Life Cycle Associates

GHG Emissions Reductions due to the RFS2: A 2018 Update

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DISCLAIMER

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

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Terms and Abbreviations

ANL	Argonne National Laboratory
ARB	California Air Resources Board
Btu	British thermal unit
BD	Biodiesel
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
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
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 expanded Renewable Fuel Standard (RFS2) has resulted in aggregate GHG emissions reductions from the use of biofuels, which exceed the original projections from the Environmental Protection Agency's (EPA) final rule for the first 10 years of its implementation. The RFS2 has resulted in significant GHG reductions, with cumulative CO_2 savings of nearly 600 million metric tonnes over the period of implementation. The GHG reductions are due to the greater than expected savings from ethanol and other biofuels. 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 11 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.

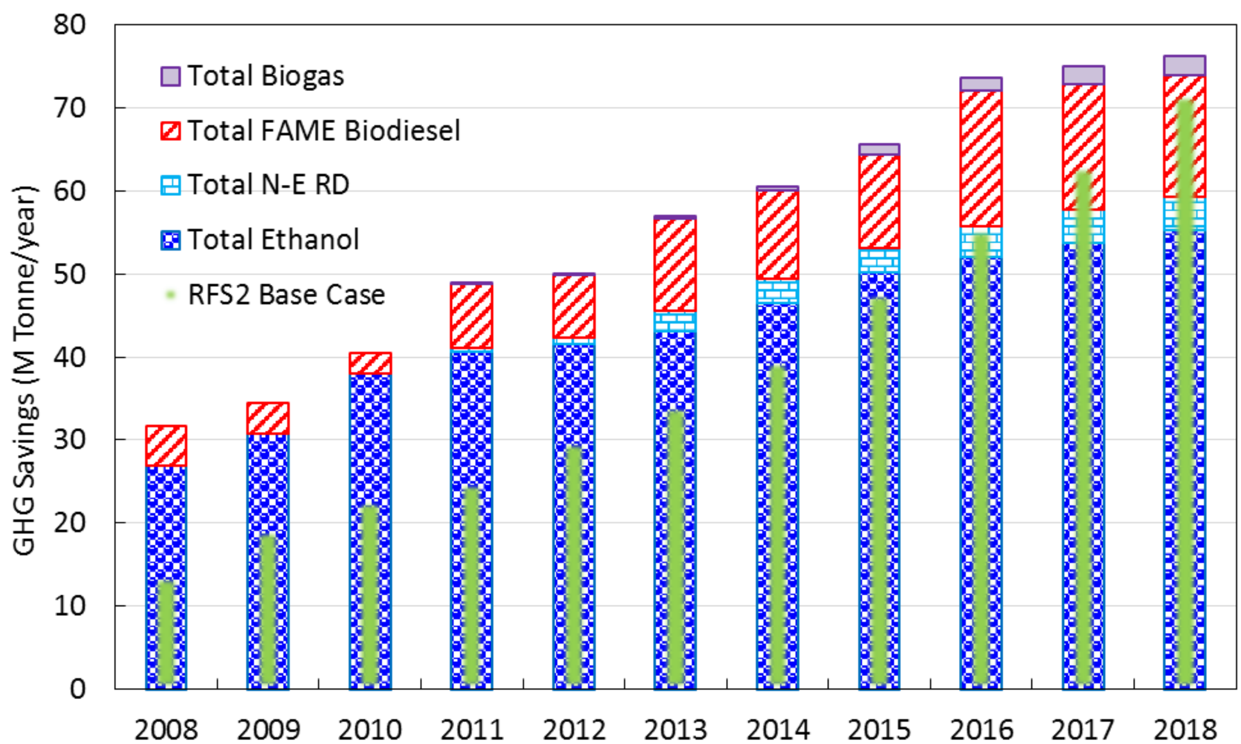

Figure 1. GHG Emissions Reductions Due to the RFS2.

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1. Introduction

This study builds upon the 2014 Carbon Intensity of Marginal Petroleum and Corn Ethanol Fuels report and subsequent update (Boland, 2014) (Boland, 2015) 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. RFS2 requires the addition of 36 billion gallons of renewable transportation fuels to the U.S. slate by 2022. The RFS2 established mandatory CI 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.

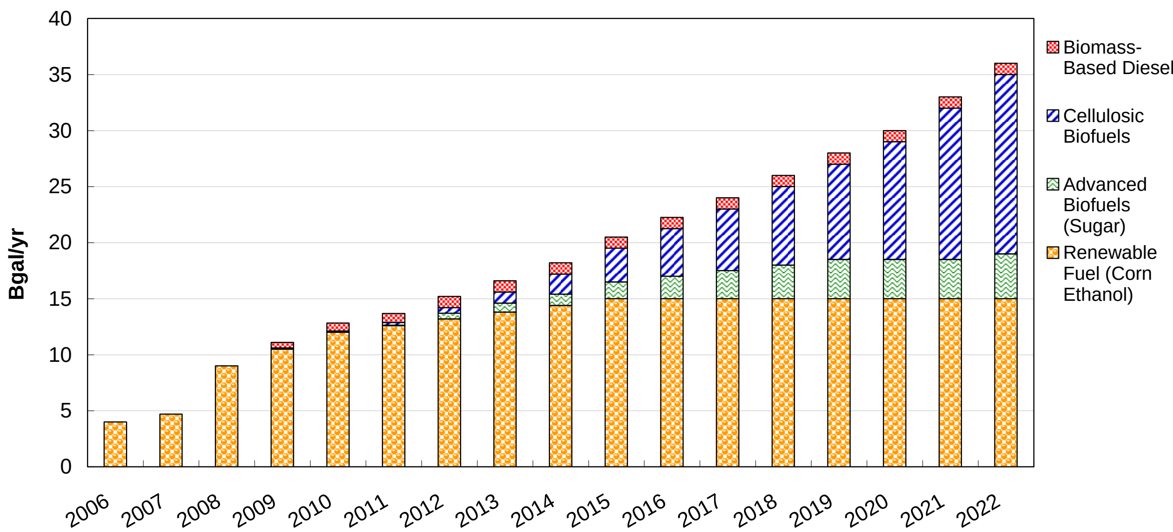

Figure 2. RFS2 renewable fuel volume requirements for the United States.

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 96.82 g CO_2 e/MJ.

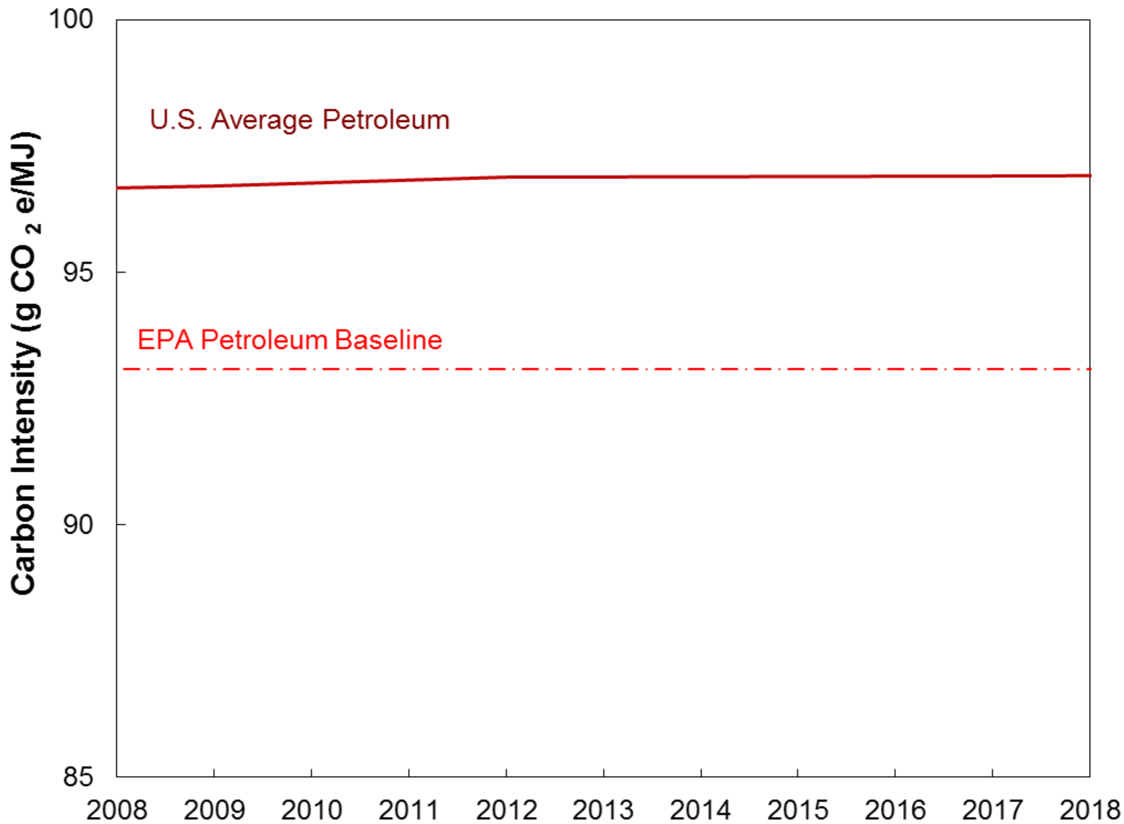

Figure 3. Weighted carbon intensity (g CO_2 e/MJ) of petroleum fuels consumed in the U.S.

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, 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 greater 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 D-code	Fuel Category	Fuel Type	Feedstock
6	Renewable Fuel	Ethanol	Corn, Sorghum
6	Renewable Fuel	Biodiesel	Palm oil
6	Renewable Fuel	NERD* (EV 1.7)	Palm oil
5	Advanced Biofuel	Ethanol	Sugarcane, Beverage waste
5	Advanced Biofuel	Biogas	Landfill, Wastewater Treatment
5	Advanced Biofuel	NERD* (EV 1.6)	Tallow, Used Cooking Oils, Soybean, Canola
5	Advanced Biofuel	NERD* (EV 1.7)	Tallow, Used Cooking Oils, Soybean, Canola
5	Advanced Biofuel	Bio-Naphtha	Soybean, Canola, Tallow, Used Cooking Oils
4	Biomass-Based Diesel	Biodiesel	Soybean, Canola, Tallow, Used Cooking Oils
4	Biomass-Based Diesel	NERD* (EV 1.5)	Tallow, Used Cooking Oils, Soybean, Canola
4	Biomass-Based Diesel	NERD* (EV 1.6)	Tallow, Used Cooking Oils, Soybean, Canola
4	Biomass-Based Diesel	NERD* (EV 1.7)	Tallow, Used Cooking Oils, Soybean, Canola
3	Cellulosic Biofuel	Ethanol	Corn kernel Fiber, Biomass Stover
3	Cellulosic Biofuel	RCNG	Landfill, Wastewater Treatment
3	Cellulosic Biofuel	RLNG	Landfill, Wastewater Treatment
3	Cellulosic Biofuel	Renewable Gasoline	Forest Waste
7	Cellulosic Diesel	NERD* (EV 1.7)	Forest Waste

*NERD = Non-Ester Renewable Diesel

Table 2 shows the U.S. renewable fuel volumes generated (million gallons of fuel) from 2008 - 2018 (i.e., the period of RFS2 implementation).

[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.

Table 2. U.S. Renewable Fuel Volumes Produced

D-code	Fuel Type	Fuel Volumes (Million Gallons)										
		2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018[a]**
6	Ethanol	9,309	10,938	13,298	13,609	12,987	13,099	14,017	14,390	14,725	14,864	15,000
6	Biodiesel	0	0	0	4	1	37	53	74	113	0	0
6	NERD (EV 1.7)	0	0	0	0	0	116	151	201	166	144	112
5	Ethanol	530	198	16	194	603	458	90	114	61	99	77
5	Biogas	0	0	0	1	3	26	20	0	0	2	1
5	NERD (EV 1.6)	0	0	5	12	2	0	0	0	0	0	0
5	NERD (EV 1.7)	0	0	3	5	10	41	9	6	6	6	23
5	Bio-Naphtha	0	0	0	0	0	0	12	16	18	21	20
4	Biodiesel	678	516	343	1,077	1,056	1,534	1,435	1,515	2,194	2,050	1,983
4	NERD (EV 1.5)	0	0	0	0	1	1	0	0	0	0	0
4	NERD (EV 1.6)	0	0	0	15	9	29	7	4	0	0	0
4	NERD (EV 1.7)	0	0	1	30	80	230	320	303	423	455	439
3	Ethanol	0	0	0	0	0	0	1	2	4	10	9
3	RCNG	0	0	0	0	0	0	15	81	117	157	188
3	RLNG	0	0	0	0	0	0	17	58	72	83	73
3	Renewable Gasoline	0	0	0	0	0	0	0	0	0	0	0
7	NERD (EV 1.7)	0	0	0	0	0	0	0	0	1	2	2
	Anhydrous Ethanol	9,839	11,136	13,314	13,803	13,590	13,557	14,108	14,506	14,791	14,974	15,086
	Denaturant	197	223	266	276	272	271	282	290	296	299	302
	FAME Biodiesel	678	516	343	1,082	1,057	1,571	1,501	1,606	2,325	2,071	2,003
	Total N-E RD	0	0	9	62	103	417	488	514	595	607	576
	Total Biogas	0	0	0	1	3	26	53	140	189	243	262
	Total	**10,517**	**11,652**	**13,665**	**14,948**	**14,753**	**15,571**	**16,149**	**16,766**	**17,899**	**17,895**	**17,928**

[a]2018 is the assumed 12 month production total of biofuels based on the 10 months (January - October 2015) data available.

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 biofuels life cycle impact, including the direct emissions associated with potential land conversion and indirect emissions associated with economic impacts induced by the change in land use.

EPA, ARB and ANL have developed estimates for LUC 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	7.6	n/a	-1.1	n/a	n/a	n/a	n/a	0	0
Best Estimate	**7.6**	**7.6**	**-1.1**	**11.8**	**18.3**	**14.5**	**48.2**	**0**	**7.6**[a]

[a] Biodiesel from corn oil and ethanol from corn should have the same ILUC. Considering the extra corn oil volume may reduce the ILUC values shown here but was not examined further.

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 2018.

Table 4. Corn Ethanol Production Capacity and Technology Aggregation

Plant Energy Source, Aggregated data[a,b]	Capacity (Million Gallons per Year) 2008	2010	2012	2014	2016	2018
Wet Mill, Coal	1,888	1,877	1,893	1,474	800	498
Wet Mill, NG	107	328	473	854	1,100	1312
Dry Mill, Coal	54	36	19	15	0	0
Dry Mill, NG, DDGS	2,919	2,366	1,812	1,613	1,600	500
Dry Mill, NG, WDGS	1,442	1,178	913	903	900	230
Dry mill, corn oil DDGS	1,946	4,617	5,471	5,336	7,000	8,500
Dry mill, corn oil, WDGS	961	2,145	2,728	2,589	2,700	3,000
Dry Mill NG, WDGS CRF[c]	325	361	397	461	700	800
Dry Mill, NG, Biomass	195	406	488	901	1,050	1,150
Corn Stover/Fiber				0.73	4	9
Total Corn Ethanol	9,839	13,314	14,194	14,197	15,850	15,990

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

[b] Custom projections in consultation with industry experts.

[c] CRF can be combined with any or all of the above cases, WDGS is illustrative.

Table 5 shows the representative CI of ethanol produced at each type of production facility described in the RIA.

Table 5. Carbon Intensity of Corn Ethanol

Corn Ethanol Production Type	Carbon Intensity (g CO_2 e/MJ) [a] 2008	2015	2018
Wet Mill, Coal	97.35	93.07	90.44
Wet Mill, NG	77.35	73.34	70.84
Dry Mill, Coal	67.61	63.38	63.38
Dry Mill, Average	64.27	56.04	54.55
Dry Mill, NG, DDGS	60.80	58.72	58.72
Dry Mill, NG, WDGS	54.38	48.78	48.78
Dry mill, corn oil DDGS	63.82	58.26	57.35
Dry mill, corn oil WDGS	54.92	49.79	49.79
Dry Mill NG, CRF	49.37	41.14	39.65
Dry Mill, NG, Biomass	38.00	34.14	30.00

[a] CI based on GREET1_2015 model. Data form the latest National Corn Mill Ethanol Survey (Mueller, 2010) and GREET1_2015, provided energy inputs data to these calculations.

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 were modelled for the years 2008 through to 2015. The biodiesel feedstock production volumes are shown in Table **6**.

Table 6. Biodiesel Feedstocks Volumes (million gallons)

Product	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Total BD	678	516	343	1,077	1,056	1,534	1,435	1,515	2,194	2,050	1,983
Canola oil	59	45	30	93	91	133	124	127	133	171	149
Corn oil	72	54	36	114	111	162	151	154	153	186	242
Palm oil	16	13	8	26	26	37	35	37	56	0	0
Soybean oil	360	274	182	572	561	814	762	757	1,530	1,383	1,207
Tallow/Poultry	42	32	21	66	65	94	88	90	90	69	90
UCO	130	99	66	206	202	294	275	350	231	242	295

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 (Lambert, 2012). 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, for the years 2008 through 2015. 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).

Table 7. Carbon Intensity Estimates of All Biofuels plus EPA Minimum Threshold

Fuel	Threshold	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Ethanol, D6	74.5	66.3	65.1	63.6	62.8	62.0	60.3	58.6	57.0	56.5	56.0	55.1
Biodiesel, D6	74.5	71.8	71.8	71.5	71.5	71.5	71.5	71.5	71.2	90.0	90.0	90.0
Non-Ester , D6	74.5	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0	90.0
Ethanol, D5	46.5	41.9	41.9	42.1	42.1	42.1	42.2	42.2	38.6	39.6	39.6	39.6
Biogas, D5	46.5	25.6	25.6	24.4	24.4	24.4	23.7	23.8	23.3	23.3	23.3	23.3
Non-Ester RD (EV 1.6)	46.5	46.4	46.4	46.4	46.4	46.5	46.2	46.2	46.2	46.2	46.2	46.2
Non-Ester RD (EV 1.7)	46.5	46.4	46.4	46.4	46.4	46.5	46.2	46.2	45.9	45.9	45.9	45.9
Bio-Naphtha	46.5	46.4	46.4	46.4	46.4	46.5	46.2	46.2	45.9	45.9	45.9	45.9
Biodiesel	46.5	42.5	42.5	42.1	42.1	42.3	42.2	42.2	41.9	41.9	41.9	41.9
Non-Ester RD (EV 1.5) Corn	46.5	46.4	46.4	46.4	46.4	46.5	46.2	46.2	46.2	46.2	46.2	46.2
Non-Ester RD (EV 1.6) Canola	46.5	46.4	46.4	46.4	46.4	46.5	46.2	46.2	45.9	45.9	45.9	45.9
Non-Ester RD (EV 1.7) Soy, Tallow	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
Ethanol, Cellulosic	37.2	37.2	37.2	37.4	37.6	37.8	38.1	38.4	35.4	33.5	31.7	30.0
RCNG	37.2	25.6	25.6	24.4	24.4	24.4	23.7	23.8	23.3	23.3	23.3	23.3
RLNG	37.2	29.6	29.6	28.3	28.3	28.3	27.6	27.6	27.0	27.0	27.0	27.0
Renewable Gasoline	37.2	28.0	28.0	27.0	27.0	27.0	26.5	26.6	26.1	26.1	26.1	26.1
Non-Ester RD, D3	37.2	28.0	28.0	27.0	27.0	27.0	26.5	26.6	26.1	26.1	26.1	26.1
US Electricity		204.6	204.6	182.5	182.5	182.5	169.3	170.3	159.9	159.9	159.9	159.9
Denaturant	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0	81.0
Gasoline Blendstock	93.08	96.7	96.7	96.8	96.8	96.9	96.9	97.0	97.1	97.2	97.3	97.3
Diesel	93.08	98.7	98.7	98.8	98.8	98.8	98.9	99.0	99.1	99.2	99.2	99.3

3.1 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. Figure 5 shows the CO_2 saving from all other biofuels. Since ethanol is thus far the major component of the RFS2, the majority of CO_2 savings are due to the ethanol fuels. 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 Congressionally mandated minimum CI threshold in the RIA (EPA, 2009) and as shown in Table 7. The RFS2 has resulted in the cumulative CO_2 savings of 579 million metric tonnes over the period of implementation. 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 422 million metric tonnes of CO_2.

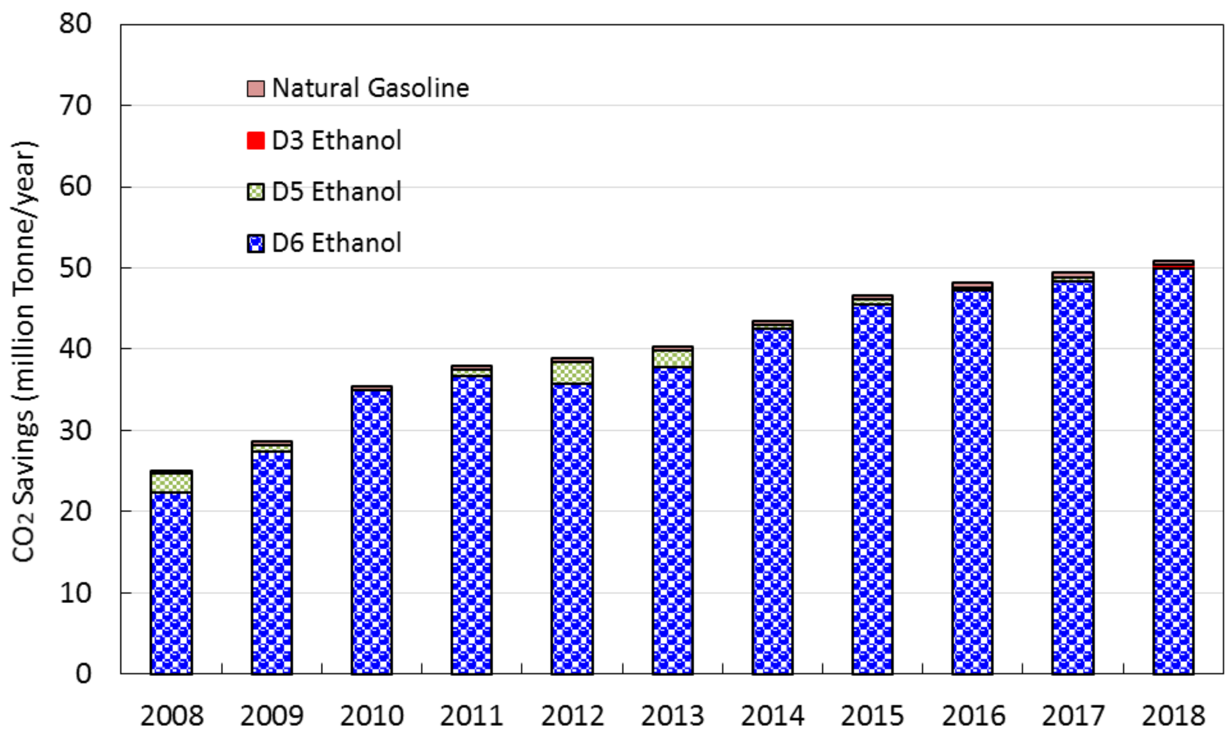

Figure 4. GHG Savings from Ethanol

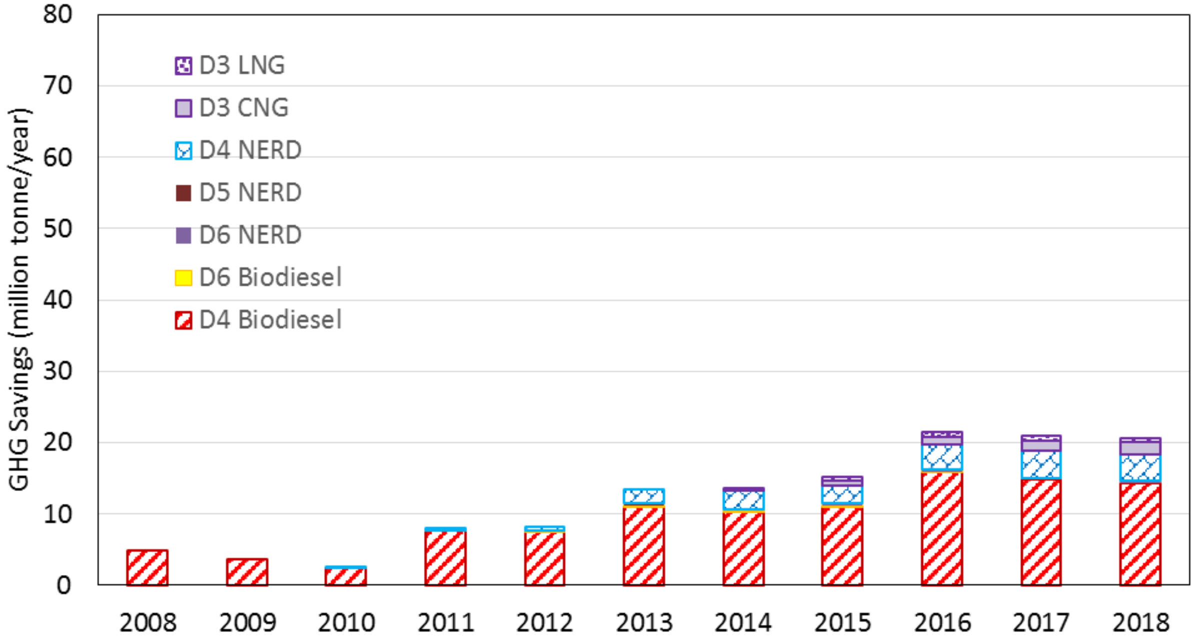

Figure 5. GHG Savings from Other RFS2 Biofuels (Excluding Ethanol).

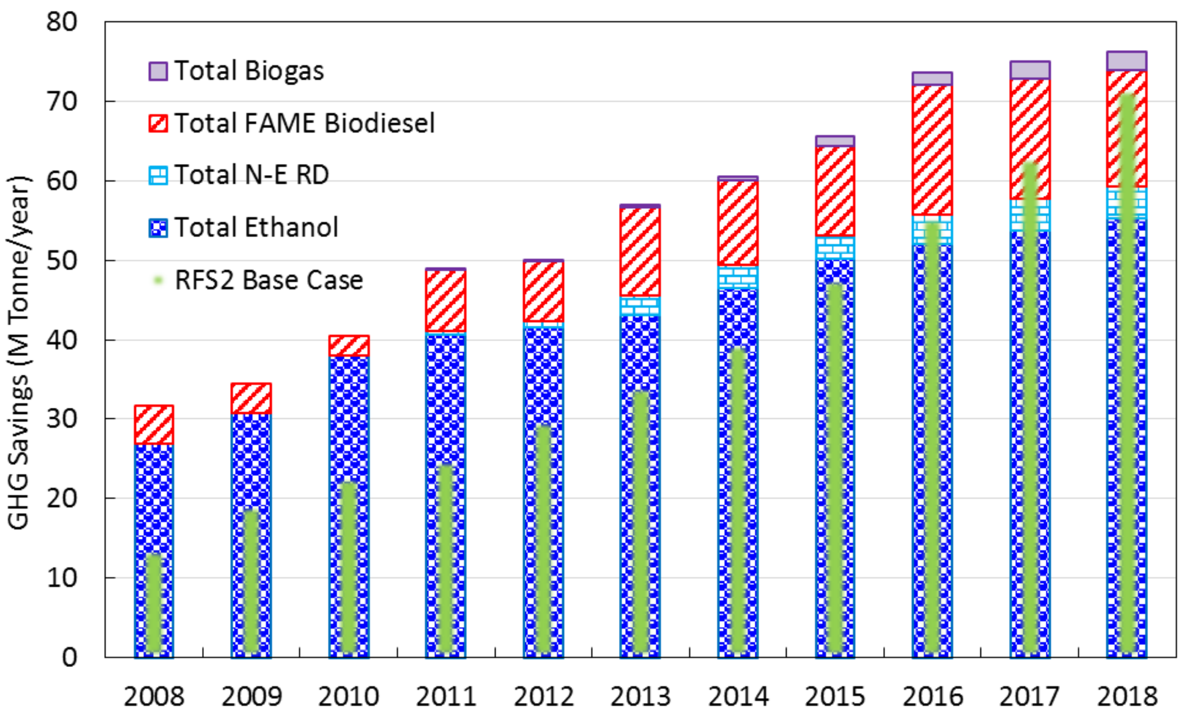

Figure 6. GHG Savings from the RFS2 Program

3.2 GHG Calculation Methods

GHG emissions were calculated based on the displacement of petroleum fuels. The aggregate mix of crude oil resources provided the basis for the petroleum fuel CI rather than the marginal mix that was displaced by biofuels. The net change in GHG emissions corresponds to the aggregation of each component fuel in the RFS. For ethanol, the terms are:

$$\text{Ethanol volume} \times LHV_{\text{ethanol}} \times (\text{Gasoline CI} \times LHV_{\text{gasoline}} / LHV_{\text{ethanol}} - \text{Ethanol CI})$$

The denaturant component of ethanol is calculated separately. For biodiesel and renewable diesel, the petroleum baseline fuel is diesel. Biogas displaces a mix of gasoline and diesel.

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 adopted technology improvements, which results in GHG reductions far greater than the 20% reduction assumed by EPA;
2. Petroleum GHG emissions are higher than the baseline projected by EPA; and
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 minimum GHG reduction thresholds specified within the RFS2 (which served as the basis for EPA's original GHG reduction estimates) because technology improvements have greatly reduced energy use in the renewable fuel production process. These GHG reduction thresholds (i.e., 20% for conventional biofuels, 50% for advanced biofuels, and 60% for cellulosic biofuels) are minimums to qualify for the RFS2 and were not intended to represent the weighted GHG reductions of all fuels produced under the program.

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