Life Cycle Associates

GHG Emissions Reductions due to the RFS2

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DISCLAIMER

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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 RFS2 has resulted in aggregate GHG emissions reductions from the use of biofuels, which exceed the original projections from the final Rule. The RFS2 has resulted in significant GHG reductions, with cumulative CO_2 savings of 353 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, 2015, 2012). 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 eight 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.

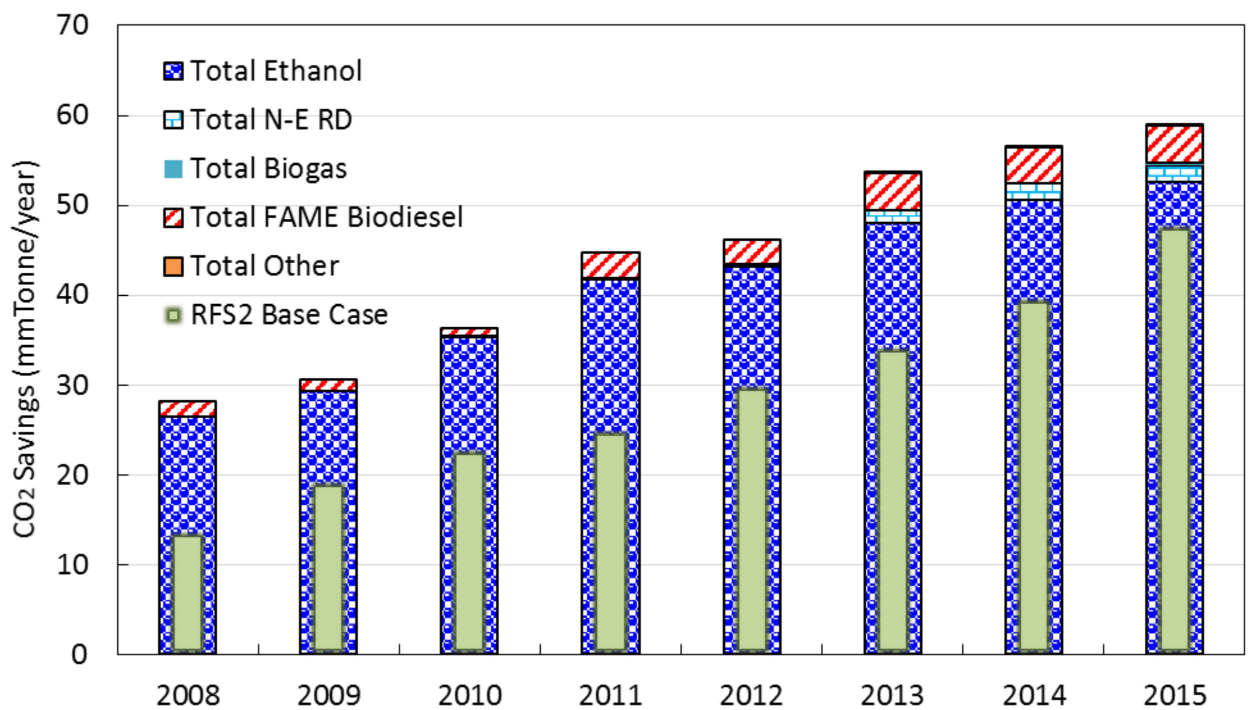

Figure 1. GHG Emissions Reductions Due to the RFS2.

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1. Introduction

This study builds upon the 2014 Carbon Intensity of Marginal Petroleum and Corn Ethanol Fuels report (Boland, 2014) 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 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.

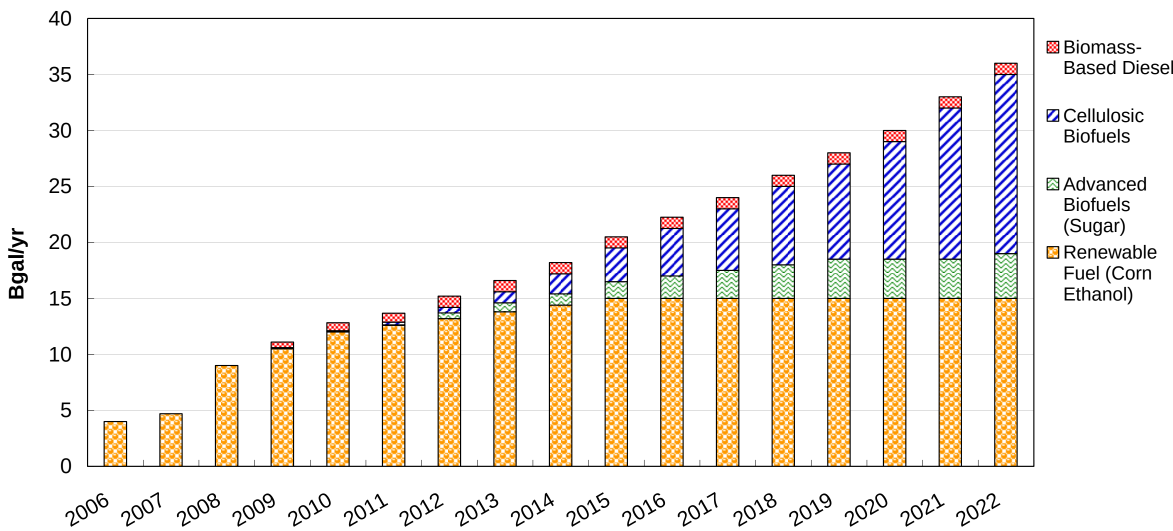

Figure 2. RFS2 renewable fuel volume requirements for the United States.

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.

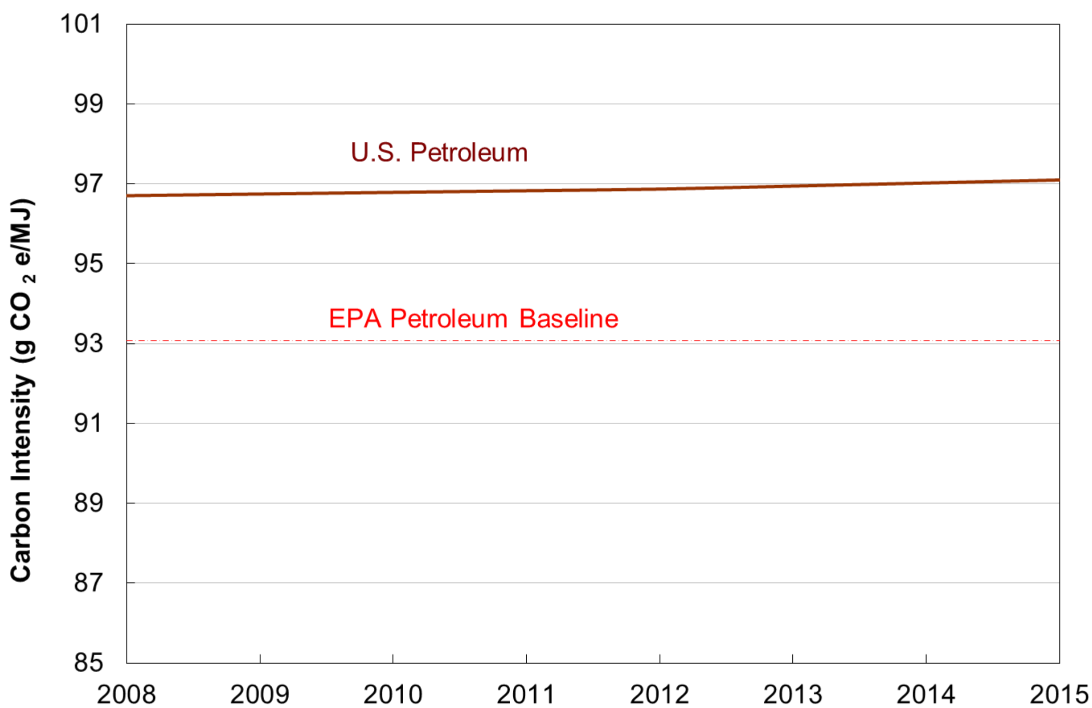

Figure 3. Weighted carbon intensity (g CO_2 e/MJ) of petroleum fuels consumed in the U.S.

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

[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.

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 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 - 2015 (i.e., the period of RFS2 implementation). Table 3 shows the corresponding number of RINS generated from each type of fuel.

Table 2. U.S. Renewable Fuel Volumes Produced

RIN D-code	Fuel Type	Fuel Volumes (Million Gallons)							
		2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015A***
6	Ethanol	9,309	10,938	13,298	13,609	12,987	13,099	14,017	14,236
6	Biodiesel	-	-	-	4	1	37	53	79
6	NERD (EV 1.7)	-	-	-	-	-	116	151	199
5	Ethanol	530	198	16	194	603	458	90	86
5	Biogas	-	-	-	1	3	26	20	-
5	NERD (EV 1.6)	-	-	5	12	2	0	0	-
5	NERD (EV 1.7)	-	-	3	5	10	41	9	5
5	Bio-Naphtha	-	-	-	-	-	-	12	16
4	Biodiesel	678	516	343	1,077	1,056	1,534	1,435	1,463
4	NERD (EV 1.5)	-	-	-	0	1	1	0	-
4	NERD (EV 1.6)	-	-	0	15	9	29	7	5
4	NERD (EV 1.7)	-	-	1	30	80	230	320	314
3	Ethanol	-	-	-	-	0	-	1	2
3	RCNG	-	-	-	-	-	-	15	68
3	RLNG	-	-	-	-	-	-	17	48
3	Renewable Gasoline	-	-	-	-	-	0	0	-
7	NERD (EV 1.7)	-	-	-	-	0	0	0	-
	Total Ethanol	9,839	11,136	13,314	13,803	13,590	13,557	14,108	14,325
	Total FAME Biodiesel	678	516	343	1,082	1,057	1,570	1,489	1,542
	Total N-E RD	-	-	9	62	103	417	488	524
	Total Biogas	-	-	-	1	3	26	53	116
	Total Other	-	-	-	-	-	0	12	16
	TOTAL	**10,517**	**11,652**	**13,665**	**14,948**	**14,753**	**15,571**	**16,149**	**16,523**

*2015A is the assumed 12 month production total of biofuels based on the 10 months (January - October 2015) data available.

Table 3. U.S. Renewable Fuel RINS Generated

RIN D-code	Fuel Type	RINS Generated (Million RINS)							
		2008	2009	2010	2011	2012	2013	2014	2015A*
6	Ethanol	9,309	10,938	13,298	13,609	12,987	13,099	14,017	14,236
6	Biodiesel	-	-	-	6	1	55	80	119
6	NERD (EV 1.7)	-	-	-	-	-	196	257	338
5	Ethanol	530	198	16	194	603	458	90	86
5	Biogas	-	-	-	1	3	26	20	-
5	NERD (EV 1.6)	-	-	8	19	3	0	0	-
5	NERD (EV 1.7)	-	-	4	8	17	70	15	9
5	Bio-Naphtha	-	-	-	-	-	-	18	25
4	Biodiesel	1,017	774	515	1,616	1,585	2,300	2,153	2,195
4	NERD (EV 1.5)	-	-	-	0	1	1	0	-
4	NERD (EV 1.6)	-	-	0	24	15	46	12	9
4	NERD (EV 1.7)	-	-	1	51	136	392	544	533
3	Ethanol	-	-	-	-	0	-	1	2
3	RCNG	-	-	-	-	-	-	15	68
3	RLNG	-	-	-	-	-	-	17	48
3	Renewable Gasoline	-	-	-	-	-	0	0	1
7	NERD (EV 1.7)	-	-	-	-	0	0	0	-
	TOTAL D6	9,309	10,938	13,298	13,615	12,988	13,350	14,354	14,694
	TOTAL D5	530	198	28	222	627	554	143	120
	TOTAL D4	1,017	774	516	1,692	1,737	2,739	2,710	2,737
	TOTAL D3/D7	-	-	-	-	0	1	34	119
	TOTAL	**10,856**	**11,910**	**13,842**	**15,529**	**15,352**	**16,645**	**17,241**	**17,669**

*2015A 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 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 4. 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 4. 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**	**0**

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 5. 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 2015.

Table 5. Corn Ethanol Production Capacity and Technology Aggregation

Plant Energy Source, Aggregated data[a,b]	2008	2009	2010	2011	2012	2013	2014	2015A*
				Capacity (MGY)				
Wet Mill, Coal	1,888	1,882	1,877	1,871	1,893	1,783	1,474	1,465
Wet Mill, NG	107	199	328	420	473	596	906	866
Dry Mill, Coal	54	45	36	28	19	17	15	14
Dry Mill, NG, DDGS	2,919	2,643	2,366	1,790	1,812	1,712	1,613	1,513
Dry Mill, NG, WDGS	1,442	1,310	1,178	945	913	908	903	897
Dry mill, corn oil DDGS	1,946	3,036	4,617	5,399	5,471	5,404	5,336	5,269
Dry mill, corn oil, WDGS	961	1,403	2,145	2,486	2,728	2,659	2,589	2,519
Dry Mill NG, WDGS CRF[c]	325	343	361	379	397	245	461	631
Dry Mill, NG, Biomass	195	276	406	486	488	692	901	1,234
Total Corn Ethanol	9,839	11,137	13,314	13,803	14,194	14,016	14,197	14,409

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

Table 6. Carbon Intensity of Corn Ethanol

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

[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 for modelled for the years 2008 through to 2015. The biodiesel feedstock production volumes are shown in Table **7**.

Table 7. Biodiesel Feedstocks Volumes from 2008 through 2015

	Volume (Million Gallon)							
Feedstock	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015A***
Total BD	678	516	343	1,077	1,056	1,534	1,435	1,463
Canola oil	59	45	30	93	91	133	124	127
Corn oil	72	54	36	114	111	162	151	154
Palm oil	16	13	8	26	26	37	35	36
Soybean oil	360	274	182	572	561	814	762	777
Tallow/Poultry	42	32	21	66	65	94	88	90
UCO	130	99	66	206	202	294	275	280

*2015A is the assumed 12 month production total of biofuels based on the 10 months (January - October 2015) data available.

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 were assumed to be landfill gas and wastewater treatment facility biogas.

Table 8 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.

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

Min. GHG			Carbon Intensity (g CO_2 e/MJ)							
Reduction	**Fuel Type**	**Threshold**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015A**
	Gasoline		96.71	96.75	96.79	96.83	96.87	96.88	96.89	96.89
	EPA Baseline	93.08	93.08	93.08	93.08	93.08	93.08	93.08	93.08	93.08
20%	Ethanol	74.46	67.31	65.69	63.88	62.88	61.99	60.15	58.36	57.59
20%	Biodiesel	74.46	71.78	71.78	71.55	71.55	71.55	71.49	71.50	71.17
20%	NERD (EV 1.7)	74.46	71.73	71.73	71.54	71.54	71.54	71.47	71.48	71.39
50%	Ethanol	46.54	41.89	41.90	42.11	42.11	42.10	42.24	42.25	38.61
50%	Biogas	46.54	25.56	25.56	24.42	24.42	24.42	23.73	23.79	23.25
50%	NERD (EV 1.6)	46.54	46.41	46.41	46.41	46.41	46.45	46.22	46.18	46.18
50%	NERD (EV 1.7)	46.54	46.41	46.41	46.41	46.41	46.45	46.22	46.18	45.94
50%	Bio-Naphtha	46.54	46.41	46.41	46.41	46.41	46.45	46.22	46.18	45.94
50%	Biodiesel	46.54	42.48	42.50	42.10	42.12	42.33	42.18	42.22	41.86
50%	NERD (EV 1.5)	46.54	46.41	46.41	46.41	46.41	46.45	46.22	46.18	46.18
50%	NERD (EV 1.6)	46.54	46.41	46.41	46.41	46.41	46.45	46.22	46.18	45.94
50%	NERD (EV 1.7)	46.54	46.41	46.41	46.41	46.41	46.45	46.22	46.18	45.94
60%	Ethanol	37.23	37.23	37.24	37.43	37.62	37.81	38.13	38.45	35.44
60%	RCNG	37.23	25.56	25.56	24.42	24.42	24.42	23.73	23.79	23.25
60%	RLNG	37.23	29.55	29.55	28.30	28.30	28.30	27.55	27.61	27.02
60%	Renewable Gasoline	37.23	27.99	27.99	27.05	27.05	27.05	26.52	26.57	26.10
60%	NERD (EV 1.7)	37.23	27.99	27.99	27.05	27.05	27.05	26.52	26.57	26.10

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 minimum CI threshold mandated in the RIA (EPA, 2009) and as shown in Table 8. The RFS2 has resulted in the cumulative CO_2 savings of 353 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 232 million metric tonnes of CO_2.

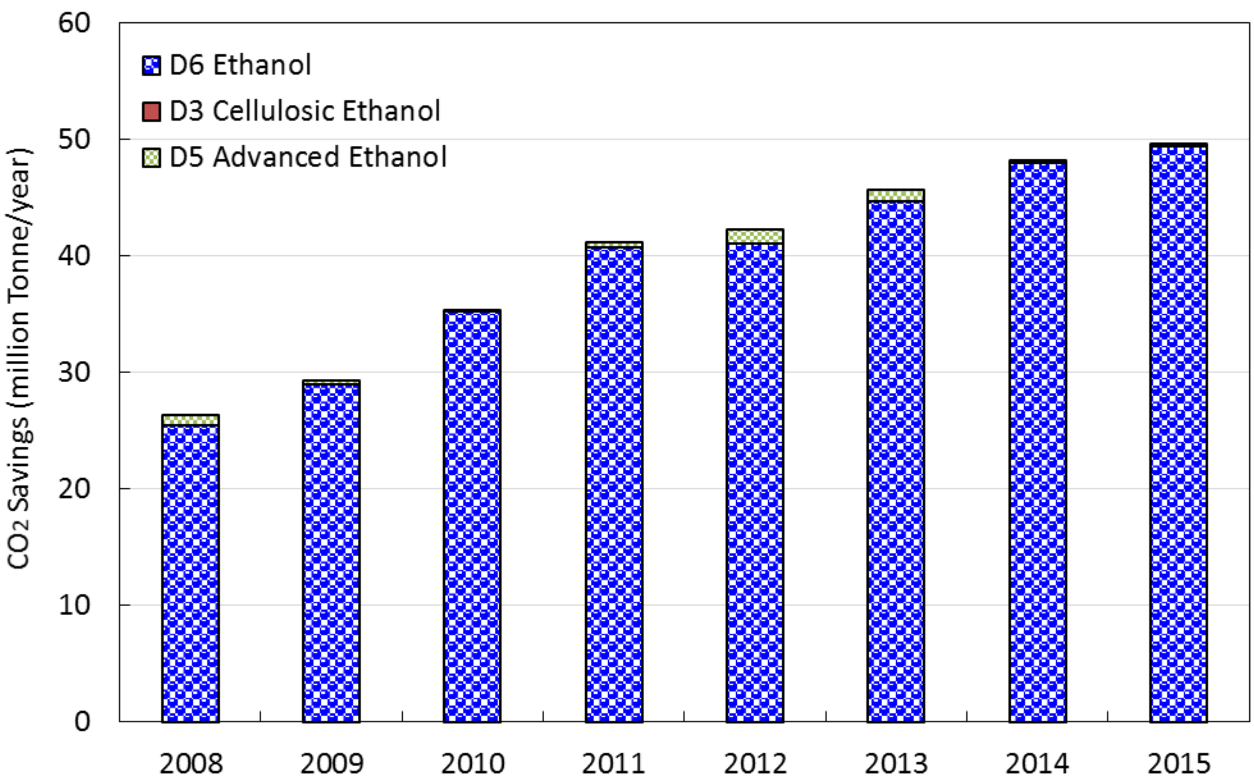

Figure 4. GHG Savings from Ethanol

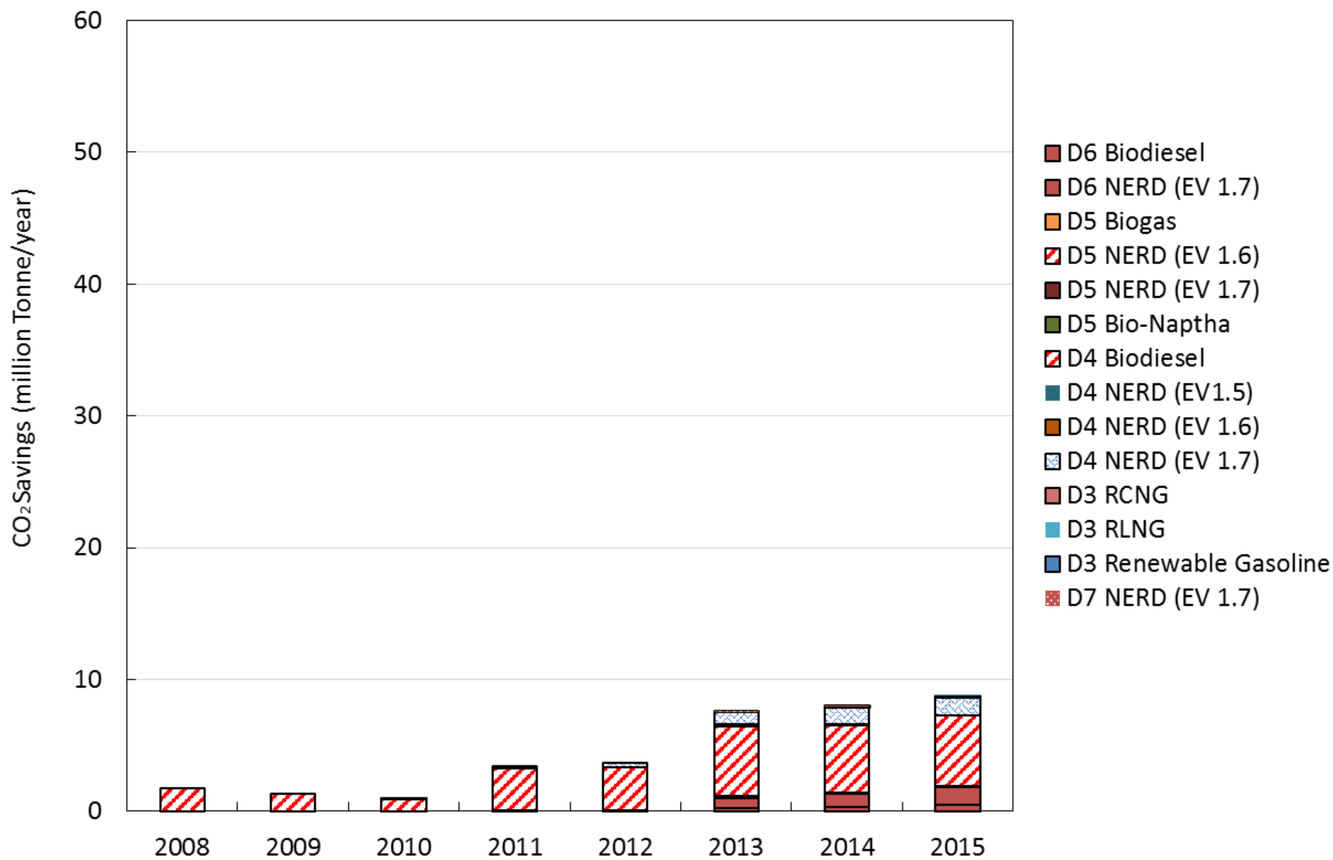

Figure 5. GHG Savings from Other RFS2 Biofuels (Excluding Ethanol).

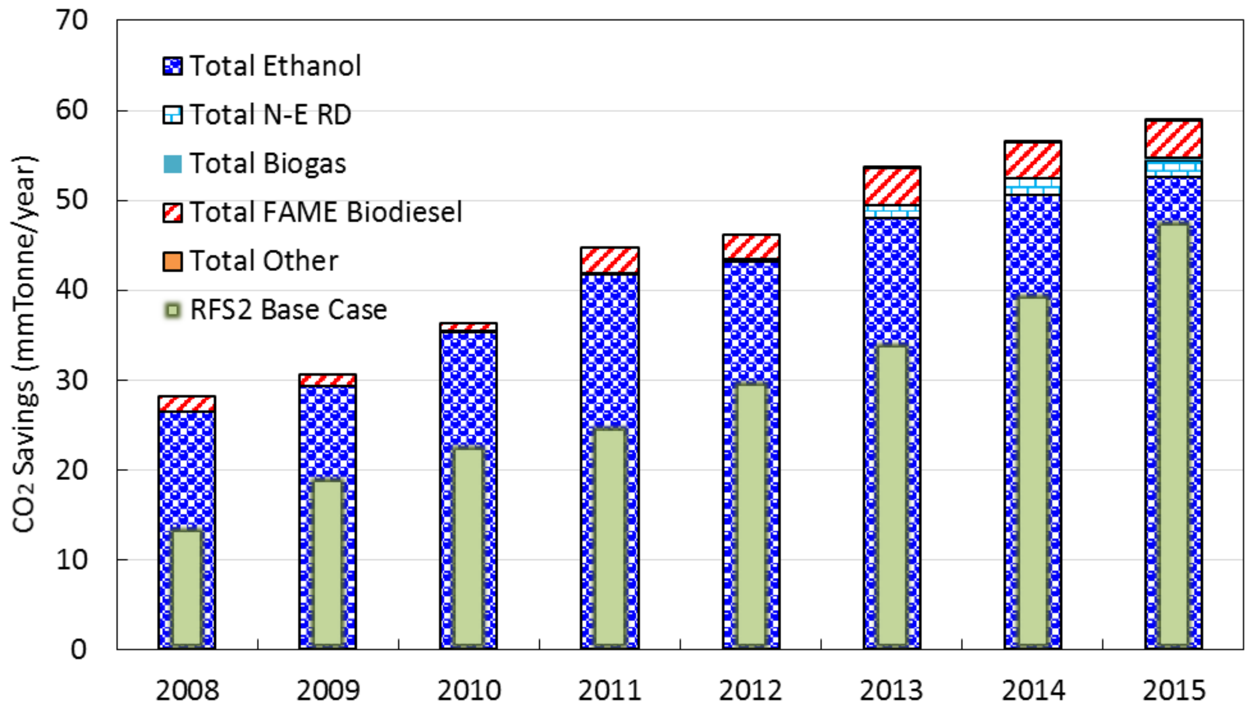

Figure 6. GHG Savings from the RFS2 Program

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:

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

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 greater than 20% reduction in GHG emissions.
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.

5. References

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