3	5.41	18.3	~15	48.2	0	0
2014 ARB	19.6	19.4	0	11.8	29.1	14.5	71.4	0	0
ANL/CCLUB	3.7[a]	n/a	-0.6	n/a	7.9[b]	n/a	n/a	0	0
Best Estimate	**3.7**	**3.7**	**-0.6**	**5.41**	**7.9**[c]	**7.9**	**48.2**	**0**	**0**[d]

[a] Corn Ethanol GTAP 2013 database

[b] Soy Biodiesel GTAP 2011 database

[c] The ILUC associated with soy BD is consistent with the crop yield per acre. If ILUC per acre of corn is the same as ILUC per acre of soybeans, then ILUC for soybean-based BD or RD is about twice that of corn ethanol depending upon the displacement value of co-products from ethanol and soybean meal. The RFS and LCFS values for soybean and canola ILUC are used as a conservative assumption. The ILUC values for BD and RD should differ slightly depending on oil to fuel yield but these values are assumed invariant with biomass-based diesel type.

[d] Several approaches are available to assigning ILUC to ethanol and corn oil used for biodiesel production. The California ARB assigns all of the ILUC to ethanol and this approach is followed here.

3. Carbon Intensity of Corn Ethanol and Biofuels production

Ethanol represents the largest volume of renewable fuel produced and consumed in the U.S. The Marginal Emissions report (Boland, 2014) developed aggregated weighted CI estimates for the corn ethanol produced in the U.S. based on the installed capacity shown in Table 4. The installed capacity is based on the production cases described in the EPA Regulatory Impact Analysis (EPA, 2010). The capacity per plant type (including projections for capacity expansions) was used to model the trend in corn ethanol production for RFS operational years of 2008 through to 2022.

Important developments in the mix of corn ethanol technology include the following:

- Rapid adoption of corn oil extraction for dry mill plants (95% by 2022)
- Introduction of corn fiber/kernel fiber/stover in 37 plants by 2022[2]
- Growth in the use of low CI biogas as process fuel
- Elimination of coal as fuel for dry mill ethanol plants
- Carbon Capture, Utilization and Storage (CCUS) is an emerging technology expected to further improve CI scores.

Further emission reduction strategies include the use of corn replacement from stover and by implementing sustainable agricultural practices during corn cultivations such as use of green ammonia, no-till practice, and cultivation of cover crops. If the reduction strategies are implemented correctly at the ethanol facility, the CI value of ethanol can reach zero or even negative values.

[2] While EPA has not approved corn fiber petitions, the California ARB has approved 37 pathways as of 2022. This technology results in about a 3% increase in ethanol production capacity. The adoption rate should grow to over 80 plants by 2025.

Table 4. Corn Ethanol Production Capacity and Technology Aggregation

Plant Energy Source,	Capacity (Million Gallons per Year)							
Aggregated data[a,b]	**2008**	**2010**	**2012**	**2014**	**2016**	**2018**	**2020**	**2022**
Wet Mill, Coal	1,888	1,877	1,893	1,474	1318	1162	745	480
Wet Mill, NG	107	328	473	854	1,100	1312	538	974
Dry Mill, Coal	54	36	19	15	0	0	0	0
Dry Mill, NG, DDGS[c]	2,919	2,366	1,812	1,613	1,600	500	522	510
Dry Mill, NG, WDGS[c]	1,442	1,178	913	903	900	230	183	208
Dry mill, CO[d] DDGS	1,946	4,617	5,471	5,336	7,000	8,500	9,917	9,681
Dry mill, CO[d] WDGS	961	2,145	2,728	2,589	2,700	3,000	3,484	3,954
Dry Mill, CRF[e]	325	361	397	461	700	800	965	980
Dry Mill, Biogas[f]	195	250	305	360	415	470	525	700
Corn Stover/Fiber[g]	0	0	0	0.73	4	10	85	200
Total Corn Ethanol	9,837	13,158	14,011	13,606	15,737	15,984	16,965	17,686

[a] EPA Regulatory Impact Analysis (RIA)for the final Transport Rule.(EPA, 2009)

[b] Projections in consultation with industry experts.

[c] The rapid adoption of corn or extraction in dry mill ethanol plants has penetrated most of the market due to the improvement in energy consumption, reduction in GHG emissions, and production of corn oil. Total corn oil biodiesel from EIA data corresponds to 0.13 lb of corn oil per gallon of ethanol, which is about half of the potential yield. The balance of corn oil is used as animal feed.

[d] CO – Corn Oil

[e] Corn replacement feed (CRF)/green corn and low GHG corn farming can reduce GHG emissions by producing additional co-product credit and implementing low impact farming practices. The introduction of lower emission corn is projected based on projections from industry analysts. (ACE, 2018).

[f] 11 ethanol plants with biogas or biomass process fuel have approved LCFS pathways.

[g] 37 corn fiber/stover/kernel fiber ethanol pathways were approved under CA LCFS in 2022. Assume corn fiber ethanol is an additional 3% of plant capacity. CARB reports corn fiber ethanol gallons.

Table 5 shows the representative CI of ethanol produced at each type of production facility described in the RIA. The CI reflects the ILUC values from the latest GREET model (ANL 2022).

Table 5. Carbon Intensity of Corn Ethanol

Corn Ethanol Production Type	Carbon Intensity (g CO_2 e/MJ) 2008 [a]	2015 [a]	2018 [a]	2020[a]	2022[b]
Wet Mill, Coal	97.35	94.82	93.44	92.52	90.95
Wet Mill, NG	77.35	74.95	73.65	72.78	71.29
Dry Mill, Coal	74.00	71.01	71.01	70.16	65.80
Dry Mill, Average	64.27	56.92	56.61	55.71	53.07
Dry Mill, NG, DDGS	60.80	59.75	59.75	58.83	55.42
Dry Mill, NG, WDGS	54.38	48.43	47.20	46.37	46.02
Dry mill, corn oil DDGS	63.82	59.58	57.91	56.81	55.25
Dry mill, corn oil WDGS	54.92	48.77	48.77	47.86	46.00
Dry Mill NG, CRF	49.37	39.65	39.65	38.36	36.56
Dry Mill, Biomass/Biogas	38.00	34.14	30.00	28.15	27.28

[a] CI values from GREET for their respective years. CI of corn, electricity mix, and other life cycle factors have changed since then.

[b] Based on GREET1_2022 model. Data from GREET1_2022, provided energy inputs data to these calculations. Data from California LCFS pathways provide insight to corn fiber and biomass based – based pathways. GREET CCLUB estimates for ILUC included in this table.

Similar to ethanol, estimates for the production of bio- and renewable diesel were based on the feedstock use per fuel. The U.S. Energy Information Agency (EIA) provides inputs on the U.S. feedstock inputs into biodiesel production (EIA, 2015). The production volumes for modelled for the years 2008 through to 2022. The biodiesel feedstock production volumes are shown in Table 6.

Table 6. Feedstocks for U.S. Biodiesel Production (MGPY)

Product	2008	2010	2012	2014	2016	2018	2020	2022
Total BD[a]	678	343	1,056	1,501	2,325	2,052	2,053	1,921
Canola oil	59	30	91	130	133	149	155	145
Corn oil	72	36	111	158	153	245	252	236
Palm oil	16	8	26	37	56	0	0	0
Soybean oil	360	182	561	797	1,619	1,212	1,275	1,193
Tallow/Poultry	42	21	65	92	133	151	165	155
UCO	130	66	202	288	231	295	206	192

[a]Total BD volumes based on EPA-reported RINs. Split among oil types based on EIA data.

Similar estimates for the renewable diesel feedstocks were developed from the study of hydrogenation derived renewable diesel as a renewable fuel option in North America. The biogas feedstocks are primarily landfill gas and wastewater treatment facility biogas. Biogas from anaerobic digestion of food waste and manure is also a source of biogas for CNG.

Table 7 shows the volumetric weighted carbon intensity estimates (developed by weighting the production capacity with the CI for each technology/feedstock) for the each of the biofuel categories included in the RFS2. The table also shows the assumed minimum reduction threshold CI for the RFS2 for each fuel type.

More recent studies of petroleum GHG emissions also indicate that the estimates for the original 2005 petroleum baseline in fact somewhat higher (EIA, 2013; Elgowainy, 2014; Unnasch, 2009).

3.1 Fuel Impacts

In addition to displacing higher GHG fossil fuels, alternative fuels have several other impacts on the transportation system. High octane ethanol allows to produce less energy intense hydrocarbon blending components and results in higher efficiency in high octane fuels. Renewable diesel results in an ultra-low sulfur fuel with a high cetane number that helps refiners meeting fuel specifications. These factors contribute to the overall GHG benefit of renewable fuels.

Fuel Efficiency and Octane

Reformulated gasoline is produced by blending a hydrocarbon component for oxygenate blending (BOB) with ethanol. To produce regular gasoline with an Anti-Knock Index (AKI) (R+M)/2 octane of 87 an 84 octane BOB is blended with ethanol[3]. Refiners take advantage of ethanol's octane produces a BOB with few high-octane components. Typically, the reformer is operated at a lower severity or less blending from alkylation units contribute to the octane of gasoline (Hirshfeld, 2015; Kwasniewski, 2015). Kwasniewski presents the different scenarios on a GHG intensity basis with a difference of 1 g CO_2e/MJ of gasoline between E10 and zero ethanol blending cases. The result is consistent with the energy intensity in a paper from Argonne National Laboratory (Elgowainy, 2014)[4].

[3] The AKI for ethanol is 99.3 (Pearson, 2015) but its blending octane number at 10% level is 114.
[4] For example, alkylation units require 1.2 MJ input per MJ gasoline compared with 1.03 MJ/MJ for crude distillation. Displacing the higher energy intensity component with ethanol reduces the CI of the BOB.

Table 7. Carbon Intensity Estimates of All Biofuels and RFS GHG Reduction Threshold (g CO_2e/MJ)

Fuel	Threshold	2008	2010	2012	2014	2016	2018	2020[a]	2022	2025
Ethanol, D6	74.5	66.3	63.6	62.0	58.6	56.4	55.1	53.0	51.2	47.0
Biodiesel, D6	74.5	71.8	71.5	71.5	71.5	90.0	90.0	90.0	90.0	90.0
Non-Ester RD, D6	74.5	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
Ethanol, D5	46.5	41.9	42.1	42.1	42.2	39.6	39.6	38.0	37.0	35.0
Biogas, D5	46.5	25.6	24.4	24.4	23.8	23.3	23.3	21.0	20.0	17.0
Non-Ester RD (EV 1.6)	46.5	46.4	46.4	46.5	46.2	46.2	46.2	44.4	43.7	42.8
Non-Ester RD (EV 1.7)	46.5	46.4	46.4	46.5	46.2	45.9	45.9	43.8	40.3	39.0
Bio-Naphtha	46.5	46.4	46.4	46.5	46.2	45.9	45.9	33.1	30.0	29.0
Biodiesel	46.5	42.5	42.1	42.3	42.2	31.0	27.7	24.7	22.2	19.0
Non-Ester RD (EV 1.5)	46.5	46.4	46.4	46.5	46.2	46.2	46.2	28.7	26.0	25.0
Non-Ester RD (EV 1.6)	46.5	46.4	46.4	46.5	46.2	45.9	45.9	39.8	38.3	38.0
Non-Ester RD (EV 1.7) Soy/Tallow	46.5	35.0	35.0	35.0	35.0	33.4	31.0	27.2	23.0	21.0
Ethanol, Cellulosic	37.2	37.2	37.4	37.8	38.4	33.5	30.0	28.5	27.0	26.4
RCNG[b]	37.2	25.6	24.4	24.4	23.8	23.3	23.3	16.9	9.0	7.0
RLNG	37.2	29.6	28.3	28.3	27.6	27.0	27.0	20.6	12.0	9.0
Renewable Gasoline	37.2	28.0	27.0	27.0	26.6	26.1	26.1	22.6	21.6	20.0
Non-Ester RD, D3	37.2	28.0	27.0	27.0	26.6	26.1	26.1	26.1	26.1	26.1
US Electricity		204.6	182.5	182.5	170.3	159.9	159.9	159.9	140.0	130.0
Denaturant	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0
Gasoline Blendstock	93.1	96.7	96.8	96.9	97.0	97.2	97.3	97.3	97.3	97.3
Diesel	93.1	98.7	98.8	98.8	99.0	99.2	99.3	99.3	99.3	99.3

[a]CI for Biodiesel (D6) and NERD (D6) is constant and rounded to equal 90 as CARB gives palm oil diesel the high CI equal to gasoline.

[b]CI for RCNG and RLNG is associated with the growing swine manure farms and digesters. Corn ETOH, mix of plants, ANL GREET, new iLUC, Veg oil BD and RD based on GREET

The benefit of blending ethanol on the BOB produced at the oil refiners is examined for E10 and E15. For 87 octane fuels the E10 BOB results in a 1.0 g CO_2e/MJ reduction while a BOB formulated for E15 receives a 1.5 g CO_2e/MJ GHG reduction, which is proportional to the GHG savings from the ethanol in E10. In this case of E15 a lower octane BOB is possible to produce 87 AKI blended gasoline.

In the case of E15 that results in a higher octane, the BOB is assigned the same 1 g CO_2e/MJ savings as the E10 BOB as it is the same refined product. The balance of E15 and E85 are estimated to result in higher octane fuels the same gasoline BOB used for E10 blending. All of the BOB for E10 or higher-octane blends is assigned 1 g CO_2e/MJ GHG reduction due to the effect on oil refineries. A 5% increase in ethanol will result in an extra octane point while E85 can have an octane number close to 93.

Several studies examine the effect of octane on fuel economy. Higher octane allows for an advance in ignition timing and higher turbocharger boost in engines with knock sensors. A 1% to 3% increase in energy economy is consistent with data from the EPA fuel economy guide where fuel consumption is reported or both E10 and E85 vehicles. The improvement in fuel economy from engine testing studies also indicates an efficiency improvement on the order of 1% for a 2-point increase in octane (Shuai, 2013; Stradling, 2015; Leone, 2017). Energy-economy ratio values of 1.005 and 1.02 were estimated for E15 and E85 respectively. The EER represents the energy economy of gasoline (E10) relative to the alternative fuel.

3.2 GHG Calculation Methods

GHG emissions were calculated based on the displacement of petroleum fuels. The aggregate mix of biofuels as well as crude oil resources provided the basis for GHG calculations. Displaced gasoline and diesel are calculated for each category of biofuel. In the case of ethanol, the effect on octane blending is also calculated. The net change in GHG emissions corresponds to the aggregation of each component fuel in the RFS. GHG emissions were calculated for each fuel category in equations 1, 2, and 3.

GHG from alternative fuel = Fuel volume × LHV × CI for each fuel (1)

The denaturant component of ethanol is calculated separately along with the biofuels

Displaced emissions correspond to severe effects including:

Alternative fuel volume × EER × LHV × CI for each fuel (2)

In the case of E15, E85, and CNG the EER values in this study are 1.005, 1.02, and 0.9 respectively

BOB volume associated with achieving 87 octane fuel × LHV × 1 g CO_2e/MJ savings (3)

For biodiesel and renewable diesel, the petroleum baseline fuel is diesel. Biogas displaces a mix of gasoline and diesel with a more conservative EER of 0.9 assumed for diesel displacement.

Net GHG emissions are calculated based on the CI of the renewable fuel minus the displaced fuel. In the case of ethanol, additional octane blending benefits are included as part of the impact. Table 8 provides an example for 1 billion gallons of ethanol with two CI value deployed either as E10 or E15. In the case of E10, 1 billion gallons corresponds to 81,224 TJ of energy and displaces the same energy in the BOB. For the E15 example here, half the ethanol displaces a proportional quantity of BOB. The other half of the E15 (500 million gallons) results in an EER of 1.005 and displaces more BOB. The effect on octane blending is also shown for each fuel volume.

Table 8. Carbon Intensity Estimates of All Biofuels plus EPA Minimum Threshold

	E10 87 Octane		**E15 87 Octane**		**E15 88 Octane**	
	TJ	**Gg GHG**	**TJ**	**Gg GHG**	**TJ**	**Gg GHG**
Energy Inputs and Emissions[a]						
10% Wet Mill Coal Ethanol	8,122	720	4,061	360	4,061	360
90% Dry Mill WDGS Ethanol	73,101	3,639	36,551	1,819	36,551	1,819
Total Ethanol	81,224	4,359	40,612	2,180	40,612	2,180
EER	1		1		1.005	
Displaced BOB	-81,224	-7,862	-40,612	-3,931	-42,515	-4,115
Total BOB	1,080,000		340,000		340,000	
Refinery Octane	1,080,000	-1,080	340,000	-510	226,667	-227
Net Emissions		-4,583		-2,262		-2,162
Fuel Volume						
Ethanol (B gal)	1		0.5[b]		0.5[b]	
RFG (B gal)	10		3.33		3.33	

[a]CI of Wet Mill Coal, Dry Mill WDGS, and BOB are 88, 49, and 96.8 g CO_2e/MJ respectively. Octane blending effect of E10 and E15 are 1 and 1.5 g CO_2e/MJ respectively.

[b] 50% of the billion gallons of ethanol in the E10 example are calculated for an 87 octane and 88 octane strategy. In the 87 octane case, ethanol reduces the refinery octane requirement with reduced refinery emissions. In the 88 octane calculation the BOB receives a lower octane blending credit as 1 octane point is “given away” while displacing more gasoline is displaced due to the higher EER.

3.3 Avoided GHG Emissions

The avoided GHG emissions are calculated from the reduction in CI from the revised petroleum baseline, as developed by Boland et al. (Boland, 2014). Figure 4 shows the total CO_2 savings, in million metric tonnes per year (Million tonne/yr) from the inclusion of ethanol in the RFS2.

Key changes in fuel volume include a growth in the production capacity of corn fiber ethanol, NERD, low CI RNG and biogas from animal waste.

The effect of different levels of E15 in 2025 are also examined using the approach outline previously assuming that 50% is blended at 87 octane and the balance results in higher octane fuel. 84% E15 in a gasoline pool of 138 billion gallons per year could be achieved with the current corn ethanol capacity in the U.S. of 17.4[5] billion gallons per year[6]. Note that the scenario for E15 shown here for 2025 uses more than the 15 billion gallons of D6 ethanol required under the RFS2. E15 results in additional GHG reductions because more ethanol is consumed as fuel and it enables the production of a lower octane BOB.

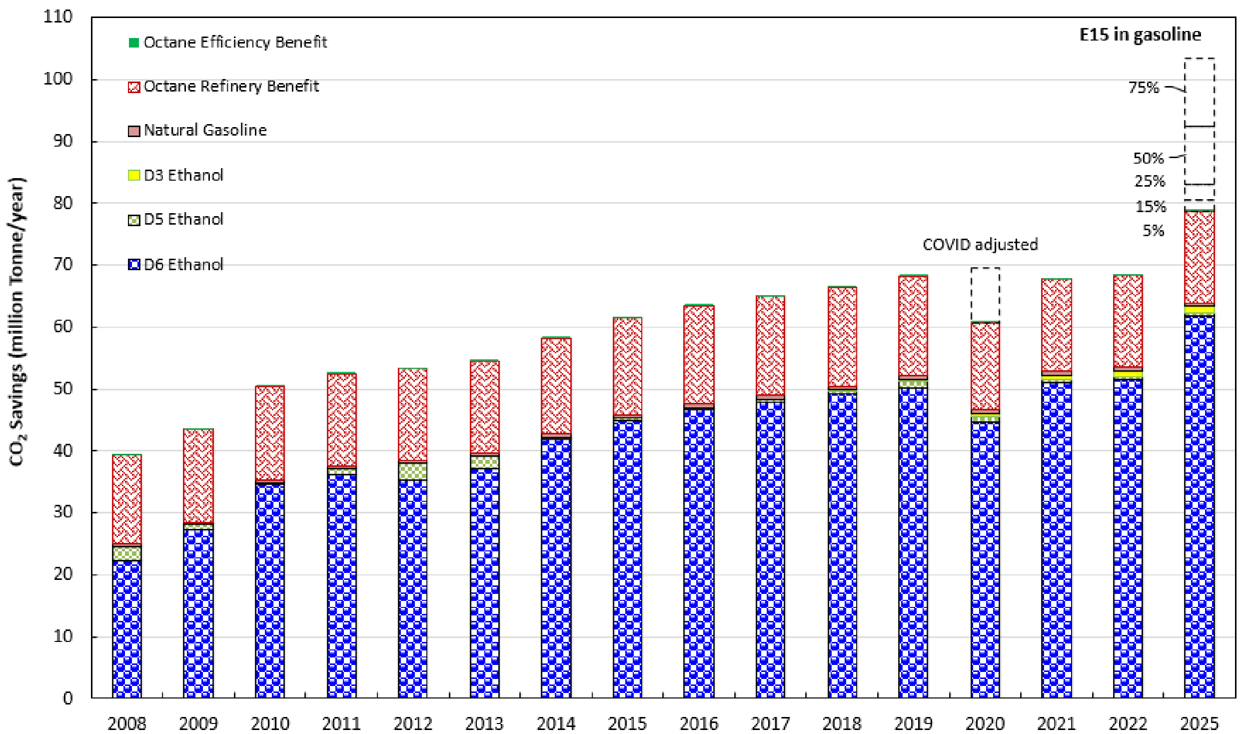

Figure 4. GHG Savings from Ethanol

Figure 5 shows the CO_2 saving from all other biofuels. Since ethanol is thus far the major component of the RFS2, most of the CO_2 savings are due to ethanol fuels.

[5] US fuel ethanol production capacity for the year 2022.
[6] EIA projects 9 million bbl/d of gasoline consumption in 2022 or 138 billion gallons per year. 29% of ethanol as E15 could be achieved with U.S. ethanol production capacity for 150 billion gallons per year of gasoline consumption.

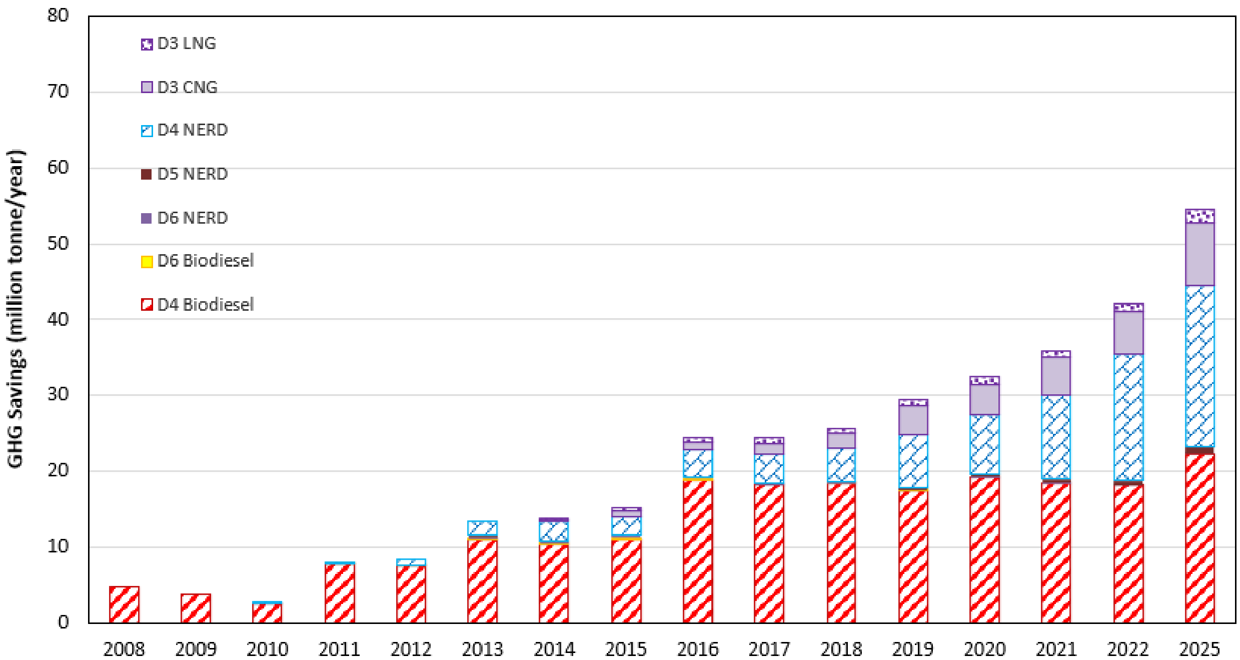

Figure 5. GHG Savings from Other RFS2 Biofuels (Excluding Ethanol).

Figure 6 shows the total CO_2 reductions of the RFS2 based on the analysis presented here. The base RFS assumptions are also shown in the graph, where the biofuels meet the minimum CI threshold mandated in the RIA (EPA, 2009) and as shown in Table 7. The RFS2 has resulted in the cumulative CO_2 savings of 1,212 million metric tonnes over the period of implementation (until 2022) as shown in Figure 6. The CO_2 savings as calculated from the minimum CI threshold base assumptions outlined in the RIA (EPA, 2009) results in the cumulative CO_2 savings of 812 million metric tonnes of CO_2[7].

[7] Green bars indicate the annual GHG savings from the minimum RFS CI thresholds.

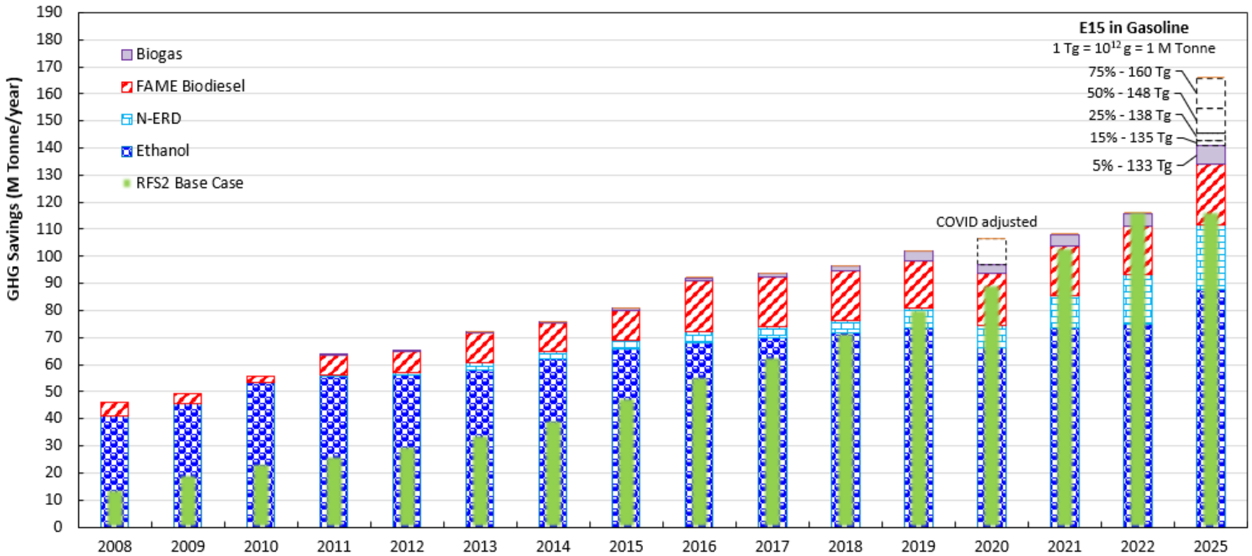

Figure 6. GHG Savings from the RFS2 Program

4. Conclusions

The RFS2 has resulted in GHG emissions reductions, which exceed the original projections from the 2010 final Rule. The increased GHG reductions are due to the following:

1. Corn ethanol has continuously adopted technology improvements, which results in greater than the 20% reduction in GHG emissions originally required under the RFS.
2. Petroleum GHG emissions are higher than the baseline projected by EPA.
3. The mix of other renewable fuels has also contributed to additional GHG reductions even though cellulosic ethanol targets in the original rule have not been met.

Biofuels have achieved and exceeded the GHG reductions estimated by EPA. The reductions are greater than the categories within the RFS2 because technology improvements have resulted in reductions in energy use and the RFS categories characterize typical renewable fuels. These categories were not intended to represent the weighted GHG reductions of all fuels produced under the rule.

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