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TRANSPORTATION FUEL LIFE CYCLE ASSESSMENT: VALIDATION AND UNCERTAINTY OF WELL-TO-WHEEL GHG ESTIMATES

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Executive Summary

Within the last two decades there has been increasing development of, and reliance upon, Life Cycle Assessment (LCA) models to assess greenhouse gas emissions (GHG) and other emissions from vehicle and fuel pathways. These models are designed to quantify emissions from the different stages of vehicle and fuel production and use. Since the production of fuels and vehicles involves many possible feedstocks and processes, these models are quite complex; they rely on large and varied sets of input data and they contain assumptions that influence final results. LCA models were initially used to quantify, from a technical perspective, the emissions from new fuel pathways in comparison to the emissions of conventional fuel pathways such as gasoline or diesel. This use provides useful guidance for the research and engineering community involved in vehicles and fuels development. With the large increase in investments in new fuels development, initially for biofuels and potentially for electricity to power vehicles, it is important for researchers, vehicle and fuels producers, and government agencies to understand the environmental and GHG emissions impacts of the various vehicle and fuels options. LCA models can be of great assistance for this.

More recently, some governments have moved to regulate some aspects of the fuel supply and have incorporated LCA models into their regulations. Thus, in some cases LCA models are being used for applications that they were not originally intended for.

This work for the Coordinating Research Council (CRC) is intended to better quantify sources of uncertainty and variability in selected LCA models that are being used to regulate fuels by conducting an in-depth evaluation of model inputs, and the uncertainties around those inputs for several specific fuel pathways. Validation of the inputs and resulting outputs from the models is discussed and pathway variability and overall model uncertainty for the different pathways is assessed.

There are dozens of LCA models that have been used to analyze transportation fuels in the past decade. However, four models are being used in various regulatory schemes around the world and these four models are the focus of this work. The four models that are to be investigated are:

1. BioGrace, used in the European Union (EU) Renewable Energy Directive (RED) program.
2. The US Environmental Protection Agency (EPA) modelling framework for RFS2. The EPA used a series of models to determine the direct and indirect emissions of renewable fuels and petroleum fuels. Not all of the models are publicly available but there is a significant amount of information available on the model inputs for many of the pathways.
3. The GREET model and the variant of the model used in California for the California LCFS program.
4. GHGenius, used in the British Columbia LCFS program and the Alberta RFS program.

The latest versions of the models are evaluated and in the case of GREET, the changes between the CA_GREET version used by the California Air Resources Board (CARB) and the latest version are identified and the impacts discussed.

The CRC has proposed six pathways (and eight fuels) for analysis. They are:

- Petroleum gasoline/diesel
- Corn ethanol
- Soy biodiesel (BD)/renewable diesel (RD)
- Sugarcane ethanol
- Cellulosic ethanol
- Natural gas (NG)

Not all of the pathways are included in all of the models. The matrix of models and pathways is shown in the following table.

Table ES- 1 Model – Pathway Matrix

	BioGrace	EPA RFS2	GREET	GHGenius
Petroleum	No	Yes	Yes	Yes
Corn Ethanol	Yes	Yes	Yes	Yes
Sugar cane Ethanol	Yes	Yes	Yes	Yes
Cellulosic Ethanol	No	Yes	Yes	Yes
Soybean Biodiesel/RD	Yes (BD only)	Yes (RD only generally)	Yes	Yes
Natural Gas	No	No	Yes	Yes

BioGrace is partially based on the JEC Wells to Wheels studies, which do have petroleum and natural gas pathways. Discussion of these pathways from this study is included as a substitute for the lack of BioGrace petroleum pathways. BioGrace does have some renewable diesel pathways, but not one for soybean oil. We have added this pathway following the same approach used for the other vegetable oil renewable diesel pathways in the model. The EPA pathways all have a value for NG GHG emissions, as natural gas is an input to those pathways for process fuel, these values will be discussed.

A comparison of the primary model attributes is shown in the following table. There are differences in many of the parameters of the models and thus it should not be too surprising when they produce some different results. GREET and GHGenius are the closest in concept, but even with those two models there are some differences.

Table ES- 2 Model Summary

	BioGrace	EPA RFS2	GREET	GHGenius
Developed for Regulatory Use	Yes	Yes	No	No
IPCC GWP	2001 (2007)	1995	2007	User Choice
Type	Attributional	Consequential	Attributional	Attributional
Type	Process Chain	Partial Equilibrium	Process Chain	Process Chain
Heating Values	Lower	Lower	User Choice, LHV default	User Choice, HHV default
Geography	Europe	United States	United States	Canada/US/ Mexico/India
Co-product Allocation	Energy	Displacement	User Choice	User Choice
Data	Typical plus 40%	Expected Incremental	Average	Average
Year	Not stated, present	2022	User Choice (1990-2020)	User Choice (1995-2050)
Includes fuel combustion	No	Yes	Yes	Yes
Impact Categories	GHG	GHG, CAC	Energy, GHG, CAC	Energy, GHG, CAC, Cost Effectiveness

Petroleum Fuels

The gasoline results are compared in the following table. In the JEC V3c report (the more recent JEC V4 report values are the same), the crude oil extraction values have increased to 5.2 gCO_2eq/MJ and the IPCC GWP values from 2007 (and not 2001) were used. Version 3c was not used for this work because we used the version that was closest to the version used in the BioGrace model. The CA GREET model has the highest emissions.

Table ES- 3 Petroleum Fuels Summary - Gasoline

	BioGrace/JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	2007	2007	2007	2007
	g CO_2eq/MJ (LHV)				
Crude Oil Extraction	3.6	3.2	2.38	11.39	7.94
Crude Oil VFF	0.0	3.6	2.42	inc	2.45
Crude Oil Transport	0.9	1.36	2.97	inc	2.04
Refining	7.0	9.24	10.80	13.72	12.18
Refined Products Distribution	1.0	1.03	0.56	0.36	1.37
Sub-total	12.5	18.43	19.12	26.27	25.99
Vehicle Use	75.2	72.43	73.61	72.91	68.96
Total	87.7	90.98	92.73	99.18	94.95

The stage with the largest difference in results is the crude oil production stage. The two models with the most robust methodology, CA-GREET and GHGenius, have the highest emissions. The GREET1 2012_rev2 crude oil emissions from energy use are based on expert opinion assumptions, whereas the other three models are based on calculations using secondary data. The RFS2 venting, flaring and fugitive emissions (VFF) have high venting and fugitive emission but low flaring emissions since they assume greater than 99.9% methane destruction in the flares. The CA-GREET energy use in the crude oil stage is influenced by the significant contribution of thermally enhanced production in California. The JEC analysis either excludes venting flaring and fugitive emissions or has them at such a low rate they are reported as zero.

Crude oil transportation emissions should vary depending on the location of the refinery and the locations of the oil fields. Beyond that there are assumptions that need to be made concerning the size of the tankers and the energy use in the tankers and pipelines.

There are also large differences in the refining stage between the JEC model and the other models. Some of this may be due to the average vs. marginal approach used for the data, although it is unusual that the marginal emissions in the JEC modeling are lower than the average emissions found in other models. As the emissions from the refining stage are not reported in detail in the JEC report, it is not possible to determine the source of the differences compared to the other models.

The RFS2, GREET, and GHGenius models all rely on data on fuel consumption in refineries produced by the DOE Energy Information Administration. The models choose data for different years and can use different emission factors. The hydrogen consumed in the refineries can be produced inside the refinery gate or purchased. It is only in the past couple of years that the EIA has been reporting hydrogen purchased and natural gas purchased for hydrogen production. NETL calculated hydrogen production emissions separately from other energy related emissions; they extrapolated hydrogen purchases from some 2003 data.

Natural Gas

The emissions for natural gas used as an industrial fuel from all four models are shown in the following table. The RFS2 values are based on an earlier version of GREET and had relatively low methane losses. BioGrace and the RFS2 data are similar and both have relatively low methane loss rates. GREET1 2012_rev2 and GHGenius results are also similar and have similar, but higher methane loss rates.

Table ES- 4 Natural Gas Summary

	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA GREET	
GWP	2001	1995	2007	2007	2007
	g CO_2eq /MJ (LHV)				
NG Production	3.8	4.9	11.0	3.5	9.6
NG Processing	-	-	3.6	3.7	2.9
NG Transportation	7.5	-	4.4	0.97	7.5
NG Use	56.4	55.6	57.6	57.7	57.0
Lifecycle	67.7	60.5	76.6	62.4	77.0

Corn Ethanol

The following table summarizes the GHG emissions for the production of corn ethanol from the five models. The default values used for process energy for the fuel production stages in each of the fuel chains analyzed in the RED (and thus in BioGrace) are 40% higher[1] than the typical values. The BioGrace values shown in the following table are based on the use of

[1] This additional energy is applied to ensure that the model produces conservative results. In actual practice plants can use their actual values.

actual values and do not include the 40% gross up of processing energy that is included in the model.

Table ES- 5 Corn Ethanol Summary[2]

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement			
	g CO_2eq/MJ (LHV)				
Feedstock Production	36.78	15.63	33.50	35.85	37.22
Feedstock Transport	0.51	2.83	2.21	2.22	1.62
Ethanol Production	61.43	30.7	33.74	38.30	38.26
Co-product (power)	-33.38	-	-	0.00	0.00
Co-product (DDG)	-29.66	-	-14.52	-11.51	-18.87
Ethanol Distribution	1.54	1.18	1.52	2.70	1.61
Sub total	37.22	50.38	56.44	67.56	59.84
Fuel Use	-	0.83	-	0.80	2.22
Total	37.22	51.21	56.44	68.36	62.16

There is a fair range in the results and it is not possible to directly compare all of the stages as the RFS2 model has no way to break out the co-product credit. It reports feedstock emissions net of co-product credits. The GREET1_2012 model has significantly lower emissions than the CA-GREET model. Most of this is due to more recent data being used in the model, with a small contribution from the different assumptions made concerning the displacement impacts of DDG.

There are three primary components to the GHG emissions in the feedstock production stage, the fuel used, the fertilizer and chemicals applied and the N_2O emissions from the decomposition of the nitrogen fertilizer and crop residue. The models have larger variations in these three categories than they do in the total feedstock emissions.

The BioGrace model considers a very different process configuration than the other models. It is a full steam plant (including the DG dryers) and has a full co-gen plant. Significant amounts of power are exported and credited with the emissions from a natural gas combined cycle plant (124 g CO_2eq/MJ). There are also issues with double crediting some of the DDG emissions in the BioGrace/RED methodology.

Sugarcane Ethanol

The results for sugarcane ethanol from the five models are shown in the following table. Some of the models had multiple pathway options, the basic pathway is shown here. The results range from 24 to 44 g CO_2eq/MJ. There is a large variation in the results for almost all of the stages of the lifecycle.

[2] Indirect land use change estimates are not included in these results.

Table ES- 6 Sugarcane Ethanol Summary

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy		Displacement		
	g CO_2eq/MJ (LHV)				
Feedstock Production	14.11	37.26	22.30	19.0	28.93
Feedstock Transport	0.84	1.69	2.31	2.0	2.31
Ethanol Production	0.85	2.27	2.76	2.1	5.81
Co-product (power)	0.0	-13.29	-1.63	0.0	-4.26
Ethanol Distribution	8.16	2.71	9.09	3.5	11.04
Total	23.97	32.03	34.83	26.6	43.83

The EPA RFS2 modelling produces the highest emissions for the feedstock production stage, but they have the lowest rate of burning and thus the highest quantity of residues left in the field. BioGrace has the lowest field emissions but it is not transparent how the N_2O emissions were calculated and it may be that there is no N_2O from the field burning of the crop residues. The components of sugarcane production in the different models are compared in the following table.

Table ES- 7 Sugarcane Ethanol Feedstock Summary

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation		Displacement			
	g CO_2eq/MJ (LHV)				
Diesel Fuel	1.29	4.88	4.79	1.8	4.49
Fertilizer	3.80	2.94	5.58	5.7	4.90
N_2O emissions	5.49	27.74	11.92	3.5	11.26
Other	3.53	1.70	-	8.0	8.28
Total	14.11	37.26	22.30	19.0	28.93

The ethanol plant emissions range from less than 1 to almost 6 g CO_2eq/MJ. BioGrace excludes the methane and N_2O emissions from the bagasse (fibre remaining after sugarcane juice is extracted) combustion. The RFS2 and GREET have no chemical related emissions for the production process and only GHGenius also includes some non-combustion process emissions.

BioGrace and the CARB base case do not consider any power exports. The EPA and GREET use different kinds of power to displace (average vs. marginal production). GHGenius uses a similar assumption about the type of displaced power but uses a current estimate of quantity vs. a forecast of the quantity in 2022.

Cellulosic Ethanol

There is a very wide range in the emissions for this pathway. That is perhaps not too surprising given that there are no commercial operations and thus the data quality for this pathway is quite low. Nevertheless there are also some fundamental differences to what is included (or not included) in the models. The results are compared in the following table.

Table ES- 8 Cellulosic Ethanol Summary

	RFS2	GREET		GHGenius
		2012_rev2	CA-GREET	
IPCC GWP	1995	2007	2007	2007
Feedstock	Stover	Stover	Wood	Stover
	g CO_2eq/MJ (LHV)			
Feedstock Production	0.34	10.32	4.44	10.52
Feedstock Transport	1.11	1.05	2.10	2.48
Ethanol Production	2.66	8.19	2.56	33.14
Co-Product (Power)	-33.60	-17.11	-10.2	-15.84
Ethanol Distribution and storage	1.18	1.52	2.70	2.25
Total	-28.31	3.97	1.60	32.55

The EPA RFS2 modelling is the simplest; it does not include any inputs into the system other than the biomass. It has the most optimistic estimates of yield and power available for sale to the grid. This modelling also has a one-time increase in soil carbon at the beginning of the time period and some changes in the domestic livestock sector resulting in increased emissions.

The GREET1_2012 model includes the emissions associated with enzymes and yeast but none of the other chemicals that are included in most cellulosic ethanol processes. The CA GREET model includes no process chemicals. It does include the emissions from the combustion of the biomass and a small amount of diesel fuel.

GHGenius has the most complete accounting of process chemicals and the highest emissions. The process information that is included as the defaults has a large quantity of chemicals including potentially emission intensive chemicals like sodium hydroxide. These chemicals account for most of the emissions difference between GREET and GHGenius.

Soybean Biodiesel

The soybean biodiesel results are summarized in the following table. The combustion emissions are not shown in the table, nor are emissions from indirect land use change.

Table ES- 9 Soybean Biodiesel Summary

	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement	Displacement	Mass/energy	Displacement
	g CO_2eq/MJ (LHV)				
Feedstock Production	56.21	-16.78	20.76	5.42	61.65
Feedstock Transport	35.95	2.52	2.96	0.50	2.20
Oilseed Crushing	17.24	-	22.74	20.53	19.21
Biodiesel Production	12.50	17.83	7.48	5.47	14.80
Co-products meal	-72.89	-	-22.40	-15.33	-46.53
Co-products glycerine	-0.58	-5.35	-34.75	-0.27	-17.69
Biodiesel Distribution	1.26	0.76	0.71	0.75	1.15
Total	49.69	-1.03	-2.52	17.06	34.80

There is a very wide range in the results. The soybean transportation scenario selected impacts the BioGrace results. Soybeans are not a significant crop in Europe so the pathway was built using soybeans imported from Brazil and this adds significant emissions that are only partially offset by the soybean meal credit. GREET has very low emissions for soybean production, the primary driver being very low N_2O emissions compared to BioGrace and GHGenius.

The emission credit for glycerine varies widely as well. The energy allocation provides a small credit, as does the displacement of energy. Glycerine production by the Farben process is very energy and emission intensive, so if the biodiesel glycerine displaces Farben produced product there is a much larger co-product credit, as is the case for GREET1 2012_rev2, as well as GHGenius.

There is also a variation between the models on how the fossil carbon in the methanol is treated. The biodiesel production process sees methanol being added to the oil and biodiesel and glycerine being produced. The fossil carbon in the methanol ends up in the biodiesel and an equivalent amount of biogenic carbon from the oil ends up in the glycerine. In BioGrace the oxidation of the fossil carbon from methanol is included in the biodiesel production emissions, in CA GREET, the oxidation of the carbon is added to the vehicle emissions. In GHGenius it is assumed that the glycerine from the process displaced fossil glycerine and only the difference in the emissions is needed to be included.

Variability

The analysis of the variability of the six pathways has demonstrated how complex some of the systems are and how there can be real differences in the same system in different locations and how some aspects of the systems change over time.

All of the systems demonstrate spatial variability, particularly in the feedstock production stage of the lifecycle. In some cases this is due to factors out of the control of operators (climate, soil conditions, etc.) but in other cases there are opportunities to reduce the emissions from some regions, flaring of associated gas in oil production, for example.

Many of the systems have temporal variability. In some cases this leads to increasing emissions, increasing energy use in crude oil production, and in other cases the emissions tend to decrease with time as a result of better fertilizer utilization for example.

No two production facilities are identical and design differences that accommodate local conditions will lead to variability between two similar production facilities.

The different models also contribute to the variability in the results as they use data from different time periods, from different regions, and they have some different methodological approaches to co-products and system boundaries.

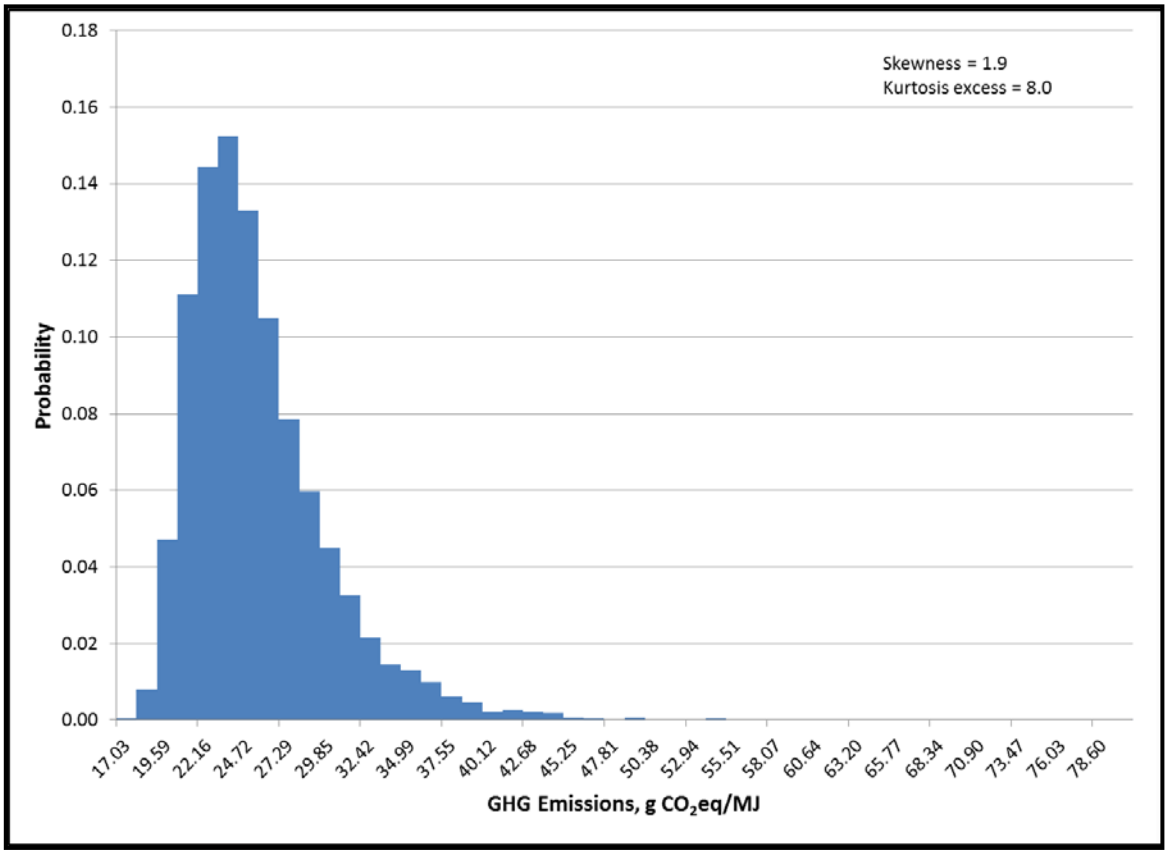
Uncertainty

Uncertainty is different from variability. Uncertainty results from a lack of knowledge about the parameters that characterize the physical system that is being modeled, and can arise from inaccurate measurements, and/or a lack of appropriate data. Sometimes the uncertainty can be reduced through access to better information but in other cases it may not be feasible to collect the quality of data that is required. Uncertainty can also result from natural randomness, for example the N_2O emissions from a field can vary from one year to the next due to different precipitation patterns.

Uncertainty analysis provides quantitative information of the dispersion of values (the shape of the distribution curve) and qualitative information on the uncertain parameters. It does not change the mean values from the analysis.

There is uncertainty in all of the pathways studied. The results found here for the pathways that have been studied by others are quite similar in terms of the shape of the distribution of the results and the range of the results. Some of the other analyses found in the literature undertook simulations with many more model parameters rather than just the major ones that impact the major sources of emissions and uncertainties; this added complexity does not appear to significantly reduce the level of uncertainty. The following figure is typical of the uncertainty analysis results.

Figure ES- 1 Gasoline Monte Carlo Results – Well to Tank



The quantitative results that are produced from Monte Carlo analysis and are typically reported include the mean, standard deviation, and the 90% confidence range. The mean value is a function of the other modelling parameters and is subject to variability but a comparison of the standard deviation and the range of the results is informative. These results are shown in the following table.

Table ES- 10 Range and Standard Deviations from Monte Carlo Results[3]

Pathway	Mean	Std Deviation	5% Value	95% Value	90% Range
	g CO_2eq/MJ				
Gasoline	26.0	4.6	19.6	33.7	14.1
CNG	26.1	3.0	21.3	30.8	9.5
Corn Ethanol	59.8	4.9	51.6	67.7	16.1
Sugarcane Ethanol	46.9	4.9	36.8	51.6	14.8
Cellulosic Ethanol	32.5	5.5	22.6	40.5	17.9
Soybean Biodiesel	34.8	3.1	29.1	39.4	10.3

These results exclude the combustion emissions. There is much less uncertainty with respect to the combustion emissions compared to the production emissions. The standard deviations and the 90% ranges are relatively close for all of the six pathways modelled.

[3] Excludes vehicle emissions.

This work has analyzed four LCA models and six fuel pathways. For each pathway significant variation was identified between models. Some of this variability is due to the modelling approaches used including system boundaries, allocation approaches and the use of different global warming potentials. Other sources of variability include regional variations, temporal variability, and process variability.

One of the models (BioGrace) assesses generally European fuels, whereas the other models consider the fuels in a US context and this introduces regional variances in the results. The models also consider different time periods, with the EPA RFS2 modelling framework looking at renewable fuels in 2022 and petroleum fuels in 2005. BioGrace is generally silent on the issue of time and GREET and GHGenius can be run for different time periods. It is shown that many of the important modelling parameters do change with time. There is also some variation between models in terms of the exact process model or the quantity of co-products produced.

Users of these models would be well served to be more explicit in terms of the spatial, temporal, and process variations that have been considered when model results are presented. Sensitivity analyses on these variables should be considered and understood if the models are being used for policy development or regulation.

LCA modelling also involves uncertainty. Most systems today cannot be modelled using just data collected for the specific system being analyzed. These analyses require the use of secondary data, information that has been collected or aggregated from sources other than the one being analyzed. The use of this secondary data introduces some uncertainty into the results. The six fuel production systems considered here have relatively similar levels of uncertainty. Better quality sources of data are being produced all of the time, and consistent with the ISO principles of lifecycle assessment, these need to be incorporated into the models as they become available.

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AEO – Annual Energy Outlook
BAU – Business as Usual
BBL – Barrel, unit of measurement.
CAC – Criteria Air Containments
CARB – California Air Resources Board
CARBOB – California Reformulated Gasoline Blendstock for Oxygenate Blending
CARD – The Centre for Agricultural and Rural Development
CF – Carbon Footprint
CFP – Carbon Footprint of Products
CHP – Combined Heat and Power
CNFAP – Center for National Food and Agricultural Policy
CNG – Compressed Natural Gas
COD – Chemical Oxygen Demand
CONCAWE – Conservation of Clean Air and Water in Europe. The organization representing crude oil refiners in the EU, focusing on environment, health and safety issues.
CPPI – Canadian Petroleum Products Institute
CRC – Coordinating Research Council
CSS – Cyclic Steam Simulation
DDG – Dried Distillers' Grains
DDGS – Dried Distillers' Grains with Solubles
DME - Dimethyl Ether
DOE – Department of Energy
EIA – Energy Information Agency
EII – Solomon Energy Intensity
EISA – The Energy Independence and Security
EPA – Environmental Protection Agency
EU – European Union
EUCAR – European Council for Automotive R&D
FAO – Food and Agriculture Organization
FAPRI – The Food and Agricultural Policy Research Institute
FASOM – The Forest and Agricultural Sector Optimization Model
GaBi – a lifecycle assessment model
GEMIS – Global Emissions Model for Integrated
GHG – Greenhouse Gas
GREET – Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
GTAP – Global Trade Analysis Project
GWP – Global Warming Potential
HDO - Hydrodeoxygenation
HRD - Hydrotreated Renewable Diesel
HRJ - Hydrotreated Renewable Jet Fuel
ICCT – International Council for Clean Transportation
IFA – International Fertilizer Association
IFEU – Institute for Energy and Environmental Research
ILUC – Indirect Land Use Change
IPCC – Intergovernmental Panel on Climate Change
IPFRI – International Food Policy Research Institute
ISO – International Standards Organization

JEC – Jacobs Engineering Group
JRC – European Commission's Joint Research Centre
LBST - Ludwig Bölkow Systemtechnik
LCA – Life Cycle Assessment
LCFS – Low-Carbon Fuel Standard
LCI – Life Cycle Impact/Inventory
LCIA – Life Cycle Impact Assessment
LEM – Lifecycle Emissions Model
LFG - Landfill Gas
LHV – Lower Heating Value
LNG – Liquefied Natural Gas
LPG – Liquefied Petroleum Gas
LUC – Land Use Change
MOVES – an EPA LCA model
NBB – National Biodiesel Board
NETL – National Energy Technology Laboratory
NG – Natural Gas
NRCan – Natural Resources Canada
OGP – International Oil and Gas Producers Association
OPGEE – Oil Production Greenhouse Gas Emissions Estimator
PADD – Petroleum Administration for Defense Districts
RD – Renewable Diesel
RED – Renewable Energy Directive
RDF - Refuse-Derived Fuel
RFG – Reformulated Gasoline
RFS – Renewable Fuel Standard
RFS2 – Renewable Fuel Standard 2
SAGD – Steam Assisted Gravity Drainage
SCO - Synthetic Crude Oil
SMR – Steam Methane Reforming
SOR – Steam to Oil Ratio
UAN - Urea and Ammonium Nitrate Solution
ULSD – Ultra Low Sulphur
UOP – Honeywell UOP
US DOT – United States Department of Transportation
USDA – United States Department of Agriculture
VOC – Volatile Organic Compound
WDGS – Wet Distillers' Grains with Solubles
WTT – Well to Tank
WTW – Well to Wheels

DEFINITIONS

Bagasse: fibrous matter that remains after sugarcane stalks are crushed to extract their juice.
Filtercake: Sugarcane filtercake is the residue of the filtration of sugarcane juice. Commonly used as fertilizer.
Gas Plant Fuel: Natural gas used as fuel in natural gas processing plants.
Lease fuel: Natural gas used in well, field, and lease operations, such as gas used in drilling operations, heaters, dehydrators, and field compressors.
Primary data: information obtained from a direct measurement or a calculation based on direct measurements at its original source.
Secondary data: data obtained from sources other than a direct measurement or a calculation based on direct measurements at the original source within the product system.
Stover: the leaves and stalks of plants that are left in a field after harvest.
Vinasse: the material remaining after the ethanol is distilled from fermented sugarcane juice.

1. INTRODUCTION

Within the last two decades there has been increasing development of, and reliance upon, Life Cycle Assessment (LCA) models to assess greenhouse gas emissions (GHG) and other emissions from vehicle and fuel pathways. These models are designed to quantify emissions from the different stages of vehicle and fuel production and use. Since the production of fuels and vehicles involves many possible feedstocks and processes, these models are quite complex; they rely on large and varied sets of input data and they contain assumptions that influence final results. LCA models were initially used to quantify, from a technical perspective, the emissions from new fuel pathways in comparison to the emissions of conventional fuel pathways such as gasoline or diesel. This use provides useful guidance for the research and engineering community involved in vehicles and fuels development. With the large increase in investments in new fuels development, initially for biofuels and potentially for electricity to power vehicles, it is important for researchers, vehicle and fuels producers, and government agencies to understand the environmental and GHG emissions impacts of the various vehicle and fuels options. LCA models can be of great assistance for this.

More recently some governments have moved to regulate some aspects of the fuel supply and have incorporated LCA models into their regulations. Thus in some cases LCA models are being used for applications that they were not originally intended for.

1.1 OBJECTIVES

This work for the Coordinating Research Council (CRC) is intended to better quantify sources of uncertainty and variability in selected LCA models that are being used to regulate fuels by conducting an in-depth evaluation of model inputs, and the uncertainties around those inputs for several specific fuel pathways. Validation of the inputs and resulting outputs from the models is discussed, pathway variability and overall model uncertainty for the different pathways is assessed.

1.2 MODELS

There are dozens of LCA models that have been used to analyze transportation fuels in the past decade. However, four models are being used in various regulatory schemes around the world and these four models are the focus of this work. The four models that are to be investigated are:

1. BioGrace, used in the European Union (EU) Renewable Energy Directive (RED) program.
2. The US Environmental Protection Agency (EPA) modelling framework for RFS2. The EPA used a series of models to determine the direct and indirect emissions of renewable fuels and petroleum fuels. Not all of the models are publicly available but there is a significant amount of information available on the model inputs for many of the pathways.
3. The GREET model and the variant of the model used in California for the California LCFS program.
4. GHGenius, used in the British Columbia LCFS program and the Alberta RFS program.

The latest versions of the models are evaluated and in the case of GREET, the changes between the CA_GREET version used by the California Air Resources Board (CARB) and the latest version are identified and the impacts discussed.

1.3 PATHWAYS

The CRC has proposed six pathways (and eight fuels) for analysis. They are:

- Petroleum gasoline/diesel
- Corn ethanol
- Soy biodiesel/renewable diesel
- Sugarcane ethanol
- Cellulosic ethanol
- Natural gas

Not all of the pathways are included in all of the models. The matrix of models and pathways is shown in the following table.

Table 1-1 Model – Pathway Matrix

	BioGrace	EPA RFS2	GREET	GHGenius
Petroleum	No	Yes	Yes	Yes
Corn Ethanol	Yes	Yes	Yes	Yes
Sugar cane Ethanol	Yes	Yes	Yes	Yes
Cellulosic Ethanol	No	Yes	Yes	Yes
Soybean Biodiesel/RD	Yes (BD only)	Yes (RD only generally)	Yes	Yes
Natural Gas	No	No	Yes	Yes

BioGrace is partially based on the JEC Wells to Wheels study, which does have petroleum and natural gas pathways. Discussion of these pathways from this study is included. BioGrace does have some renewable diesel pathways, but not one for soybean oil. We have added this pathway following the same approach used for the other vegetable oil renewable diesel pathways in the model.

The EPA pathways all have a value for NG GHG emissions, these values will be discussed.

1.4 LIFECYCLE ASSESSMENT

The concept of life cycle assessment (LCA) emerged in the late 1980's from competition among manufacturers attempting to persuade users about the superiority of one product choice over another. As more comparative studies were released with conflicting claims, it became evident that different approaches were being taken related to the key elements in the LCA analysis:

- Boundary conditions (the "reach" or "extent" of the product system);
- Data sources (actual vs. modeled); and
- Definition of the functional unit.

1.4.1 ISO 14040

In order to address these issues and to standardize LCA methodologies and streamline the international marketplace, the International Standards Organization (ISO) has developed a series of international LCA standards, specifications, and technical reports under its ISO 14000 Environmental Management series. In 1997-2000, ISO developed a set of four standards that established the principles and framework for LCA (ISO 14040:1997) and the requirements for the different phases of LCA (ISO 14041-14043). The main contribution of these ISO standards was the establishment of the LCA framework that involves the four phases in an iterative process:

- Phase 1 - Goal and Scope Definition;
- Phase 2 - Inventory Analysis;
- Phase 3 - Impact Assessment; and
- Phase 4 - Interpretation

By 2006, these LCA standards were consolidated and replaced by two current standards: one for LCA principles (ISO 14040:2006); and one for LCA requirements and guidelines (ISO 14044:2006). Additionally, ISO has published guidance documents and technical reports (ISO 14047-14049) to help illustrate good practice in applying LCA concepts.

The ISO 14040:2006 standard describes the principles and framework for life cycle assessment including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements. ISO 14040:2006 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies. It does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA. The intended application of LCA or LCI results is considered during definition of the goal and scope, but the application itself is outside the scope of this International Standard.

1.4.2 ISO Principles

It is useful to consider seven basic principles in the design and development of life cycle assessments as a measure of environmental performance. The seven principles outlined below are the basis of ISO Standard 14040:2006:

- Life cycle Perspective (the entire stages of a product or service);
- Environmental Focus (addresses environmental aspects);
- Relative Approach and Functional Unit (analysis is relative to a functional unit);
- Iterative Approach (phased approach with continuous improvement)
- Transparency (clarity is key to properly interpret results)
- Comprehensiveness (considers all attributes and aspects)
- Priority of Scientific Approach (preference for scientific-based decisions)

1.4.3 ISO 14067 Carbon Footprint

This ISO work plan was under development at the committee stage but a Draft International Standard failed two ballots. It has now been issued as a technical specification, rather than a standard. This focuses on the unique requirements of doing an LCA with a specific focus of GHG emissions.

ISO 14067 details the principles and framework requirements for the quantification of the carbon footprint of products (CFP) (including both goods and services). It includes requirements for determining the boundaries for the assessment of GHG emissions, removals and storage over the life cycle of a product. Requirements for partial carbon footprint (partial CF) assessment are also provided.

ISO 14067 is expected to benefit organizations, governments, project proponents and other affected parties worldwide by providing clarity and consistency for quantifying, reporting and verifying the CFP. Specifically, the use of ISO 14067 could:

- enhance the credibility, consistency and transparency of the quantification and communication of product-level carbon footprinting;
- promote continuous improvement by facilitating the evaluation of alternative product design and sourcing options, production and manufacturing methods, raw material choices and the selection of suppliers on the basis of a life cycle assessment using climate change as the impact category;
- facilitate the development and implementation of GHG management strategies and plans across product life cycles as well as the detection of additional efficiencies along the supply chain;
- facilitate the ability to track performance and progress in reducing GHG emissions;
- encourage changes in consumer behaviour in contributing to reductions in GHG emissions due to consumption; and
- through public reporting, facilitate product selection by customers, including consumers, on the basis of a life cycle assessment using climate change as the impact category.

1.4.4 Data Quality

ISO 14067 has some defined terms with respect to data and data quality. Understanding these will have some benefit when the data in the models are considered.

Primary data: quantified value of a unit process or an activity obtained from a direct measurement or a calculation based on direct measurements at its original source.

- Primary data need not necessarily originate from the product system under study because primary data may relate to a different but comparable product system to that being studied.
- Primary data may include GHG emission factors and/or GHG activity data

Site-specific data: data obtained from a direct measurement or a calculation based on direct measurement at its original source within the product system

- All site-specific data are “primary data” but not all primary data are site-specific data because they may also relate to a different product system

Secondary data: data obtained from sources other than a direct measurement or a calculation based on direct measurements at the original source within the product system

- Such sources can include databases and published literature validated by competent authorities.

Uncertainty: parameter associated with the result of quantification, which characterizes the dispersion of the values that could be reasonably attributed to the quantified amount

- Uncertainty information typically specifies quantitative estimates of the likely dispersion of values and a qualitative description of the likely causes of the dispersion.

A carbon footprint that is undertaken in compliance with ISO 14067 will require that the entity that is undertaking the study shall use primary data for those operations that are under their direct financial or operational control. For other data requirements secondary data can be used.

Some of the models have used data that does not meet the requirements of either primary or secondary data. This unpublished data is often referenced as personal communications. Ideally over time the models can be updated so that all of the data used in the models is either primary or secondary data.

1.4.5 LCA Models

There are no ISO standards or guidelines for LCA models. The models are generally designed to facilitate the organization and use of large sets of data. ISO compliant LCA studies can be undertaken with LCA models but it is up to the LCA practitioner to ensure that the ISO guidelines with respect to goals, scope, inventory analysis, impact assessment, and data quality, and that the ISO principles are honoured.

LCA models can give different results even when all ISO guidelines are followed for a number of reasons including:

- The processes employed to produce the fuel (or other product) are different.
- The activities are carried out in different regions.
- The quality of data in the models can vary due to regional issues.
- The models use different approaches to allocation (the ISO guidelines suggest a number of different options.
- The ISO guidelines are not prescriptive in a number of areas allowing some latitude for modellers as long as they state what is being done.

1.4.6 Co-Products

Many real world systems produce more than one product and an important issue for LCA practitioners is to determine what portion of the emissions should be assigned to which product. ISO 14044:2006 (dealing with requirements and guidelines) reports the following:

<u>Allocation General (4.3.4.1)</u>

> *The inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure.*
>
> *The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation.*
>
> *Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.*

The ISO document provides further advice on how to do this with a suggested priority. The document states:

<u>Allocation Procedure (4.3.4.2)</u>

> *The study shall identify the processes shared with other product systems and deal with them according to the stepwise procedure presented below.*

a) *Step 1: Wherever possible, allocation should be avoided by*
   1) *dividing the unit process to be allocated into two or more sub-processes and collecting the Input and output data related to these sub-processes, or*
   2) *expanding the product system to include the additional functions related to the co-products, taking into account the requirements of 4.2.3.3.*

b) *Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationship between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.*

c) *Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationship between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products.*

Some outputs may be partly co-products and partly waste. In such cases, it is necessary to identify the ratio between co-products and waste since the inputs and outputs shall be allocated to the co-products part only.

Allocation procedures shall be uniformly applied to similar inputs and outputs of the system under consideration. For example, if allocation is made to usable products (e.g. intermediate or discarded products leaving the system), then the allocation procedure shall be similar to the allocation procedure used for such products entering the system.

The inventory is based on material balances between input and output. Allocation procedures should therefore approximate as much as possible such fundamental input/output relationships and characteristics.

Not all LCA practitioners agree with the ISO guidelines. Wang et al (2011) report:

> *Although the International Standard Organization's ISO 14040 advocates the system boundary expansion method (also known as the "displacement method" or the "substitution method") for life-cycle analyses, application of the method has been limited because of the difficulty in identifying and quantifying potential products to be displaced by biofuel co-products. As a result, some LCA studies and policy-making processes have considered alternative methods. In this paper, we examine the available methods to deal with biofuel co-products, explore the strengths and weaknesses of each method, and present biofuel LCA results with different co-product methods within the U.S. context.*

Wang et al. outline five potential methods to address multiple products from biofuel production:

1. Mass-based allocation
2. Energy-content-based allocation
3. Market-value-based allocation
4. Process-purpose-based allocation

5. Displacement (aka “substitution” or “system expansion”)

Wang et al. argue that the use of the displacement method for dealing with co-products can pose some major challenges, which is particularly true when non-fuel products are a large share of the total output and the displacement method can generate “distorted fuel-based results.” They cite soy biodiesel as an example fuel pathway that falls into this category, as 82% of the mass from the soybean crushing process is soybean meal and only 18% is soy oil.

Wang et al. go on to say that although the displacement method is generally accepted, this method should not be applied without examining the individual situation. If non-fuel products are the main product and fuel is the co-product, the displacement method may not be appropriate and other allocation methods may need to be used. They do note, however, that selection on a case-by-case basis could at times be arbitrary.

2. MODELLING APPROACHES

The four modelling systems that are studied for this project are briefly described in this section. The model background, the original intended use of the modelling system, their approach to data inputs, their allocation approaches, and their boundary conditions are stated and compared in a summary.

2.1 BIOGRACE

The BioGrace model (www.biograce.net) was the result of an EU funded project to harmonize the calculations of biofuel greenhouse gas (GHG) emissions and thus support the implementation of the EU Renewable Energy Directive (2009/28/EC) and the EU Fuel Quality Directive (2009/30/EC) into national laws.

In 2009, the European Union set sustainability criteria for biofuels with the legislation of the Renewable Energy Directive and the Fuel Quality Directive. GHG emission savings from biofuels must be at least 35% compared to fossil fuels; this figure rises to at least 50% by 2017, and 60% by 2018 for biofuels produced in new installations[4].

The directives gave default values for GHG emission savings of 22 biofuel production pathways (Annex V of the Renewable Energy Directive or Annex IV of the Fuel Quality Directive). For economic operators who want or need to do the calculations themselves a formula is given; the formula states that total GHG emissions are the sum of emissions from cultivation, processing and transportation of the biofuels. Yet the directives do not specify either the “standard conversion values” or the "input numbers" that were used to obtain the default values.

The aim of the BioGrace project was to retrace and publish how the default values were calculated and elaborate a uniform and transparent list of standard conversion values for GHG calculations. BioGrace version 4b – Public has been used for this work. It can be downloaded here, http://biograce.net/app/webroot/files/file/BioGrace_GHG_calculations_-_version_4b_-_Public.zip. A final report on the project and a list of standard values is also available (BioGrace, 2012, 2012b).

BioGrace is the simplest of the four models studied. It is a Process Chain LCA model with 22 biofuel pathways (eight ethanol pathways, six biodiesel pathways, four hydrotreated vegetable oil pathways, one pure vegetable oil pathway, and three compressed biogas pathways). The only output is the GHG emissions for the pathways. The model allows the use of either the 2001 or 2007 IPCC GWPs. The RED uses the 2001 values of 1, 23 (methane), and 296 (nitrous oxide).

The model generally uses data from Europe. It does not specify a time period but most of the data used was from the 1990s up to 2005. It does allow economic operators to use their actual data in the model.

2.1.1 Intended Use

The BioGrace project identified three target audiences for their work.

1. European biofuel policy makers

[4] A new proposal from the European Commission is proposing to increase the emission reduction threshold for new installations to 60% effective July 2014. http://ec.europa.eu/clima/policies/transport/fuel/docs/com_2012_595_en.pdf

Policy makers responsible for implementing the Renewable Energy Directive and the Fuel Quality Directive into national laws are the first to benefit from the BioGrace greenhouse gas calculation (GHG) tools. By making reference from national legislation to the list of standard values policy makers assure that GHG calculations will be performed by economic operators in a transparent and harmonized way.

In addition, Germany, the Netherlands, Spain, and the United Kingdom cooperated with BioGrace for harmonizing their user-friendly GHG calculators that each of the countries had been developing.

2. Economic operators

All entities that are involved in the production and distribution of biofuels will find guidance for calculating the GHG emission saving of their biofuel products by using the BioGrace calculation tools. These are e.g. the farmers that grow the crops, and the biofuel producers that produce biofuels from crops, residues or wastes, as well as the companies that distribute and sell biofuels either unblended or blended with fossil fuels. In the Renewable Energy Directive and the Fuel Quality Directive these entities are referred to as "economic operators". Some of them will be obliged to perform (their) own GHG calculations; others can do so if they want to prove that the saving value of their products is above the default value stated in the Directive.

3. Auditors, advisors, and certifiers

The third target group are auditors, advisors, and certifiers of voluntary sustainability schemes that are being hired by economic operators to help them perform or verify greenhouse gas emission calculations.

2.1.2 Data Approach

The RED allows economic operators to use default values, their own values, or a combination of default and own values for different stages in their GHG calculations. The default values used for process energy for the fuel production stages in each of the fuel chains study in the RED (and thus in BioGrace) are 40% higher than the typical values. This provides some incentive for the fuel production facilities to use actual values.

The default values for the stages other than fuel production are all equal to the typical values. The overall variance between the typical values and the default values thus vary with the fuel supply chain.

The data used in BioGrace is aligned with the default values identified in the RED directive. Those values were largely derived from the work of the JEC Consortium. The JEC Consortium was a collaboration between the European Commission's Joint Research Centre (JRC), EUCAR (European Council for Automotive R&D) and CONCAWE (the organization representing crude oil refiners in the EU and focusing on environment, health and safety issues). The JEC consortium has published a series of “Well to Wheel” reports beginning with version 1 in 2003 and the most recent version 4 published in July 2013. Version 3, published in November 2008 was the version that generally aligned with the RED default values.

The data is generally representative of European conditions in the 1990s, although there are some exceptions in some of the pathways. This will be discussed in greater detail in the discussion of each pathway.

2.1.3 Allocation

The Renewable Energy Directive requires the use of allocation by energy content between the primary fuel product and any co-products that are produced in the process. During the development of the RED default values, the various allocation approaches were studied and the use of energy allocation was chosen based on it producing the fewest unintended consequences (Hodson, 2008). On the issue of allocation rather than substitution the following reasons for choosing allocation were provided:

- Substitution is more appropriate for policy analysis than for regulatory purposes
- Substitution cannot be used for petrol and diesel, or other fuels produced in refineries
- Substitution requires arguable hypotheses about the substituted product
- Avoid perverse incentive to maximize co-product production
- Avoid perverse incentive to use co-products for energy purposes

On the issue of which allocation method to use, the rationale was:

- Mass: results are much more generous than other methods
- Economic value: creates undesirable uncertainty for investors
- Energy: results are comparable to those of substitution (depending on use of co-product).

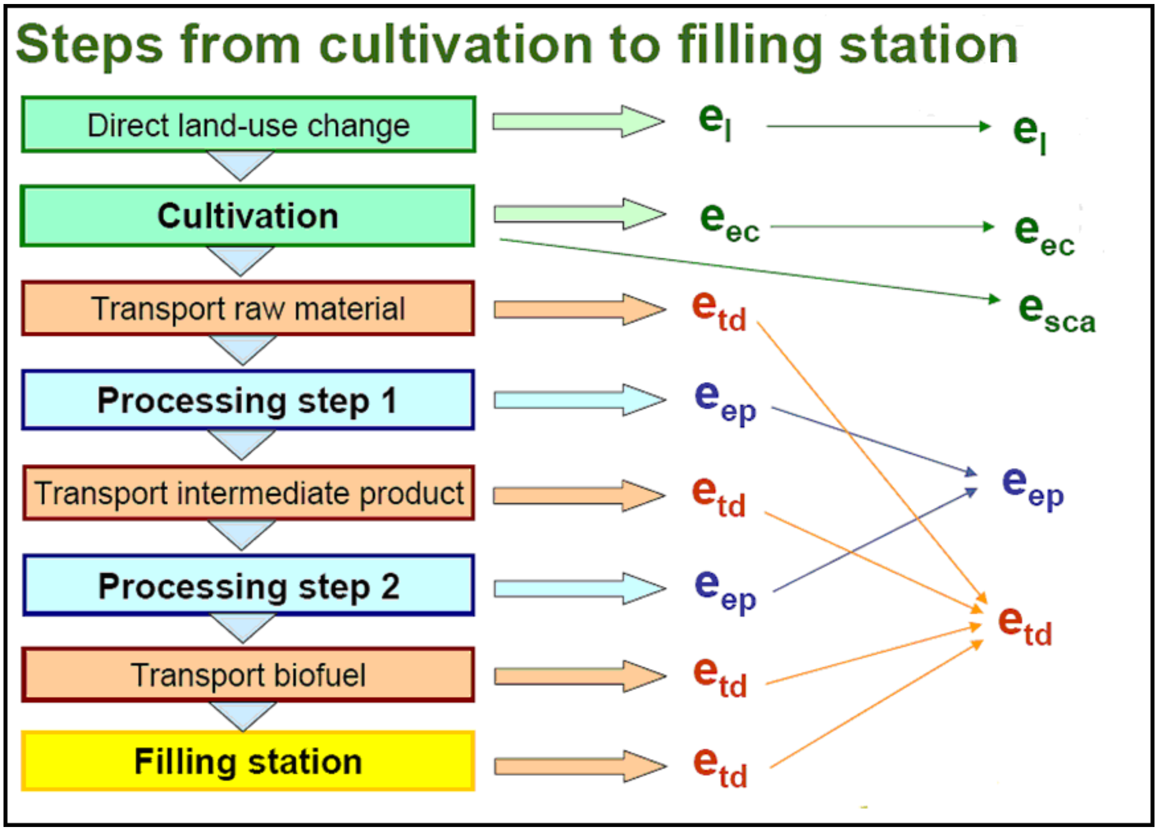
This is different than the JEC studies (including those published prior to the adoption of the RED) that favoured the "substitution method" (JEC, 2011). The JEC report states:

> *We strongly favour this "substitution" method which attempts to model reality by tracking the likely fate of by-products. Many other studies have used "allocation" methods whereby energy and emissions from a process are arbitrarily allocated to the various products according to e.g. mass, energy content, "exergy" content or monetary value. Although such allocation methods have the attraction of being simpler to implement they have no logical or physical basis. It is clear that any benefit from a by-product must depend on what the by-product substitutes: all allocation methods take no account of this, and so are likely to give flawed results.*

2.1.4 Boundary Conditions

The BioGrace model is a fuel system calculator. The stages included in the model are shown in the following figure. The model is not iterative and changes in one pathway do not impact the results in any other pathway.

Figure 2-1 BioGrace Boundary Conditions



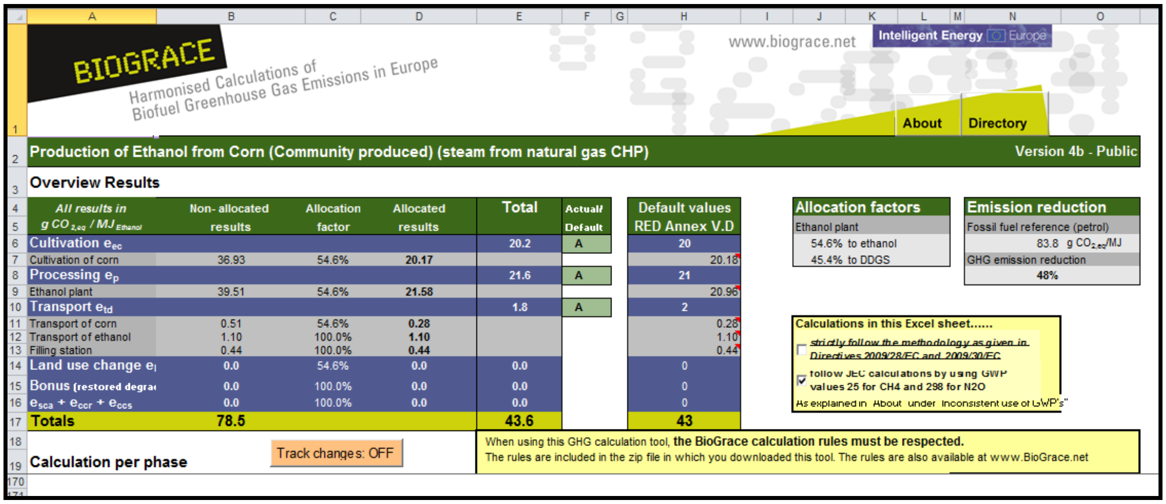
Source: BioGrace

The model includes stages from cultivation of the crop to the delivery of the fuel into the vehicle. This includes any direct land use change emissions but excludes any emissions associated with the combustion of the fuel and any infrastructure related emissions (for example, manufacture of tractors used in cultivation).

The use of an allocation approach also excludes any emissions or avoided emissions associated with the use of the co-products.

The results are presented on a Lower Heating Value (LHV) basis. Information is presented for each of the stages in the fuel supply chain (Cultivation, Processing, Transportation, Land Use Change) and a comparison to the default values is provided as shown in the following figure.

Figure 2-2 BioGrace Output



All results in g $CO_{2,eq}$ / $MJ_{Ethanol}$	Non- allocated results	Allocation factor	Allocated results	Total	Actual/ Default	Default values RED Annex V.D
Cultivation e_{ec}				20.2	A	20
Cultivation of corn	36.93	54.6%	**20.17**			20.18
Processing e_p				21.6	A	21
Ethanol plant	39.51	54.6%	**21.58**			20.96
Transport e_{td}				1.8	A	2
Transport of corn	0.51	54.6%	**0.28**			0.28
Transport of ethanol	1.10	100.0%	**1.10**			1.10
Filling station	0.44	100.0%	**0.44**			0.44
Land use change e_l	0.0	54.6%	0.0	0.0		0
Bonus (restored degra	0.0	100.0%	0.0	0.0		0
$e_{sca} + e_{ccr} + e_{ccs}$	0.0	100.0%	0.0	0.0		0
Totals	**78.5**			**43.6**		**43**

Allocation factors	
Ethanol plant	
54.6%	to ethanol
45.4%	to DDGS

Emission reduction
Fossil fuel reference (petrol)
83.8 g $CO_{2,eq}$/MJ
GHG emission reduction
48%

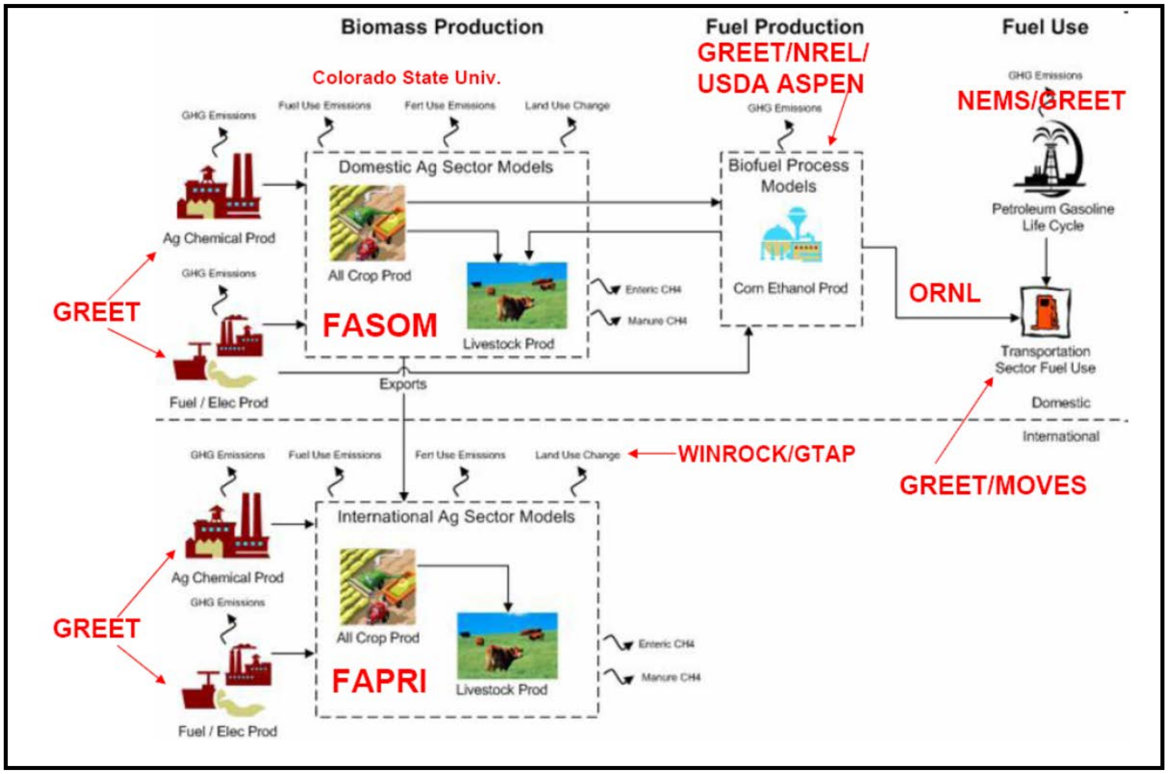
Source: BioGrace

The model does have some additional features not included in the RED. It allows for the calculation of N_2O emissions following the IPCC methodology. In some cases this provides different values than are used in the RED. The model also has a soil carbon calculator, again based on IPCC guidance. This allows for the calculation of changes in soil carbon resulting from management changes.

2.2 EPA RFS2

For biofuels, the US EPA RFS2 modelling framework utilized data from eight individual models for their work. These models were used in combination in a detailed and complex modelling framework as shown in the following figure.

Figure 2-3 EPA RFS2 Modelling Schematic



Source: EPA

Not all of the models were used for all of the pathways. The petroleum products pathways were analyzed using a different framework developed by the National Energy Technology Laboratory (NETL, 2009).

Two of the biofuel models, FASOM and FAPRI are partial equilibrium models and they form the core of the modelling framework for biofuel systems that involve cultivation of the land. The Forest and Agricultural Sector Optimization Model (FASOM) is a dynamic, nonlinear programming model of the forest and agricultural sectors in the United States. The FASOM model initially was developed to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees but also has been applied to a wider range of forest and agricultural sector policy scenarios. The model depicts the allocation of land, over time, to competing activities in both the forest and agricultural sectors. It can calculate the GHG emission impact of crop shifting, livestock production, and other indirect effects beyond land use change, offering advantages over other models.

The Food and Agricultural Policy Research Institute (FAPRI) is a unique, dual-university research program, established in 1984 by a grant from the U.S. Congress, to prepare baseline projections for the U.S. agricultural sector and international commodity markets and to develop capability for policy analysis using comprehensive data and computer modeling systems of the world agricultural market.

The Center for Agricultural and Rural Development (CARD) at Iowa State University develops the international side of the models, and the Center for National Food and Agricultural Policy (CNFAP) at the University of Missouri-Columbia develops the U.S. domestic component. Both centres conduct independent as well as joint policy analyses. It was the CARD group that did the modelling for the EPA RFS2.

The FASOM model determines the emissions from the agricultural sector within the United States and the FAPRI model determines the agricultural emissions outside of the United States.

The initial EPA analyses included corn ethanol, sugar cane ethanol, cellulosic ethanol, soybean biodiesel, waste oil biodiesel, and algae biodiesel. The models have been expanded and now include canola oil biodiesel and sorghum ethanol. Pathways that are under development include palm oil biodiesel, cottonseed oil biodiesel, jatropha biodiesel, barley ethanol, wheat ethanol, ethanol from energy beets and cellulosic ethanol from Napier grass, and arundo donax. The development of new feedstock pathways can take 12 to 24 months.

The National Energy Technology Laboratory developed the petroleum life cycle emissions for the EPA. This model calculates the 2005 national average life cycle greenhouse gas emissions for petroleum-based fuels sold or distributed in the United States in the year 2005. Specifically, the model reports, by life cycle stage, the life cycle GHG emissions for conventional gasoline, conventional diesel fuel, and kerosene-based jet fuel. The model served as the primary calculation tool for the results reported in the NETL November 26, 2008; report entitled "Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels" (NETL, 2008). The model was created in Microsoft Office Excel 2003 and requires macros to be enabled to solve iterative calculation functions. The model is available here http://www.netl.doe.gov/energy-analyses/refshelf/PubDetails.aspx?Action=View&PubId=283. Some of the data on crude oil production emissions in the model came from GaBi, a commercial LCA tool.

The EPA reported the GHG emissions and the criteria air contaminants (CAC) emissions for the fuel production and use for each of the pathways.

2.2.1 Intended Use

The Energy Independence and Security Act (EISA) of 2007 is an omnibus energy policy act. Of the sixteen titles contained within EISA, four of them can be related to alternative fuels and one (Title II) specifically to renewable fuels.

Title II – Energy security through increased production of biofuels

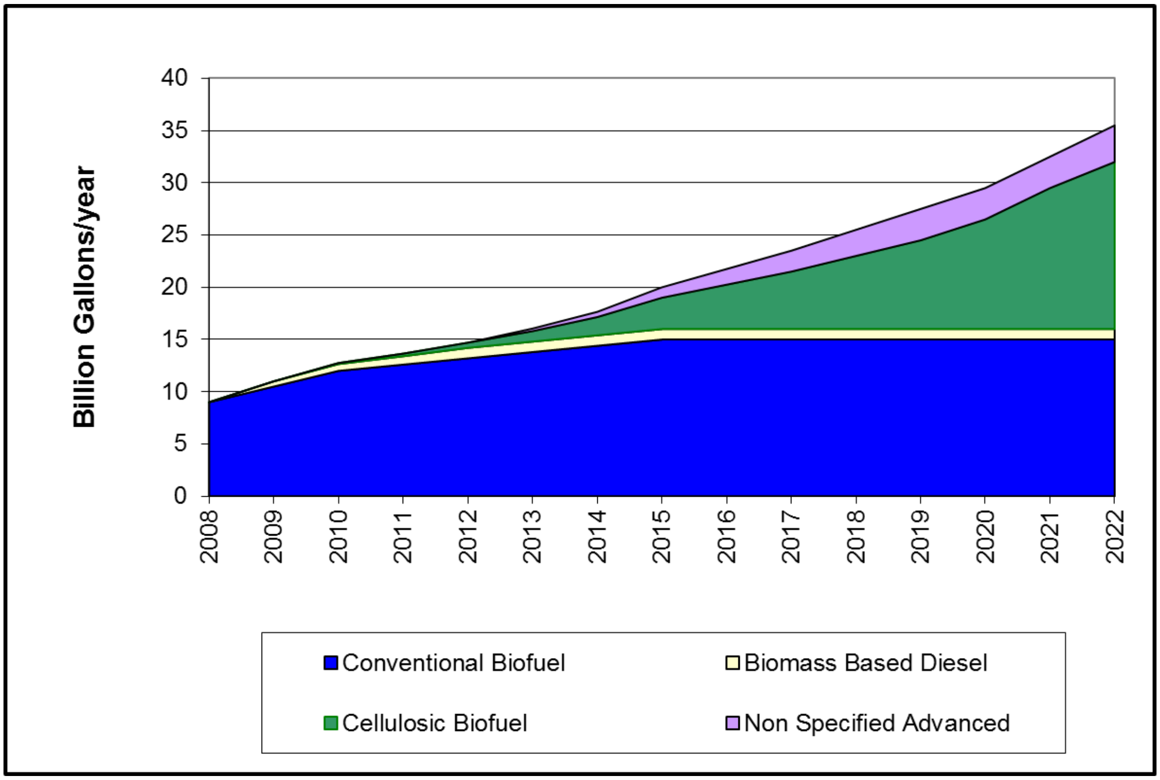
This title of EISA expanded the RFS program to include diesel, in addition to gasoline. There were a number of other changes including;

- EISA increased the volume of renewable fuel required to be blended into transportation fuel from 9 billion gallons in 2008 to 36 billion gallons by 2022;
- EISA established new categories of renewable fuel, and set separate volume requirements for each one.
- EISA required EPA to apply lifecycle greenhouse gas performance threshold standards to ensure that each category of renewable fuel emits fewer greenhouse gases than the petroleum fuel it replaces.

The new revised renewable fuel program is commonly called RFS2.

The implementation of RFS2 began in earnest in 2010, after the EPA had completed their first round of lifecycle analyses of common biofuels. The program has had some challenges in the first several years but the required volumes of conventional ethanol and biodiesel have been met in the first two years. The targets for cellulosic ethanol were reduced (by more than 98% for the 2013 compliance year) compared to the initial estimates, as the product was not yet available. The initial targets laid out in the final rulemaking are shown in the following figure. The biomass based diesel is shown at 1 billion gallons per year after 2012, but the EPA is required to propose targets each year and they can't be lower than 1 billion gallons. These volumes are ethanol equivalent volumes, except for the one billion gallons of biodiesel, which is actual volumes, and one gallon of biodiesel is equal to 1.5 gallons of ethanol.

Figure 2-4 RFS2 Volume Targets



Source: (S&T)[2]

Any biofuel produced from corn or corn starch is a conventional biofuel and is required to demonstrate a 20% reduction of lifecycle GHG emissions, including significant indirect effects (grandfathered facilities are exempt from this requirement). Biomass based diesel and non-specified advanced biofuels must show a 50% reduction in lifecycle GHG emissions, and the cellulosic fuels must show a 60% reduction in GHG emissions.

Other requirements include that the feedstock should meet the definition of renewable biomass, including the fact that it was grown on land that was in production in December 2007, and doesn't represent an expansion of agricultural land.

2.2.2 Data Approach

There are two distinct approaches within the RFS2 framework, one for the baseline petroleum fuels (a historic view), and another for the biofuels (the future view). Both modelling frameworks use the lower heating value basis for data presentation. They are discussed separately below.

2.2.2.1 Petroleum Fuels

The baseline for the petroleum fuels was specified by Congress to be 2005. NETL developed their model and report to specifically meet the definition of “baseline lifecycle greenhouse gas emissions” as defined in the Energy Independence and Security Act of 2007 (EISA 2007), Title II, Subtitle A, Sec. 201.

The purpose of the NETL study was to develop baseline data, methodologies, and results to determine the life cycle greenhouse gas emissions for liquid fuels (conventional gasoline, conventional diesel, and kerosene-based jet fuel) production from petroleum as consumed in the U.S. in 2005 to allow comparisons with alternative transportation fuel options on the same basis (i.e., life cycle modeling assumptions, boundaries, and allocation procedures).

2.2.2.2 Biofuels

For biofuels the EPA decided it was not practical nor workable to conduct an analysis and review GHG factors for every year, so to carry out the analysis required by the Act, they chose to look at the final year of the RFS2 standards when they are fully phased in. For their reference case they assumed a “business as usual” (BAU) volume of a particular renewable fuel based on what would likely be in the fuel pool in 2022 without EISA as predicted by the Energy Information Agency’s Annual Energy Outlook (AEO) for 2007 (which took into account the economic and policy factors in existence in 2007 before EISA). For the control case they assumed the higher volumes of renewable fuels as mandated by EISA for 2022. For each individual biofuel, they analyzed the incremental impact of increasing the volume of that fuel to the total mix of biofuels needed to meet the EISA requirements while holding volumes of other fuels constant. Any changes between now and 2022 in factors such as crop yields, energy costs, or production plant efficiencies, both domestically and internationally, are reflected in both scenarios (BAU and control).

Rather than focus on the impacts associated with a specific unit of fuel and tracking inputs and outputs across different lifecycle stages, the modeling framework determined the overall aggregate impacts across sections of the economy in response to a given volume change in the amount of biofuel produced. The EPA then normalize those impacts to a gallon of fuel by dividing total impacts over the given volume change. In the case of overall rule impacts, they analyzed the change in reference vs. control case volumes for all fuels together and take the absolute GHG results (e.g., do not normalize the overall rule impacts).

2.2.3 Allocation

The two modelling frameworks take different approaches to co-products and the allocation of the emissions to each product.

2.2.3.1 Petroleum Fuels

The NETL study did a study of the energy use and hydrogen consumption of every unit in the refinery. This data combined with the fraction of the seven product pools contributed by each of the process operations allowed the allocation of the energy and GHG emissions to the primary products, gasoline, diesel, and kerosene that were the focus of the study.

2.2.3.2 Biofuels

The FASOM and FAPRI models do sector wide modelling. The use of the agricultural co-products is included in the partial equilibrium models. No allocation is required when this approach is used. These models come closest to the recommended practice for dealing with co-products in the ISO 14040 series guidelines.

Non-agricultural co-products, such as glycerine from biodiesel, or fuel products from renewable diesel processes are dealt with by outside the model calculations using the displacement of other energy products.

2.2.4 Boundary Conditions

The discussion of the boundary conditions is also different in the two modelling approaches.

2.2.4.1 Petroleum Fuels

The petroleum fuels model starts with the extraction of the crude oil and includes any inputs (chemicals and energy) into that process. The material is followed through the complete process chain until it is consumed in the vehicle.

The model does not include any infrastructure emissions, as these are deemed to be pre-existing and therefore no construction related emissions are included. More information on the stages included in the analyses is provided later in the report.

2.2.4.2 Biofuels

The boundary conditions used in the biofuel models are generally the same as that used in the petroleum fuel model with one exception, land use change. The definition of lifecycle analysis provided to the EPA by congress was:

> *The term 'lifecycle greenhouse gas emissions' means the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for their relative global warming potential.*

This definition caused the EPA to adopt the consequential approach to lifecycle analyses. A consequential approach to GHG emissions accounting in products provides information about the GHG emitted, directly or indirectly, as a consequence of changes in demand for the product. This approach typically describes changes in GHG emissions levels from affected processes, which are identified by linking causes with effects.

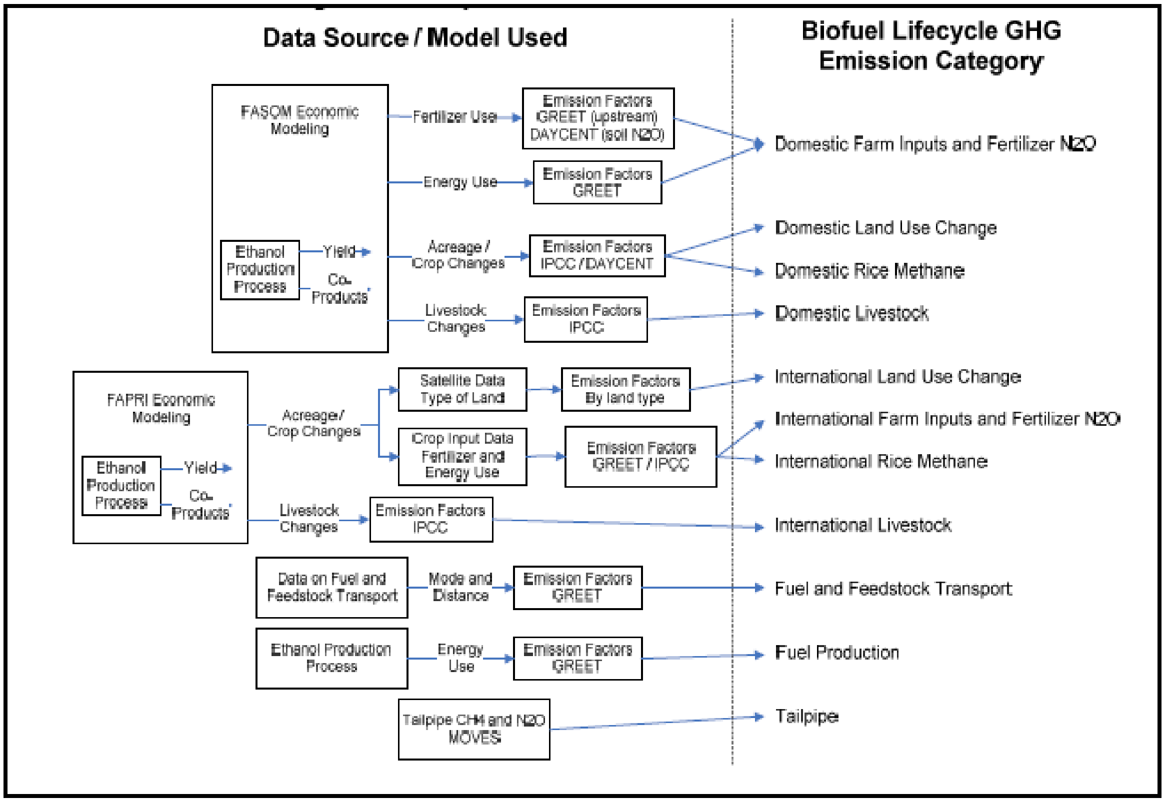
The EPA RFS2 biofuel modelling is the only model considered that included indirect land use change[5]. The EPA structured the modelling so that there was no land use change in the United States and all land use change was international. This allows the EPA results to be presented in a such a way these land use emissions can be removed for comparison to all of the other model results.

All of the other models that are being investigated in this report utilize an attributional approach to GHG emissions accounting, which provides information about the GHG emitted directly by a product and its life cycle. The product system includes processes that are directly linked to the product by material, energy flows or services following a supply-chain logic, including co-products.

[5] CARB performed their ILUC modelling outside of the GREET framework using the GTAP model.

Note that the EPA established some constraints on their models (no expansion of US agricultural land), which isolated a large portion of the indirect land use change emissions in the international emissions section of the results. Nevertheless, the output from the EPA modelling of biofuels is in a different format than the rest of the models and it makes the comparison of the emissions in each stage more difficult. The system boundaries and the results stages are shown in the following figure.

Figure 2-5 Lifecycle Stages and Models Used



Source: EPA

2.3 GREET

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model was developed by Argonne National Laboratory under the sponsorship of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. GREET allows researchers and analysts to evaluate various vehicle and fuel combinations on a full fuel-cycle/vehicle-cycle basis.

The first version of GREET was released in 1996. Since then, Argonne has continued to update and expand the model. The most recent GREET versions are:

- GREET 1 2012 for fuel-cycle analysis; and
- GREET 2.7 for vehicle-cycle analysis.

Both versions of the model are available free over the Internet as spreadsheet models in Microsoft Excel.[6] A new self-contained platform for GREET was released in Beta version in December 2012. This new platform will eventually replace the Excel version. At this time both versions are being maintained and both versions use the same input data and produce the same results.

The model covers all stages of the fuel life cycle, from well-to-pump and pump-to-wheels, including:

- feedstock production, transportation, and storage;
- fuel production, transportation, distribution, and storage,
- vehicle operation, refuelling, fuel combustion/conversion, fuel evaporation, and tire/break wear.

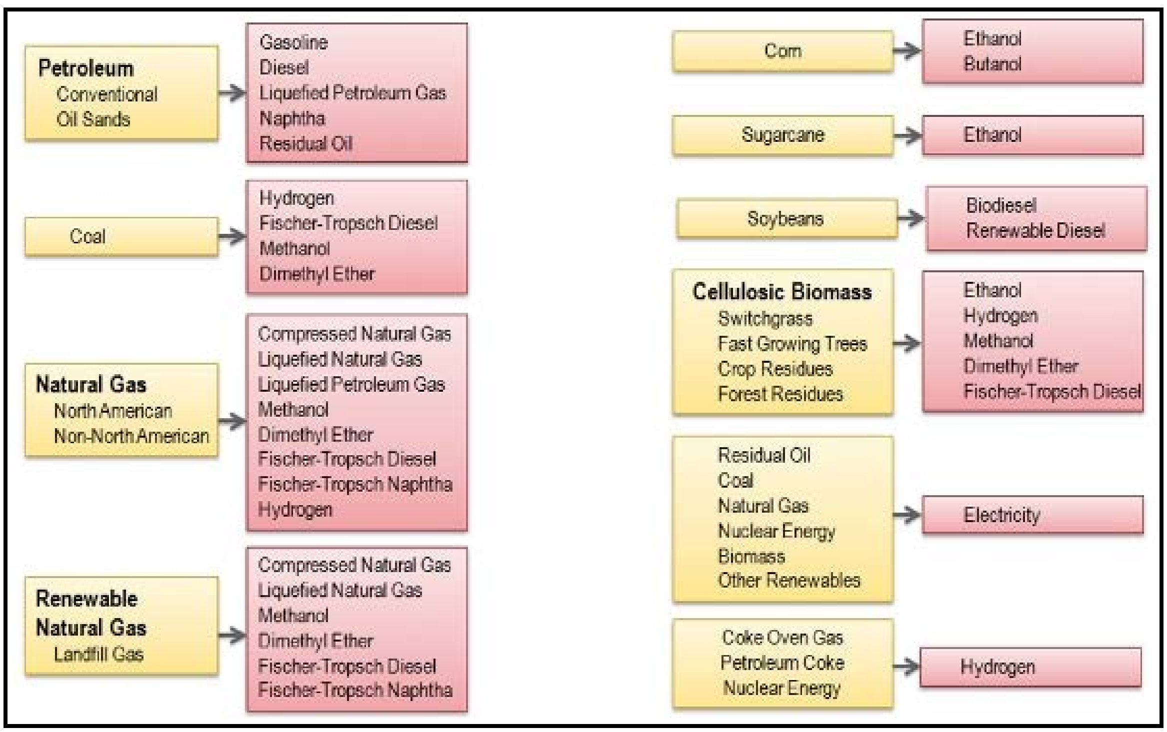
In addition, GREET simulates vehicle-cycle energy use and emissions from material recovery to vehicle disposal (raw material recovery, material processing and fabrication, vehicle component production, vehicle assembly, and vehicle disposal and recycling).

The model includes:

- emissions of greenhouse gases (CO_2, CH_4, and N_2O);
- emissions of six criteria pollutants (VOCs, CO, NO_x, SO_x, PM_{10}, and $PM_{2.5}$); and
- energy use by fuel.

GREET includes more than 100 fuel pathways including petroleum fuels, natural gas fuels, biofuels, hydrogen and electricity produced from various energy feedstock sources.

Figure 2-6 GREET Pathways



[6] http://greet.es.anl.gov/

Source: Argonne National Laboratory, GREET Model. Available at: http://greet.es.anl.gov/

Data in the model are for the United States only. When California adopted the GREET 1.8b model for use in their Low Carbon Fuel Standards (LCFS) program they modified the model to include California data on power production, transportation distances, and different assumptions about some co-products.

GREET 1.8c was released in March 2009. It appears that the major change was the incorporation of plug-in hybrid vehicles into the model.

GREET 1.8d was released in August 2010. It had a large number of changes. Some of the important changes related to the biofuels understudy here include:

- Revised corn farming energy and fertilizer use.
- Revised the ratio of DDGS and WDGS from dry mill plants to animal farms in the U.S.
- Updated dry mill corn ethanol plant assumptions on the basis of data in EPA's final rule of renewable fuels standards and the Survey on Ethanol Plants by University of Illinois at Chicago (UIC)
- Updated wet mill corn ethanol plant assumptions on the basis of the Renewable Fuels Association's survey on ethanol plants
- Updated soybean-based biodiesel pathway with revised farming and biodiesel conversion estimates from two recent studies.
    - Updated soybean farming assumptions on the basis of a USDA report
    - Updated biodiesel production assumptions on the basis of EPA's final rule of renewable fuels standards and a recent study by Omni Tech International on soybean lifecycle emissions.
- Updated overall petroleum refinery efficiency on the basis of 2008 petroleum refinery data from the Energy Information Administration's (EIA's) annual survey and revised allocation of refinery energy use among the different fuel products. This impacts the reference fuels and the use of these fuels in the production of biofuels.

GREET1_2011 was released in October 2011, it also had a large number of changes. This update included the following changes of interest for the fuels under review here:

- Updated overall petroleum refinery efficiency and models (including the conversion of inputs and the combustion of intermediate) on the basis of 2009 petroleum refinery data from the Energy Information Administration's (EIA's) annual survey. Also, revised the allocation of refinery energy use among the different refinery products.
- Updated farming assumptions (farming energy and fertilizer and pesticide inputs) for soybean based on a study co-worked by University of Idaho and USDA.
- Updated farming assumptions (farming, harvesting and collection energy and fertilizer and pesticide inputs) of sugarcane.
- Revised the emission calculations of ammonia production for fertilizer applications. The upstream emissions of non-combusted NG in ammonia production are now included, which were not taken into account in the previous versions.

GREET1_2012 was released in June 2012. This update included the following changes of interest for the fuels under review here:

- Enzyme and yeast productions are included and used for ethanol production from corn and cellulosic biomass feedstock sources.

- Developed domestic and foreign land-use change (LUC) for cellulosic-ethanol pathways (from corn stover, miscanthus, and switchgrass) and updated LUC for corn-ethanol.

A revised version of GREET1_2012 (rev 1) was released in July 2012. It had the following updates of interest.

- Parameters for field burning of sugarcane straw and sugarcane ethanol production are updated. N_2O emissions from filtercake and vinasse are included. Supplemental fertilizer inputs due to increased sugarcane collection are also taken into account. Parameters for sugarcane ethanol transport are also updated.

A second revision of GREET1_2012 (rev 2) was released in December 2012. It had the following updates of interest.

- Updated sugarcane ethanol pathways on the basis of recent studies.
- Updated electricity generation mixes, shale gas shares and oil sand shares on the basis of AEO 2013 Early Release.
- Adjusted lipid and moisture contents of oil seeds (e.g. palm, rapeseed, jatropha and camelina) and their impact on the oil and co-product yields.

This latest version of GREET has been used in this assessment. The Excel version of the model has been used, since the new platform is still in Beta and may have some bugs in it.

2.3.1 CARB GREET

When CARB started their work on developing carbon intensity values for the various fuels that were expected to be used in the Low Carbon Fuel Standard program, the then current version of GREET was version 1.8b. CARB, through their contractor, Lifecycle Associates, began to modify the GREET 1.8b model to reflect California conditions. The modified model is known as CA-GREET. The most current version is 1.8b.

The CA-GREET modifications are mostly related to incorporating California-specific conditions, parameters, and data into the original GREET model. The major changes incorporated into the CA-GREET model are listed below:

- Marine and rail emissions reflect in-port and rail switcher activity with an adjustment factor for urban emissions;
- Natural gas transmission and distribution losses reflect data from California gas utilities;
- The fuel properties data for CARBOB, ultra-low sulphur diesel (ULSD), California reformulated gasoline, natural gas, and hydrogen were revised to reflect California-specific parameters;
- The electricity transmission and distribution loss factor was corrected to reflect California conditions; the electricity mix was also changed to reflect in-State conditions, both for average and marginal electricity mix;
- The California crude oil recovery efficiency was modified to reflect the values specific to the average crude used in California including crude that is both produced in, and imported into, the State;
- Crude refining for both CARBOB and ULSD was adjusted to reflect more stringent standards for these fuels in California;
- Tailpipe CH_4 and N_2O emission factors were adapted for California vehicles where available;

- The process efficiencies and emission factors for equipment were changed to reflect available California-specific data; and
- Landfill gas to CNG pathway was coded into the CA-GREET pathway.

CARB have worked on the model more or less continually since 2008 to adjust some of the assumptions in the pathways, add new pathways, and modify the model for other feedstocks and fuels. They have not tried to harmonize their version with any of the updates developed by the GREET team at Argonne. This is always a risk when there are parallel teams working on the same model, they quickly become different.

2.3.2 Intended Use

The original goal of GREET was to develop a simple to use tool that researchers could evaluate fuel-cycle energy and emission impacts of various transportation technologies. Over the years Argonne researchers and other scientists have used the model extensively to calculate the fuel cycle energy requirements and emissions of alternative fuels and advanced vehicle technologies.

In 2007, the model was chosen by CARB to use in their Low Carbon Fuel Standard (LCFS). CARB have used the model to determine the GHG emission intensity of the fuels sold in the State of California. The CARB default values for the various fuel pathways are published and are fully transparent.

CARB also use the model in their 2A/2B pathway process. Under Method 2A, fuel providers may apply for the addition of new sub-pathways to the default fuel pathway lookup table. A sub-pathway is a modified version of a pathway currently present in the table. New sub-pathways are added when a fuel provider can demonstrate that a new or improved fuel production, transport, storage, and/or dispensing process significantly reduces the lifecycle carbon intensity of an existing reference pathway. Generally fuel providers would input their actual values for parameters such as yield, electric power and natural gas consumption into the CA GREET model and the revised model results would be their new method 2A carbon intensity.

A large number of companies have used the model to develop 2A pathways. 2A approvals are only granted when the difference in the emissions is greater than 5 g/MJ relative to the CARB developed pathway. The fact that some 34 applications have been received and reviewed for ethanol is an indication that the CA-GREET model does not reflect the current operating conditions in a large portion of the industry.

2.3.3 Data Approach

The GREET model uses average US values for most of the data. In many cases the model contains a times series of historical data and future projections that allow the same pathway to be analyzed at various points in time between 1990 and 2020.

There are a few pathways, for example Brazilian sugar cane ethanol, that have specific geographic boundaries but most of the results are presented as US average results.

GREET uses the 2007 IPCC GWPs, although it is very easy to manually change these parameters. The GREET calculations of GHG emissions also include the carbon that is in the carbon monoxide and volatile organic carbon. This differs from the other models that calculate the GHG emissions just from the carbon dioxide, methane and nitrous oxide.

2.3.4 Allocation

The GREET model enables users to choose the allocation approach to be used. Each pathway has some different combinations of options but generally there is a displacement approach with options of using an energy allocation, a mass allocation, or a market value allocation.

In the CA GREET, there are different approaches used for different pathways.

2.3.5 Boundary Conditions

GREET boundary conditions generally begin with the feedstock production and end with the combustion of the fuel. The user can choose to include some infrastructure energy use and emissions, such as for well drilling, or for the manufacture and maintenance of farm tractors.

The results are presented on a lower heating value basis as the default. The user has the option of choosing higher heating value in the model.

2.4 GHGENIUS

The GHGenius model has been developed for Natural Resources Canada (NRCan) over the past dozen years. It was originally based on the 1998 version of Dr. Mark Delucchi's Lifecycle Emissions Model (LEM). GHGenius is capable of analyzing the energy balance and emissions of many contaminants associated with the production and use of traditional and alternative transportation fuels.

GHGenius is capable of estimating life cycle emissions of the primary greenhouse gases and the criteria pollutants from combustion sources. The specific gases that are included in the model include:

- Carbon dioxide (CO_2),
- Methane (CH_4),
- Nitrous oxide (N_2O),
- Chlorofluorocarbons (CFC-12),
- Hydro fluorocarbons (HFC-134a),
- The CO_2-equivalent of all of the contaminants above.
- Carbon monoxide (CO),
- Nitrogen oxides (NOx),
- Non-methane organic compounds (NMOCs), weighted by their ozone forming potential,
- Sulphur dioxide (SO_2),
- Total particulate matter.

The model also produces the primary and secondary energy use by fuel type and stage for all of the pathways in the model. There are also GHG cost effectiveness results that are presented for each of the fuel production and use pathways.

The model is capable of analyzing the emissions from conventional and alternative fuelled internal combustion engines or fuel cells for light duty vehicles, for class 3-7 medium-duty trucks, for class 8 heavy-duty trucks, for urban buses and for a combination of buses and trucks, and for light duty battery powered electric vehicles. There are over 200 vehicle and fuel combinations possible with the model. Many of the direct pathways are shown in the following figure.

Figure 2-7 GHGenius Fuel Pathways

	Coal	Gasoline	Gasoline Lo S	Diesel	Jet Fuel	Fuel Oil	Still Gas	LPG	Coke	FT Distillate	HRD	HRJ	NG	Hydrogen	Methanol	Ethanol	Butanol	Biodiesel	DME	Mixed Alcohols	Pyrolysis Oil	Electricity
Coal	X									X			X	X	X							X
Crude Oil		X	X	X	X	X	X	X	X					X								X
Natural Gas								X		X			X	X	X				X	X		X
Uranium														X								X
Electricity														X								
Wood			X							X			X	X	X	X			X	X	X	X
Corn Stover													X	X	X	X					X	
Wheat Straw																X					X	
Switchgrass																X					X	
Hay																X					X	
Manure													X									
Corn														X		X	X					
Wheat														X		X						
Barley																X						
Peas																X						
Sugarcane																X						
Sugar beets																X						
Canola											X	X						X				
Soybeans											X	X						X				
Camelina											X	X						X				
Palm											X	X						X				
Tallow											X	X						X				
Yellow Grease											X	X						X				
Fish Oil											X	X						X				
Algae											X	X						X				
Jatropha											X	X						X				
RDF										X										X		
LFG														X	X							
Used Oil						X																

Source: GHGenius

GHGenius is different from the other models considered in that it can provide the analysis for multiple geographic regions. This includes not only country level analyses (Canada, The United States, Mexico, and India) but also regional analyses (east, central, and west in Canada, the US, and Mexico, and at the provincial level in Canada).

Like the GREET model, GHGenius is continually being updated with new pathways and new data in the existing pathways. Version 4.02a has been used for this work. To facilitate comparison between the GREET models and the EPA RFS2 models, GHGenius has been set to model the US for the six fuel pathways. There are some results presented for other regions to show the regional variability in some of the pathways.

2.4.1 Intended Use

GHGenius was originally developed under the sponsorship of NRCan as a tool to assist policy makers, much the same as GREET. Since GREET didn't have any Canadian data, the decision was made to work with the Delucchi LEM model, which did have some Canadian data, and further develop the model.

The model was adopted by the Province of BC for use in their LCFS program rather than using GREET as California had done. The availability of not only Canadian data but also pathways that are important to Canada (wheat ethanol and canola biodiesel) that were not in GREET factored into their decision.

The Province of Alberta later adopted the model for use in their renewable fuel program, where biofuels must have more than a 25% reduction in GHG emissions in order to qualify for the program.

2.4.2 Data Approach

GHGenius uses industry average data where it is available. Important data sources are Statistics Canada and the US DOE Energy Information Administration. Many of the data requirements are met with time series of data. This data is used to extrapolate into the future and also to smooth the year to year variation that is present in much of the agricultural data. EIA forecasts are combined with historical data for many of the time series.

The model can be run for any year between 1995 and 2050, and produces different results for different years.

GHGenius can use any of the IPCC GWPs, with the user making the choice in the model. The two regulatory users of the model both specify the 1995 GWPs, whereas all of the GHGenius reports use the latest versions of GWPs (currently the 2007 values).

GHGenius uses higher heating values for data input and calculations but the GHG results for fuel production are presented both on a HHV and a LHV basis.

2.4.3 Allocation

The default approach to allocation in GHGenius is system expansion/displacement. The model also provides the opportunity for users to select allocation by mass or energy for many of the pathways.

2.4.4 Boundary Conditions

The boundary conditions in GHGenius are generally similar to other models. An exception is that the emissions associated with transportation infrastructure for fuels production is included. This includes ships, trains, trucks, tractors, and pipelines.

The fuel cycle segments considered in the model are as follows:

- Vehicle Operation
  Emissions associated with the use of the fuel in the vehicle. Includes all greenhouse gases.
- Fuel Dispensing at the Retail Level
  Emissions associated with the transfer of the fuel at a service station from storage into the vehicles. Includes electricity for pumping, fugitive emissions and spills.
- Fuel Storage and Distribution at all Stages
  Emissions associated with storage and handling of fuel products at terminals, bulk plants and service stations. Includes storage emissions, electricity for pumping, space heating and lighting.
- Fuel Production (as in production from raw materials)
  Direct and indirect emissions associated with conversion of the feedstock into a saleable fuel product. Includes process emissions, combustion emissions for process heat/steam, electricity generation, fugitive emissions and emissions from the life cycle of chemicals used for fuel production cycles.
- Feedstock Transport

Direct and indirect emissions from transport of feedstock, including pumping, compression, leaks, fugitive emissions, and transportation from point of origin to the fuel refining plant. Import/export, transport distances and the modes of transport are considered. Includes energy and emissions associated with the transportation infrastructure construction and maintenance (trucks, trains, ships, pipelines, etc.)

- Feedstock Production and Recovery
  Direct and indirect emissions from recovery and processing of the raw feedstock, including fugitive emissions from storage, handling, upstream processing prior to transmission, and mining.
- Feedstock Upgrading
  Direct and Indirect emissions from the upgrading of bitumen to synthetic crude oil at a standalone facility, including fugitive emissions.
- Fertilizer Manufacture
  Direct and indirect life cycle emissions from fertilizers, and pesticides used for feedstock production, including raw material recovery, transport and manufacturing of chemicals. This is not included if there is no fertilizer associated with the fuel pathway.
- Land use changes and cultivation associated with biomass derived fuels
  Emissions associated with the change in the land use in cultivation of crops, including N_2O from application of fertilizer, changes in soil carbon and biomass, methane emissions from soil and energy used for land cultivation. This can include indirect land use emissions if the area of new land is included in the model inputs. This is not the case when the default values are used.
- Carbon in Fuel from Air
  Carbon dioxide emissions credit arising from use of a renewable carbon source that obtains carbon from the air.
- Leaks and flaring of greenhouse gases associated with production of oil and gas
  Fugitive hydrocarbon emissions and flaring emissions associated with oil and gas production.
- Emissions displaced by co-products of alternative fuels
  Emissions displaced by co-products of various pathways. System expansion is used to determine displacement ratios for co-products from biomass pathways.
- Vehicle assembly and transport
  Emissions associated with the manufacture and transport of the vehicle to the point of sale, amortized over the life of the vehicle.
- Materials used in the vehicles
  Emissions from the manufacture of the materials used to manufacture the vehicle, amortized over the life of the vehicle. Includes lube oil production and losses from air conditioning systems.

2.5 SUMMARY

A comparison of the primary model attributes is shown in the following table. There are differences in many of the parameters of the models and thus it should not be too surprising when they produce some different results. GREET and GHGenius are the closest in concept, but even with those two models there are some differences.

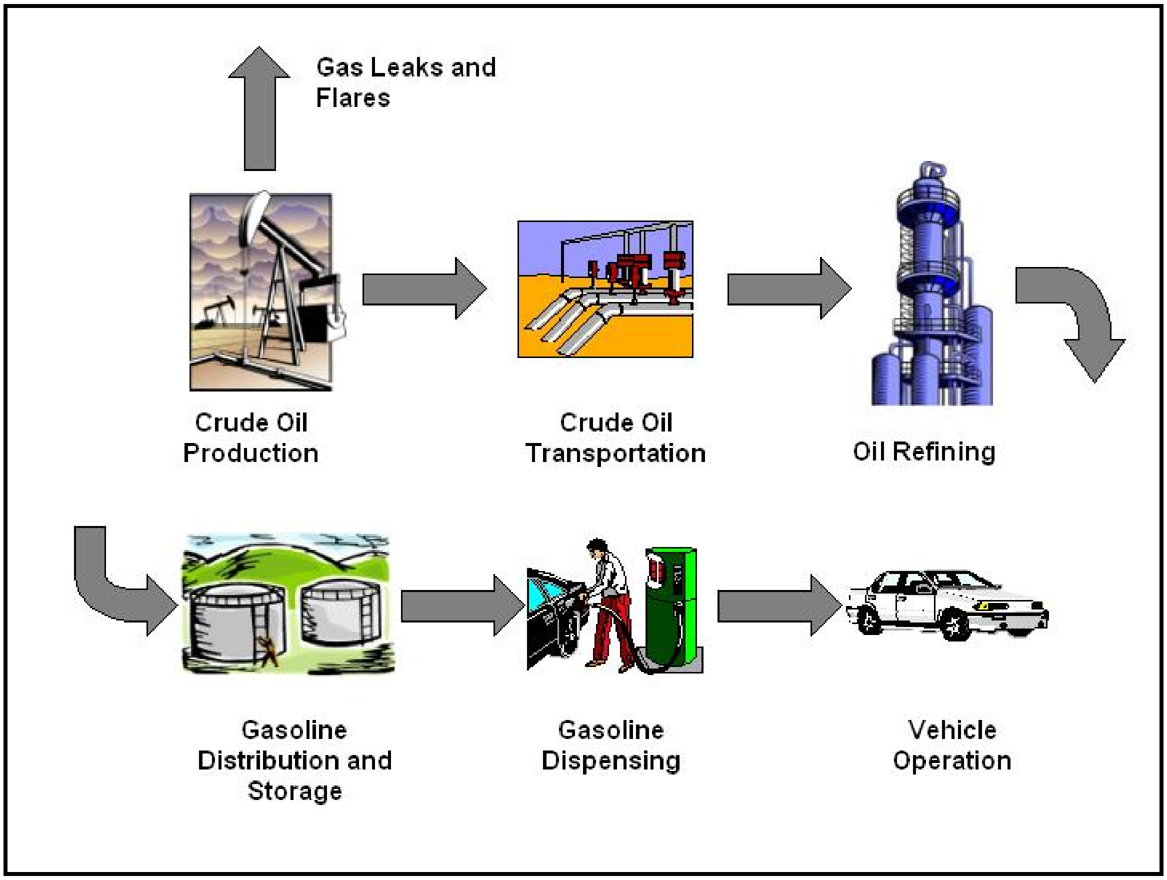
Table 2-1 Model Summary

	BioGrace	EPA RFS2	GREET	GHGenius
Developed for Regulatory Use	Yes	Yes	No	No
IPCC GWP	2001 (2007)	1995	2007	User Choice
Type	Attributional	Consequential	Attributional	Attributional
Type	Process Chain	Partial Equilibrium	Process Chain	Process Chain
Heating Values	Lower	Lower	User Choice, LHV default	User Choice, HHV default
Geography	Europe	United States	United States	Canada/United States/Mexico/ India
Co-product Allocation	Energy	Displacement	User Choice	User Choice
Data	Typical plus 40%	Expected Incremental	Average	Average
Year	Not stated, present	2022	User Choice (1990-2020)	User Choice (1995-2050)
Includes fuel combustion	No	Yes	Yes	Yes
Impact Categories	GHG	GHG, CAC	Energy, GHG, CAC	Energy, GHG, CAC, Cost Effectiveness

3. PETROLEUM FUELS

There are six primary stages to the petroleum fuels lifecycle, the crude oil production stage (which may also include the well exploration and drilling), the crude oil refining stage, the crude oil transportation stage, the petroleum products transportation stage, the dispensing stage and the vehicle use stage. These are shown in the following figure. The petroleum products transportation and dispensing stages are combined for this analysis because the contributions are usually quite small.

Figure 3-1 General System Boundaries – Petroleum Systems



In the following sections each of the modelling frameworks will be discussed. Each of the discussions will follow a similar format as much as possible to make the comparisons easier to comprehend.

3.1 BIOGRACE

BioGrace does not model either the gasoline or diesel fuel pathway. It does include a reference value of 83.8 g CO_2eq/MJ (LHV) for both the gasoline and diesel fuel from the RED. Interestingly, the standard value for diesel fuel use in BioGrace is 87.64 g CO_2eq/MJ (LHV). This standard value is used in the calculation of the emissions for any biofuel process that consumes diesel fuel.

The biofuel pathways in BioGrace are modelled using the data from Version 3 of the JEC Wells to Wheels study (2008). This study also reported the energy use and GHG emissions for gasoline and diesel fuel and they were unchanged from version 2c released in 2007 (JEC, 2007). The JEC study will be used as the basis of the "BioGrace" discussion on petroleum fuels.

The petroleum fuels upstream emissions from the 2008 version 3 JEC report are summarized in the following table.

Table 3-1 JEC Well to Wheel Emissions – Petroleum Fuels

	Total Primary Energy	GHG	CO_2	CH_4	N_2O
	MJ/MJ	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Crude oil to Gasoline					
Crude oil extraction and processing	0.03	3.6	3.6	0.0	0.0
Crude Transport	0.01	0.9	0.9	0.0	0.0
Refining	0.08	7.0	7.0	0.0	0.0
Distribution and dispensing	0.02	1.0	1.0	0.0	0.0
Total	**0.14**	**12.5**	**12.5**	**0.0**	**0.0**
Crude oil to Diesel					
Crude oil extraction and processing	0.03	3.7	3.7	0.0	0.0
Crude Transport	0.01	0.9	0.9	0.0	0.0
Refining	0.10	8.6	8.6	0.0	0.0
Distribution and dispensing	0.02	1.0	1.0	0.0	0.0
Total	**0.16**	**14.2**	**14.2**	**0.0**	**0.0**

There has been some discussion (Edwards, 2011) to increase the RED reference fuel value to 88.6 g CO_2eq/MJ (LHV). This is based on the JEC work that show higher GHG emissions for gasoline (87.7 g/MJ) and diesel fuel (89.5 g/MJ) than is used in the RED.

The assumptions behind these results are discussed below.

3.1.1 Crude Oil Production

The crude oil production energy use is based on a personal communication with J. Cadu, Shell International, April 18, 2002 (JEC, 2008b). The calculation of GHG emissions is based on the input of 1.025 MJ of crude oil into a system that produces 1.0 MJ of crude oil. The report states that:

> *Reserves of non-conventional crudes (Canadian oilsands and Venezuelan heavy crude) are very large, and these may become important in the longer term, however in the period to 2020 we expect Middle Eastern crude to remain the marginal supply source for Europe.*

The crude oil energy requirements are therefore assumed to represent the marginal value for Middle Eastern crude oils. Note that there would appear to be no venting, flaring, or fugitive emissions and no N_2O emissions from combustion sources considered in the analyses. Some of these emissions were added in later versions of the JEC reports.

3.1.2 Refining

The energy use in the refining process is shown in the following table.

Table 3-2 Refining Assumptions – Marginal production

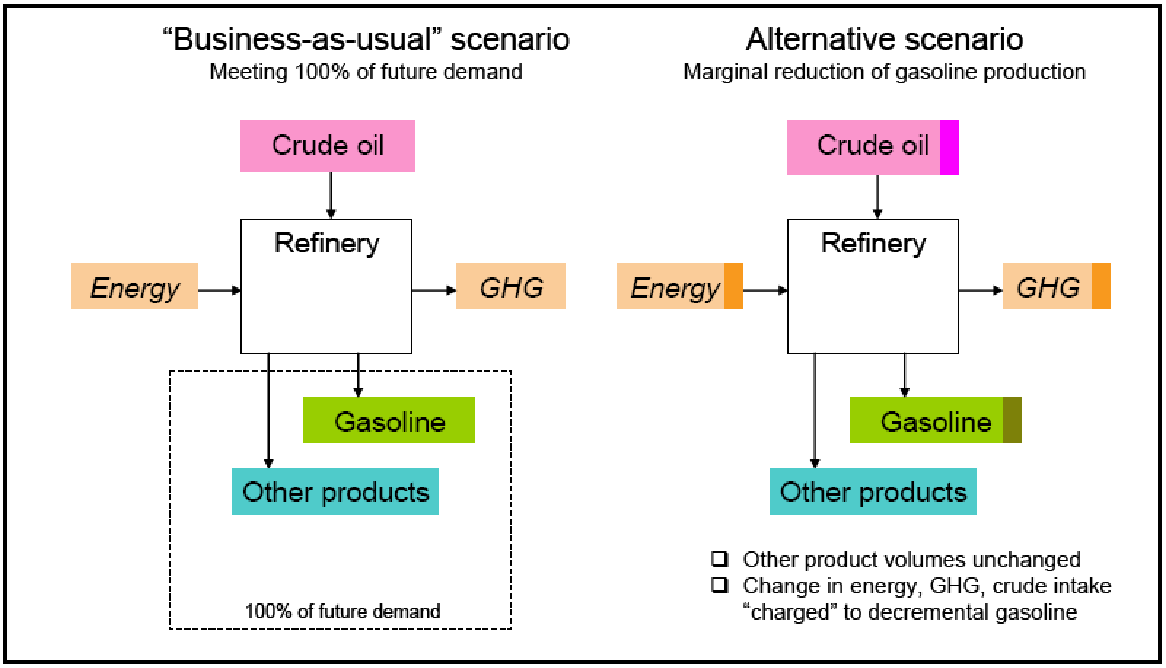
	I/O	Unit	Amount
Gasoline			
Crude oil	Input	$MJ/MJ_{Gasoline}$	1.08
Gasoline	Output	MJ	1.00
Diesel Fuel			
Crude oil	Input	MJ/MJ_{diesel}	1.10
Diesel	Output	MJ	1.00

The source for this is reported as Concawe, 2007 in the spreadsheet. The JEC report provides further information on the calculations.

> *This study therefore assumes that crude oil based fuels are manufactured from crude oil in European refineries. European refineries consume about 6% of their own intake as processing energy. Some energy is exchanged with the outside (e.g. electricity import/export, natural gas import). Although European refineries are global importers of energy/fuels other than crude oil, the bulk of the energy used by refineries comes from their crude oil intake. The refineries burn gas (mainly generated in the refinery processes) as well as liquid and solid fuels.*
>
> *In order to estimate the savings from conventional fuels the question to consider was what could be saved by using less of these rather than how much they cost in absolute terms. We thus considered that, in the context of this study, the energy and GHG emissions associated with production and use of conventional fuels should be representative of how the EU refineries would have to adapt to a marginal reduction of demand. Such figures were obtained through modelling of the EU-wide refining system.*
>
> *From this analysis it appears that, in Europe, marginal diesel fuel is more energy-intensive than marginal gasoline. In recent years Europe has seen an unprecedented growth in diesel fuel demand while gasoline has been stagnating or even dropping. According to all forecasts, this trend will continue in future years, driven by increased dieselisation of the personal car and the growth of freight transport in line with GDP. At the same time, jet fuel demand also steadily increases as air transport develops. The ratio of an ever increasing call for "middle distillates" and a call for gasoline that is at best constant goes beyond the "natural" capabilities of a refining system that was by and large designed with a focus on gasoline production. Reducing diesel fuel demand therefore "de-constrains" the system whereas decreasing gasoline demand makes the imbalance worse.*

This approach is shown graphically below.

Figure 3-2 Marginal Approach to Refinery Energy Use



Source: JEC

While the report acknowledges that some energy is sourced externally (electricity and natural gas), the spreadsheets appear to simply roll all energy into a crude oil equivalent.

3.1.3 Transportation of Crude and Refined Product

The crude oil transportation energy requirement assumptions are shown in the following table.

Table 3-3 Crude Oil Transportation Assumptions

	I/O	Unit	Amount
Crude oil	Input	$MJ/MJ_{crude\ oil}$	1.000
Heavy fuel oil	Input	$MJ/MJ_{crude\ oil}$	0.010
Crude oil	Output	MJ	1.000

The source of this assumption is the GM European Wells to Wheels Study (Choudhury et al, 2002). That study attributes the energy use and GHG estimate to Shell, who was a participant in that study.

The refined product transportation stages were calculated in significant detail as shown in the following table.

Table 3-4 Petroleum Product Transportation Assumptions

	I/O	Unit	Amount
Transport of Diesel via inland navigation over a distance of 500 km (one way)[7]			
Distance	Input	tkm/MJ_{Diesel}	0.012
Diesel	Input	MJ/MJ_{Diesel}	1.0000
Diesel	Input	MJ/tkm	0.504
Distance	Input	tkm	1.0000
Transport of Diesel via pipeline[8]			
Electricity	Input	MJ/MJ_{Diesel}	0.0002
Diesel	Input	MJ/MJ_{Diesel}	1.0000
Transport of Diesel via train over a distance of 250 km (one way)[9]			
Electricity	Input	MJ/MJ_{Diesel}	0.0002
Electricity	Input	MJ/tkm	0.2100
Distance	Input	tkm	1.0000
Diesel depot			
Electricity	Input	MJ/MJ_{Diesel}	0.00084
Transport of Diesel via a 40 t truck over a distance of 150 km (one way)			
Distance	Input	tkm/MJ_{Diesel}	0.0037
40 t truck (payload: 27 t)			
Diesel	Input	MJ/tkm	0.94
Road fuel filling station			
Electricity	Input	MJ/MJ_{fuel}	0.0034
Road fuel	Output	MJ	1.0000

The combined impact of all of these stages is an energy expenditure of 0.02 MJ/MJ of fuel delivered and GHG emissions of 1 g CO_2eq/MJ of fuel delivered.

3.1.4 Vehicle Use

The fuel properties used in the JRC work are summarized in the following table.

Table 3-5 Fuel Properties - JEC WTW Study

	Units	Gasoline	Diesel
Density	Kg/m^3	750	835
LHV	MJ/kg	42.9	43.0
	MJ/litre	32.2	35.9
Carbon Content	Fraction	0.870	0.862
CO_2 emissions	Kg/kg	3.19	3.16
	g/MJ	74.35	73.54

[7] 20% of the final fuel is transported to the depot via ship
[8] 60% of the final fuel is transported to the depot via pipeline
[9] 20% of the final fuel is transported to the depot via train

The JEC study considered a large number of vehicles; the emissions for the reference gasoline and diesel vehicle are shown in the following table. These are calculated here from the reported energy consumption (MJ/100 km) and GHG emissions g/km in the JEC report.

Table 3-6 Vehicle Emissions- JEC WTW Study

	Gasoline	Diesel
	g CO_2eq/MJ (LHV)	
Carbon dioxide	74.4	73.5
Methane	0.4	0.2
Nitrous oxide	0.4	1.6
CO_2eq	75.2	75.3

The CO_2 emissions appear to be calculated from the fuel properties and assume all carbon in the fuel is converted to CO_2. For CH_4, the JEC report states that the emissions were assumed to be 20 % of the applicable unburned hydrocarbon emission limit and for N_2O, the emissions were assumed to be 2% of the NOx emissions limit.

3.1.5 Lifecycle Emissions Summary

The petroleum fuel lifecycle emission results for the JEC 2008 study are shown in the following table for gasoline and diesel fuel. As shown above, there are a significant number of assumptions used in the modelling.

Table 3-7 2008 JEC Petroleum Fuel GHG Results

	2008 JEC WTW Study	
	Gasoline	Diesel
IPCC GWP	2001	
	g CO_2eq/MJ (LHV)	
Crude Oil Extraction (energy)	3.6	3.7
Crude Oil Venting, flaring, fugitives	0.0	0.0
Crude Oil Transport	0.9	0.9
Refining	7.0	8.6
Refined Products Distribution	1.0	1.0
Sub-total	12.5	14.2
Vehicle Use	75.2	75.3
Total	87.7	89.5

It can be seen that these results are higher than the reference fuel values used in BioGrace and as specified in the EU RED (83.5 g/MJ). Furthermore, the crude oil production stage excluded venting, and fugitive emissions. Because the emissions from the refining stage are not reported in detail in the JEC report, it is not possible to determine the source of the differences compared to the other models.

Version 3c of the JEC series does have different emissions than the earlier version and these are shown in the following table. Crude oil production emissions increase and vehicle emissions decrease due to lower emissions of methane and nitrous oxide.

Table 3-8 JEC Version 3 vs. Version 3c

	Gasoline		Diesel	
	Version 3	Version 3c	Version 3	Version 3c
Crude Oil Extraction	3.6	5.2	3.7	5.3
Crude Oil Transport	0.9	0.9	0.9	0.9
Refining	7.0	7.0	8.6	8.6
Refined Products Distribution	1.0	1.0	1.0	1.0
Sub-total	12.5	14.2	14.2	15.9
Vehicle Use	75.2	73.9	75.3	74.3
WTW	87.7	88.1	89.5	90.2

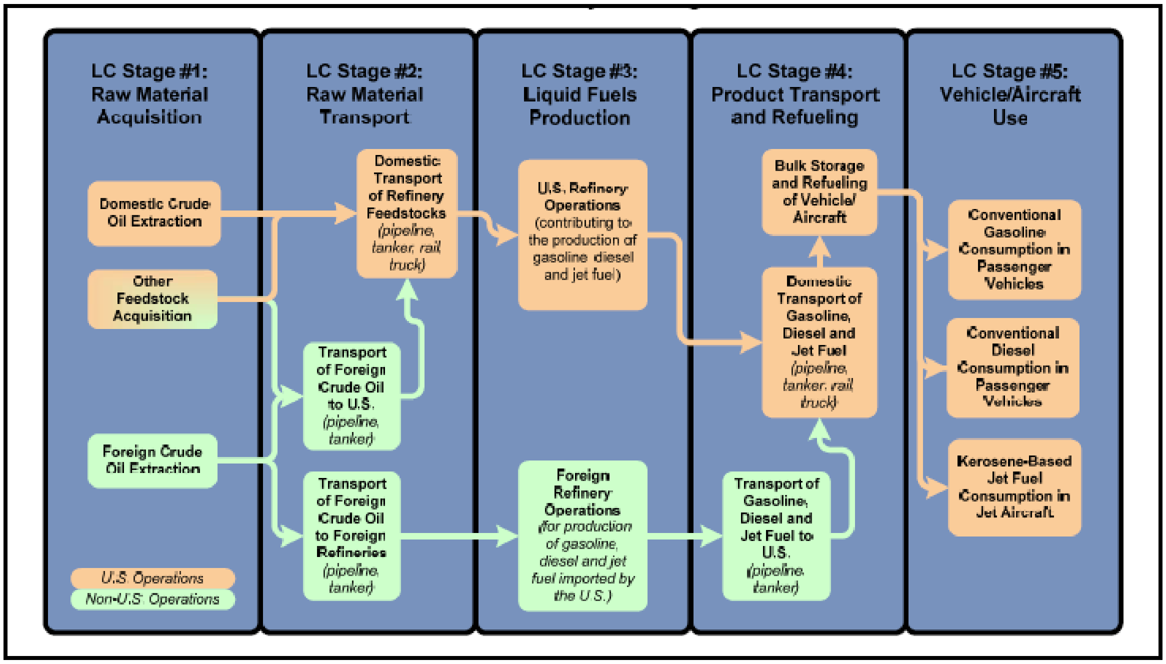
3.2 EPA RFS2

The US EPA RF2 framework for determining the petroleum fuel GHG emissions utilizes a different model and approach than the rest of the fuel pathways modelled by the EPA. The National Energy Technology Laboratory (NETL) undertook the analysis. The purpose of the NETL study was to develop a comprehensive and transparent baseline for the life cycle GHG emissions from conventional petroleum-based transportation fuels sold or distributed in the United States in the year 2005. The study goals and scope were aligned to meet the definition of "baseline lifecycle greenhouse gas emissions" as defined in the Energy Independence and Security Act of 2007 (EISA 2007), Title II, Subtitle A, Sec. 201.

A comprehensive report (NETL, 2008) and an Excel model (NETL, 2009) are available. The spreadsheet is more a documentation of the results than a model, as there are important aspects of the calculations that are done in another model (GaBi) and the resulting values are pasted into the NETL spreadsheet for further processing.

The stages and the boundaries considered by the NETL study are shown in the following figure. These are the same stages covered by the JEC WTW work.

Figure 3-3 NETL Study Stages



Source: NETL

The boundary of this study includes both domestic and foreign extraction of refinery feedstocks and fuels, transport to U.S. and foreign refineries (exporting transportation fuels to the U.S.), processing of petroleum to produce transportation fuels, transport to refuelling stations, and consumption in a light-duty passenger vehicle.

The NETL study used the 2007 IPCC GWPs. The EPA recalculated the final totals using the 1995 GWPs to be consistent with the rest of their analyses. For ease of extracting the data from the NETL report, the 2007 GWP information will be presented here. The cut-off criteria were established as 1% mass or 1% energy input into the system. All operations were considered pre-existing; therefore, no construction related emissions were included within the scope of this study.

The study team collected secondary data from a variety of sources and reduced it to the format required for the analysis. The scope of this study was the production and delivery of petroleum-based liquid transportation fuels sold or distributed in the United States in 2005. Consumption of transportation fuels in Puerto Rico and the Virgin Islands was excluded. The technology represents existing operations for 2005.

The primary source of U.S. petroleum refining operations data used in the analysis is the U.S. Department of Energy (DOE), Energy Information Administration (EIA) petroleum industry statistics.

The following table provides the summary of the NETL GHG emission results. No energy use data is available from the report. The reported data is presented as g/mmBTU (LHV) in the NETL model and has been converted to a g/MJ (LHV) basis for presentation here.

Table 3-9 NETL Well to Tank Emissions – Petroleum Fuels

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Crude oil to Gasoline				
Crude oil extraction and processing	6.92	4.62	0.09	0.00
Crude Transport	1.36	1.33	0.00	0.00
Refining	9.24	8.93	0.01	0.00
Distribution and dispensing	1.03	1.01	0.00	0.00
Total	**18.55**	**15.89**	**0.10**	**0.00**
Crude oil to Diesel				
Crude oil extraction and processing	6.27	4.21	0.08	0.00
Crude Transport	1.25	1.22	0.00	0.00
Refining	9.02	8.72	0.01	0.00
Distribution and dispensing	0.83	0.81	0.00	0.00
Total	**17.37**	**14.97**	**0.09**	**0.00**

3.2.1 Crude Oil Production

This stage of the lifecycle includes:

- The boundary includes extraction of raw feedstocks from the earth and any partial processing of the raw materials that may occur.
- Feedstocks include foreign and domestic crude oil, natural gas liquids, unfinished oils, and unconventional hydrocarbons (e.g. oil sands).

The sources of crude oil for US refineries in 2005 are shown in the following table. This information is from the EIA.

Table 3-10 Crude Oil Sources

Country	Barrels per day	% of Total
Algeria	228,381	1.5%
Angola	455,249	3.0%
Canada Conventional	1,102,578	7.2%
Canada Oil Sands	527,545	3.5%
Ecuador	275,973	1.8%
Iraq	522,805	3.4%
Kuwait	222,548	1.5%
Mexico	1,553,496	10.2%
Nigeria	1,076,816	7.1%
Saudi Arabia	1,437,458	9.4%
Venezuela	1,236,753	8.1%
Other	1,453,781	9.5%
United States	5,146,540	33.8%
Total	15,239,923	100.0%

The country-specific crude oil extraction profiles were purchased from PE International for the U.S. crude oil sources listed in Table 3-9, with the exception of Canada. The Canadian profile was derived independently by NETL. PE International is the provider of the GaBi software, a leading LCA tool. The information used in GaBi to model GHG emissions for crude oil production is derived from the International Oil and Gas Producers Association (OGP). OGP have been publishing an annual environmental review of their members operations since 2002. The 2004 report (with 2003 data) was the first to document energy use and emissions by region. It is this 2003 and 2004 OGP data that forms the basis of the energy consumption data within GaBi. In 2003 the OGP members produced 41% of the world's oil and in 2004 the quantity dropped to 34%. It has stayed at that level most years since then. There are seven regions in the OGP dataset, Africa, Asia/Australia, Europe, FSU, Middle East, North America, and South America. A single set of data is available for each region.

Flaring emissions are calculated separately using the data from the World Bank Global Gas Flaring Reduction Initiative. Venting emissions were calculated from data in the EIA International Energy Annual 2003. This data is available by country. It was not possible to determine if PE International interpreted the EIA data correctly and that it actually was venting emissions. The EIA reports CO_2 emissions for gas vented and flared and the quantity of gas flared. PE International calculated the CO_2 emissions for the quantity of gas flared, subtracted it from the emissions for flaring and venting and then, from the difference, calculated the quantity of gas vented. In most countries this resulted in 20% to 30% of the gas being vented rather than flared. The published NETL GHG emission profiles for each of the countries are summarized in the following table. These include energy related emissions, and venting and flaring emissions.

Table 3-11 NETL Crude Oil Emission Profiles

	CO_2	CH_4	N_2O	CO_2eq	
	Kg/BBL				g/MJ (LHV)
Algeria	24.0	0.435	0.000588	35.1	6.5
Angola	41.7	1.586	0.001372	81.8	14.1
Canada	24.1	0.436	0.000590	35.2	6.0
Canada Oil Sands	104	0.247	0.002830	111.0	18.3
Ecuador	21.4	0.388	0.000525	31.3	5.1
Iraq	13.4	0.243	0.000329	19.6	3.3
Kuwait	13.7	0.109	0.000277	16.5	2.8
Mexico	19.6	0.744	0.000644	38.4	6.3
Nigeria	65.6	2.494	0.002157	128.6	22.6
Saudi Arabia	25.1	0.682	0.000711	42.4	2.3
Venezuela	11.3	0.090	0.000228	13.6	3.9
Other	20.3	0.162	0.000411	24.5	4.2
United States	16.5	0.299	0.000405	24.1	6.5

There is a large degree of variability in the emissions profile for each of the crude oil sources. The source of crude oil will therefore have a large impact on the lifecycle GHG emissions. A large amount of the variability is caused by the venting and flaring emissions. The data used for these two sources is shown in the following table. NETL has assumed that the vented hydrocarbons contained 75% methane.

Table 3-12 NETL Flaring and Venting Factors

	Flared Hydrocarbons, kg/tonne oil	Vented Hydrocarbons, kg/tonne oil	Venting and Flaring, CO_2eq/MJ (LHV)
Algeria	30.0	4.1	3.8
Angola	61.0	17.0	11.6
Canada	7.2	4.3	2.4
Ecuador	33.0	1.1	2.7
Iraq	5.9	1.7	1.1
Kuwait	0.7	2.5	1.2
Mexico	22.0	5.5	3.9
Nigeria	100.0	29.0	19.5
Saudi Arabia	0.3	0.1	0.1
Venezuela	13.0	1.6	1.6
U.S.	3.7	0.9	0.7

As the NETL calculations included crude oil refined in the US, products imported into the US from foreign refineries, and the input of natural gas liquids and unfinished oils, it is a challenge to reconcile the individual country data in Tables 3-10 and 3-11 with aggregate values in Table 3-8. In the following table we have provided a breakdown of the crude oil production emissions with the components due to energy use, flaring and venting.

Table 3-13 Composition of Crude Oil Emissions

	Energy	Flaring	Vented	Total
	g CO_2eq/MJ			
Algeria	2.6	2.0	1.8	6.5
Angola	2.4	4.1	7.6	14.1
Canada (ex OS)	3.6	0.5	1.9	6.0
Ecuador	2.4	2.2	0.5	5.1
Iraq	2.2	0.4	0.8	3.3
Kuwait	1.6	0.0	1.1	2.8
Mexico	2.3	1.5	2.4	6.3
Nigeria	2.9	6.8	12.9	22.6
Saudi Arabia	2.3	0.0	0.0	2.3
Venezuela	2.3	0.9	0.7	3.9
U.S.	3.6	0.3	0.4	4.3
Weighted Average	2.9	1.2	2.1	6.2

3.2.1.1 Land Use Change Emissions

The EPA also considered emissions from land use change related to bitumen and synthetic oil produced in Alberta. The values found by the EPA analysis are shown in the following table. The oil sands contributed about 5% of the crude oil mix in 2005 and given the low emissions calculated by the EPA, they decided to exclude these land use emissions from the calculations.

Table 3-14 Oil Sands Land Use Change Emissions

	Average	Low	High
	g CO_2/MJ		
Gasoline			
Mining	0.36	0.28	0.54
In-situ	0.09	0.06	0.14
Diesel			
Mining	0.32	0.25	0.48
In-situ	0.08	0.05	0.12

3.2.2 Refining

The boundary of the refining stage starts at the entrance of the petroleum refinery with the receipt of feedstocks and ends at the entrance of the petroleum pipeline or tanker used to transport the liquid fuels to a bulk fuel storage depot.

The primary source of information used to determine greenhouse gas emissions for petroleum refineries is the EIA dataset compiled for U.S. refineries from individual government-mandated refinery surveys. EIA collects and compiles petroleum production and processing data from U.S. refineries and publishes most of the information on their website for public use.

The GHG emissions profile associated with U.S. petroleum refining operations in 2005 consists of emissions from the following activities/sources:

- Acquisition of fuels
  - Indirect emissions associated with purchased power and steam
  - Emissions associated with the acquisition of coal and natural gas purchased and consumed at the refinery as fuels
  - Emissions associated with production of fuels at the refinery which are subsequently consumed as fuels (i.e. still gas, petroleum coke)
- Combustion of fuels at the refinery
- Hydrogen production (on-site and off-site)
  - Upstream emissions associated with natural gas feed
  - CO_2 process emissions from steam methane reforming (SMR)
  - Fuel combustion and upstream emissions associated with natural gas fuel and indirect (electricity) emissions for off-site hydrogen production
- Flaring
- Venting and fugitive emissions

The model is a very thorough analysis of the energy use and emissions from all of the sources identified above. The approach is to first determine the total GHG emissions associated with the refinery and then to allocate the emissions to each of the products from the refinery. The total emissions[10] are shown in the following table.

[10] Excludes upstream emissions associated with fuels produced and consumed in refinery.

Table 3-15 Refinery Emissions

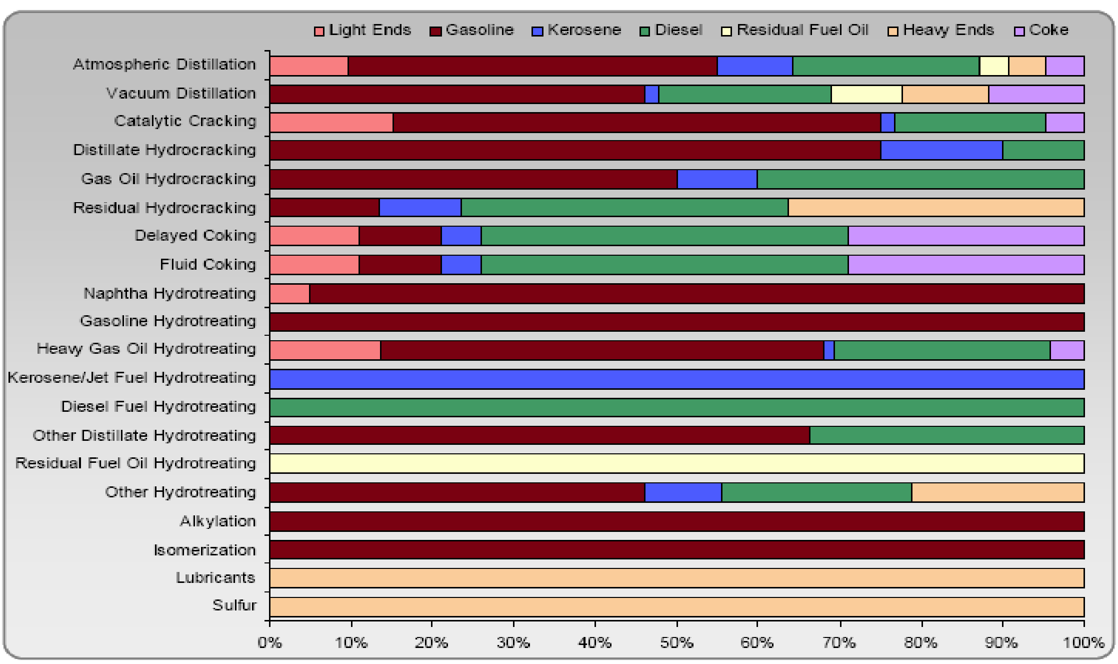
Source	kg CO_2eq/day	kg CO_2/day	kg CH_4/day	kg N_2O/day
Fuels Consumed	635,528,054	624,991,991	293,085	10,768
Fuels Combustion at Refinery	520,451,904	517,361,504	12,983	9,281
Purchased Steam & Electricity	96,645,442	93,451,488	113,716	1,178
Acquisition of Natural Gas and Coal	18,430,709	14,178,999	166,386	309
H_2 Production (not included in above)	79,131,377	76,321,567	109,133	273
Flaring	5,418,108	5,337,947	2,524	57
Venting/Fugitive Emissions	1,128,965		45,159	
Total	721,206,504	706,651,505	449,900	11,099

Refinery emissions and emissions associated with hydrogen production are allocated to products based upon each product's consumption of resources (hydrocarbon feedstocks, fuels/energy, and hydrogen). To do this, the individual unit operations within the refineries were modeled using the following steps:

1. Capacity/throughput is determined for each of the unit processes.
2. Energy requirements are determined for each of the unit processes.
3. Hydrogen consumption is determined for each of the unit processes.
4. Contribution of each of the unit processes to the final product slate is determined.
5. Resource usage (energy and hydrogen) is allocated to the product slate.

The results of these analyses are shown in the following figure.

Figure 3-4 Percent of Unit Volumetric Throughputs Allocated to Each Product



Source: NETL

The distribution of the product volume between products is different from the energy allocated to the products, the hydrogen consumption by each product and of course the GHG emissions attributed to each product. The differences are shown in the following table. Note that diesel fuel is attributed a larger share of the GHG emissions compared to its volume, whereas gasoline's share of GHGs and volume is similar.

Table 3-16 Allocation of Attributes between Products

	Gasoline	Diesel	Kerosene/ Kerosene-Type Jet Fuel	Residual Fuel Oil	Coke	Light Ends	Heavy Ends
Volume	45.2%	22.9%	9.3%	3.6%	4.8%	9.7%	4.4%
GHG	46.9%	26.2%	6.4%	2.9%	4.6%	6.3%	6.6%
Hydrogen	43.0%	37.7%	9.0%	3.4%	1.0%	3.3%	2.6%
Energy	47.4%	24.9%	6.1%	2.9%	5.0%	6.7%	7.0%

The results of the calculation of the total emissions and the allocation to the products are shown in the following table. It is apparent that much more detail is available from this model on the refinery emissions than is found in the other models.

Table 3-17 NETL Refinery Emissions

	CO_2eq	CO_2	CH_4	N_2O
Gasoline	g/MJ			
Refinery Fuels Combustion	6.09	6.06	0.0002	0.0001
Steam/Electricity Acquisition	1.13	1.09	0.0013	0.0000
Natural Gas/Coal Acquisition	0.22	0.17	0.0019	0.0000
Refinery-Produced Fuels Acquisition	0.85	0.71	0.0057	0.0000
H_2 Production	0.84	0.81	0.0012	0.0000
Flaring, Venting, Fugitive	0.08	0.06	0.0006	0.0000
Total	**9.21**	**8.90**	**0.0108**	**0.0001**
Diesel				
Refinery Fuels Combustion	5.63	5.59	0.0001	0.0001
Steam/Electricity Acquisition	1.05	1.01	0.0012	0.0000
Natural Gas/Coal Acquisition	0.20	0.15	0.0018	0.0000
Refinery-Produced Fuels Acquisition	0.79	0.65	0.0052	0.0000
H_2 Production	1.29	1.25	0.0018	0.0000
Flaring, Venting, Fugitive	0.07	0.06	0.0005	0.0000
Total	**9.02**	**8.72**	**0.0107**	**0.0001**

3.2.3 Transportation of Crude and Refined Product

The crude oil transportation energy consumption and GHG emissions are built up from the fraction of crude oil and the distances from the exporting country to the importing country. It has been assumed that there is 160 km of pipeline between the oil field and the foreign port.

There is also a small amount of crude oil transportation in the US to move the oil from the receiving port to the refinery. This is carried out by a combination of pipeline, ship and barge, rail, and truck transport. This category also includes the transport of crude oil to foreign refineries, which export refined products to the United States. The crude oil transportation emissions are shown in the following table.

Table 3-18 Crude Oil Transportation Emissions

	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Crude to US refineries				
Gasoline	1.45	1.42	0.0008	0.0000
Diesel	1.29	1.26	0.0007	0.0000
Crude to Foreign Refineries				
Gasoline	0.72	0.70	0.0004	0.0000
Diesel	0.56	0.55	0.0003	0.0000
Crude for US Consumption				
Gasoline	1.36	1.33	0.0007	0.0000
Diesel	1.25	1.22	0.0007	0.0000

Key assumptions for domestic transport include that all petroleum products travel the same distance on the same mix of transport modes. Foreign transport distances for Canada and Virgin Islands were determined using port-to-port data from EIA. All other petroleum product transport is assumed to be 8,000 km with the return trip allocated 50% to the product of interest. Pipeline transport from the foreign refinery to the foreign port of 16 kilometres is included. The petroleum product GHG emissions are summarized in the following table.

Table 3-19 Petroleum Product Transportation Emissions

	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Imported fuels				
Gasoline	1.88	1.85	0.0006	0.0000
Diesel	1.33	1.31	0.0005	0.0000
US produced fuels				
Gasoline	0.91	0.89	0.0006	0.0000
Diesel	0.80	0.79	0.0005	0.0000
Products for US Consumption				
Gasoline	0.99	0.97	0.0006	0.0000
Diesel	0.79	0.77	0.0005	0.0000

The final component of the stage is the dispensing emissions. These are shown below. The US average power carbon intensity from GaBi was used for this calculation.

Table 3-20 Petroleum Product Dispensing Emissions

	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Gasoline	0.038	0.037	0.0000	0.0000
Diesel	0.038	0.037	0.0000	0.0000

3.2.4 Vehicle Use

The vehicle emissions were developed by the EPA and are based on the EPA MOVES model. The emission results are shown in the following table.

Table 3-21 NETL Vehicle Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Gasoline	72.43	70.91	0.0046	0.0047
Diesel	72.44	72.38	0.0001	0.0002

3.2.5 Lifecycle Emissions Summary

The petroleum fuel lifecycle emission results for the EPA RFS2 work are shown in the following table for gasoline and diesel fuel.

Table 3-22 EPA RFS2 Petroleum Fuel GHG Results

	EPA RFS2 and NETL	
	Gasoline	Diesel
IPCC GWP	2007	
	g CO_2eq/MJ (LHV)	
Crude Oil Extraction (energy)	3.2	2.9
Crude Oil Extraction (VFF)	3.6	3.3
Crude Oil Transport	1.36	1.25
Refining	9.24	9.02
Refined Products Distribution	1.03	0.83
Sub-total	18.43	17.3
Vehicle Use	72.43	72.44
Total	90.98	89.61

3.3 GREET

The GREET model includes a full depiction of the petroleum pathways including the production not only of gasoline and diesel fuel, but also LPG, residual oil, naphtha and petroleum coke. Three grades of gasoline are available, conventional, RFG blendstock and California RFG blendstock. Gasoline including oxygenates can also be modelled. There are two grades of diesel fuel in the model, conventional and low sulphur diesel.

The results and discussion here focus on the default fuels in the model. In the year 2012, gasoline is a 44/56 blend of conventional and RFG (but we set the oxygen content in RFG to zero). The default diesel fuel is low sulphur diesel.

The model was run for the year 2012. The quantity of oil sands crude in the refinery mix does change with the year in the model but all of the conventional crude oil parameters are fixed. The oil sands represent 10.2% of the refinery input in 2012 and that is composed of 49.2% surfaced mined and 50.8% in situ production. Both are upgraded to synthetic crude before refining. The results for gasoline and diesel are summarized in the following table.

Table 3-23 GREET1_2012rev2 Petroleum Well to Tank Results

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Crude oil to Gasoline				
Crude oil extraction and processing	6.69	4.28	0.0958	0.0000
Crude Transport	1.08	1.00	0.0029	0.0000
Refining	10.80	9.89	0.0347	0.0001
Distribution and dispensing	0.56	0.53	0.0010	0.0000
Total	**19.12**	**15.70**	**0.1344**	**0.0002**
Crude oil to Diesel				
Crude oil extraction and processing	6.68	4.27	0.0957	0.0000
Crude Transport	1.08	1.00	0.0029	0.0000
Refining	10.79	9.89	0.0347	0.0001
Distribution and dispensing	0.51	0.48	0.0010	0.0000
Total	**19.06**	**15.64**	**0.1343**	**0.0002**

The following sections explore each of the stages in more detail.

3.3.1 Crude Oil Production

The crude oil production energy use and emissions in GREET can be determined for conventional crude oil, and for mined and in situ bitumen production and upgrading. The venting and flaring emissions can be separated from the energy related emissions. The modelling assumptions and data sources are described below.

The key modelling parameter for the emissions associated with conventional crude oil production is the efficiency for petroleum recovery. The model default value is 98% for conventional oil and it is constant over the modelling period from 1995 to 2020. The 2012 default for mining bitumen is 94.9% and for in situ bitumen is 86.4%. There are additional hydrogen requirements that are calculated separately and are not included in these efficiencies. The efficiency for upgrading bitumen is assumed to be 98.6% plus additional hydrogen. The data in GREET for oil sands production was obtained from an Alberta Chamber of Resources report (2004).

The shares of the process fuels that make up the energy use for each production method are shown below.

Table 3-24 Share of Process Fuels Crude Oil Extraction

	Conventional	Mined Bitumen		In Situ Bitumen	
		Extraction	Upgrading	Extraction	Upgrading
Crude oil	1.0%	0.0%	0.0%	0.0%	0.0%
Residual oil	1.0%	0.0%	0.0%	0.0%	0.0%
Diesel fuel	15.0%	0.6%	0.0%	0.0%	0.0%
Gasoline	2.0%	0.0%	0.0%	0.0%	0.0%
Natural gas	61.9%	82.3%	97.1%	97.2%	97.1%
Coal	0.0%	0.0%	0.0%	0.0%	0.0%
LPG					
Electricity	19.0%	17.1%	2.8%	2.8%	2.8%
Hydrogen	0.0%	0.0%	0.0%	0.0%	0.0%
Pet coke		0.0%	0.0%	0.0%	0.0%
Refinery still gas	0.0%	0.0%	0.0%	0.0%	0.0%
Feed Loss	0.1%	0.0%	0.1%	0.0%	0.1%

The 98% efficiency of conventional crude oil production has been in GREET since version 1.0 in 1996 (Wang, 1996). The sources cited for this are three reports from 1991 and 1992 by NREL, Delucchi, and Ecotraffic. These secondary data sources are now more than 20 years old.

The emissions for each of the three types of crude oil in GREET are summarized in the following table.

Table 3-25 Crude Oil Emissions – GREET

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Conventional oil				
Energy	2.05	1.77	0.011	0.000
Venting and Flaring	3.46	1.36	0.084	0.000
Total	5.51	3.12	0.095	0.000
Mined Bitumen				
Extraction	5.52	4.78	0.029	0.000
Upgrading	9.56	8.16	0.056	0.000
Venting and Flaring	0.51	0.19	0.013	0.000
Total	15.59	13.12	0.097	0.000
In Situ Bitumen				
Extraction	14.43	12.01	0.094	0.000
Upgrading	4.35	3.69	0.026	0.000
Venting and Flaring	0.00	0.00	0.000	0.000
Total	18.78	15.70	0.120	0.000

The venting and flaring emissions for conventional crude oil production are calculated from the 2008 EIA data on gas flaring and crude oil production to arrive at a flared gas/oil ratio for all of the producing countries that export to the US. A weighted average was calculated. It is further assumed that the combustion efficiency of the gas is 98%. The gas composition is 82.3% methane, 5% C3 plus C4, and 2.6% CO_2. The average flaring emissions are 1,004 grams CO_2 per GJ of crude oil and the vented emissions are 57 grams CH_4 per GJ of crude oil (Burnham et al, 2010).

One shortcoming of the GREET modelling of the oil sands is that it doesn't consider the possibility of bitumen being processed in a refinery rather than an upgrader. Almost 60% of the oil sands crude exported from Canada to the US were crude bitumen in 2011 (NEB, 2012). The energy required for upgrading in the refinery is already included in the refining energy use since actual data is used there, as discussed below.

3.3.2 Refining

The refining section of the GREET models has been updated a number of times to update the energy use data and to revise the allocation approach. In the latest model Argonne has used data from the 2011 EIA Annual Refinery Capacity Report (EIA 2011a) and the 2010 EIA Petroleum Supply Annual report (EIA 2011b) to update the process fuel use in U.S. refineries and the U.S. petroleum refinery input and output tables (Palou-Rivera et al, 2011).

The energy efficiency for all products except residual oil in GREET is now the same. The energy efficiency and distribution of fuel use is summarized in the following table. The impact of this decision is that the allocation of emissions in the refinery is equal for all products except residual oil. Early versions of GREET used different assumptions. GREET now considers refinery still gas a manufactured product and calculates the refinery emissions based solely on the primary inputs.

Table 3-26 GREET Refining Energy Use

	Gasoline, Diesel, LPG	Residual Oil
Energy efficiency	90.6%	96.3%
Share process fuel		
Residual oil	39.8%	39.8%
Diesel fuel	0.0%	0.0%
Gasoline	0.0%	0.0%
Natural gas	26.8%	26.8%
Coal	0.0%	0.0%
Liquefied petroleum gas	8.1%	8.1%
Electricity	4.3%	4.3%
Hydrogen	20.9%	20.9%
Pet coke	0.0%	0.0%
Refinery still gas	0.0%	0.0%
Feed loss	0.0%	0.0%

This new approach was described in a paper by Bredeson et al. (2010) which presents a modified allocation method that utilizes a hydrogen-energy equivalency to better allocate emissions consistently with refinery behaviour. The paper's conclusions show that the energy efficiencies of LPG, gasoline, and distillate (diesel and jet) products should be considered equal.

The GREET refining emissions for the two products of interest are shown in the following table. The small difference between the two products is related to a small difference in the loss factor for gasoline vs. diesel in GREET.

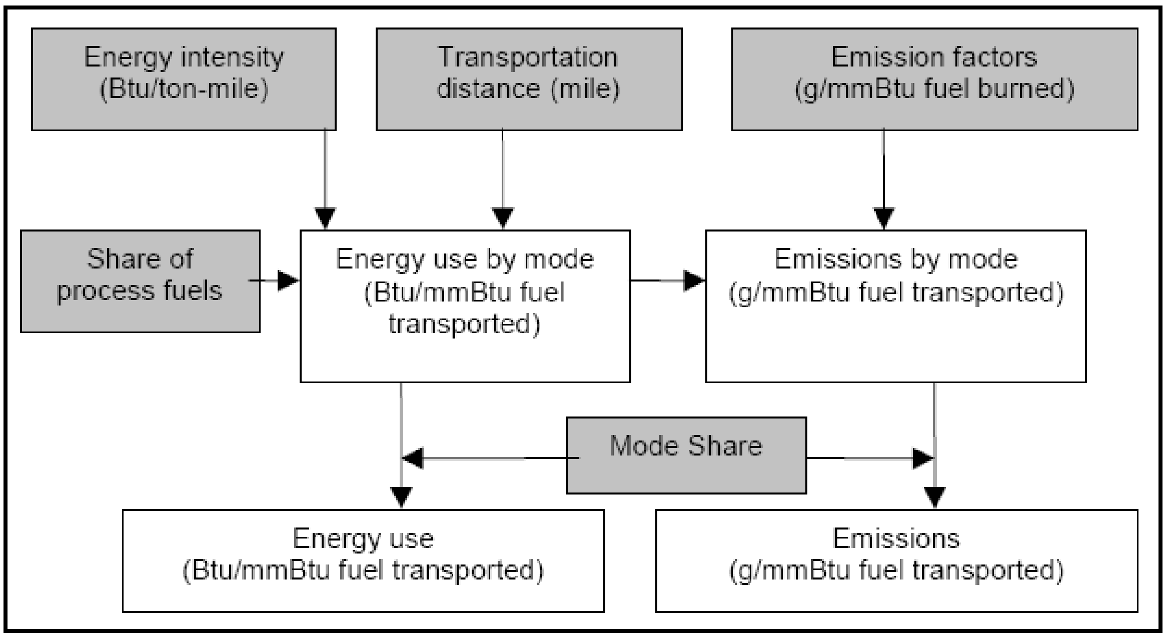
Table 3-27 GREET Refining Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	G/MJ			
Gasoline	10.80	9.89	0.0347	0.0001
Diesel	10.79	9.89	0.0347	0.0001

3.3.3 Transportation of Crude and Refined Product

The calculation logic used in GREET for the transportation emissions is shown in the following figure. It is similar to the logic used in other models.

Figure 3-5 Calculation Logic for Transportation Energy and Emissions



Source: GREET

Crude oil transportation emissions are developed using this approach from the estimated transportation modes, distances and the energy intensity of each mode of transport. This process is described in Part 1 of the GM Wells to Wheels study published in 2001 (GM et al, 2001). The assumptions used in the 2012 model are almost identical to the values used in the 2001 report. These volume shares are based on EIA data from 1999 and US DOT information from 1993. The transportation distances for crude are based on port to port distances and inland distances are from a 1997 Commodity Flow Survey from the US DOT.

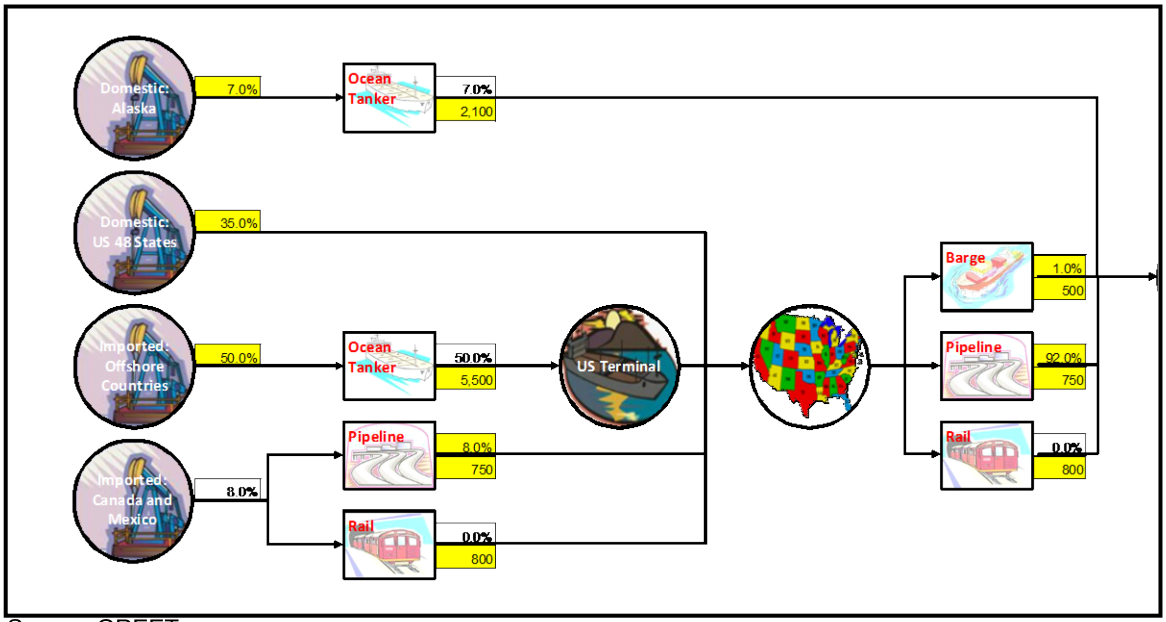
The default results are shown in the following table.

Table 3-28 Crude Oil Transportation

	Crude Oil		Oil Sands	
	Share	Distance (miles)	Share	Distance (miles)
Ocean Tanker	57.0%	5,082	58.0%	3,900
Barge	1.0%	500	0.0%	200
Pipeline	100.0%	750	42.0%	150
Rail	0.0%	800	0.0%	800

These model values are built up from the proportion of Alaskan oil, lower 48 state oil, conventional oil from Canada and Mexico, offshore oil production and the average transportation distances for each mode, as shown in the following figure. The yellow cells are user inputs and the imported from Canada and Mexico is calculated from other places in the model. The oil sands crude from Canada is calculated separately in a similar fashion.

Figure 3-6 GREET Transportation Inputs



Source: GREET

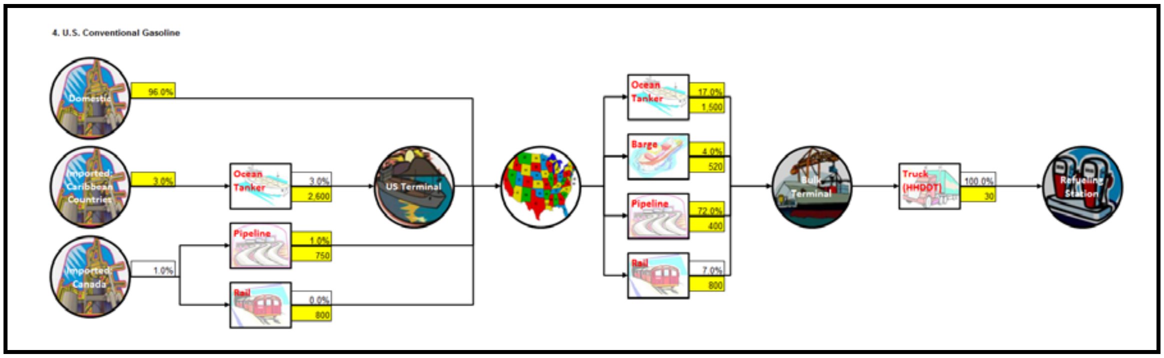
These assumptions result in the following results.

Table 3-29 Crude Oil Transportation Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	G/MJ			
Conventional crude	1.04	0.98	0.0021	0.0000
Oil Sands crude	1.25	1.15	0.0035	0.0000
Wt. Average	1.08	1.00	0.0029	0.0000

The petroleum product transportation emissions are calculated in a similar fashion to the crude oil emissions. The volume by mode and the transportation distances have been updated from the 2001 GM study.

Figure 3-7 Petroleum Product Transportation Inputs



Source: GREET

The petroleum product transportation emissions are summarized in the following table.

Table 3-30 Petroleum Product Transportation and Distribution Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Gasoline	0.56	0.53	0.0010	0.0000
Diesel	0.51	0.48	0.0010	0.0000

The emissions associated with fuel dispensing are not included in GREET1_2012.

3.3.4 Vehicle Use

The vehicle emissions from GREET are shown in the following table. The CO_2 emissions include the carbon in the carbon monoxide and unburned hydrocarbons that is ultimately oxidized to carbon dioxide in the atmosphere.

Table 3-31 GREET Vehicle Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Gasoline	73.61	72.84	0.0026	0.0024
Diesel	75.81	74.94	0.0006	0.0029

3.3.5 Lifecycle Emissions Summary and CA-GREET

As noted earlier, a different version of GREET is being used in California for the Low Carbon Fuel Standard (LCFS) program there. It is based on GREET 1.8b but has been modified by California to be more California specific. The latest changes made to CA-GREET were undertaken in September 2012, when the crude oil extraction and transportation emissions were updated with new detailed information from the OPGEE model developed by Adam Brandt of Stanford (Brandt, 2012) to estimate emissions from crude oil production on a field basis.

The CA-GREET model uses the 2007 IPCC GWP. The CA GREET model was also run for the year 2010, whereas we have run the latest GREET for the year 2012, although this has only a small impact on the results.

The following table compares the CA-GREET values with the GREET1_2012rev2 values for gasoline (CARBOB for California) and diesel fuel. The latest values from CA-GREET include crude transportation calculations as part of the crude oil extraction stage and thus they are not available separately. However, the calculation methodology is similar (more detailed in the new CA-GREET) and many of the GREET emission factors were used in the calculations.

Table 3-32 CA-GREET vs. GREET1_2012rev2

	GREET1_2012	CA-GREET	GREET1_2012	CA-GREET
	Gasoline		Diesel	
	g CO_2eq/MJ			
Crude Oil Extraction (energy)	2.38	11.39	2.38	11.39
Crude oil VFF	2.42	-	2.42	Inc.
Crude Oil Transport	2.97	-	2.96	Inc.
Refining	10.80	13.72	10.79	11.41
Refined Products Distribution	0.56	0.36	0.51	0.33
Sub-total	19.12	26.27	19.06	23.13
Vehicle Use	73.61	72.91	75.81	74.90
Total	92.73	99.18	94.87	98.03

There are a number of differences between the two models, some are a result of California values versus national values, but others reflect changes in the GREET model or updates applied by CARB.

The largest difference is in the crude oil extraction stage. The CA-GREET now uses the OPGEE model (Brandt, 2012) to estimate the emissions from producing crude oil. The results from this model have simply replaced the value previously calculated by GREET. The OPGEE output includes energy related emissions, venting, flaring and fugitive emissions and crude oil transportation emissions. It is a weighted average of all sources of crude oil used by California refineries in 2010. It is the most detailed estimate undertaken to date of the GHG emissions associated with particular crude oils but it does still rely on a large number of assumptions and default values. On the other hand, the GREET value relies on an old, poorly documented estimate of energy use in oil production.

The refinery emissions difference is caused by a difference in refining efficiency, a difference in allocation between the products, and a different mix of fuels used in the refinery. The differences are summarized below. The different mix of refinery fuel is caused, in part, by a different treatment of pet coke and still gas as intermediate products in the refinery in the model. California refineries do have more stringent product standards to meet, but they also process heavy, higher sulphur crude oils than the average US refinery, which will also lead to higher refining energy use and emissions.

Table 3-33 Differences in CA-GREET

	GREET1_2012	CA-GREET
Gasoline refining efficiency	90.6%	84.5%
Diesel refining efficiency	90.6%	86.7%
Share process fuel		
Crude oil	0.0%	0.0%
Residual oil	39.8%	3.0%
Diesel fuel	0.0%	0.0%
Gasoline	0.0%	0.0%
Natural gas	26.8%	30.0%
Coal	0.0%	13.0%
Electricity	8.1%	4.0%
Hydrogen	4.3%	0.0%
Pet coke	20.9%	
Refinery still gas	0.0%	50.0%

The refined products distribution emissions are lower in the CA-GREET version as they utilize California specific modes of transport and distances. California has twice the truck emissions but only 13% of the pipeline distance and none of the ocean tanker or barge emissions. The distances are compared in the following table. The truck fraction is more than 100% because some fuel is moved by truck to an intermediate storage point before it is then moved to the retail outlet.

Table 3-34 Comparison of Refined Product Transportation

	GREET1_2012		CA-GREET	
	Mode fraction	Distance	Mode fraction	Distance
Ocean Tanker	0.20	1,665	0	3,900
Barge	0.04	520	0	200
Pipeline	0.73	405	0.80	50
Rail	0.07	800	0	0
Truck	1.0	30	1.19	50

The small differences in vehicle emissions are driven by different assumptions on the density of the gasoline and diesel fuel used in California.

3.4 GHGENIUS

GHGenius has information in the model for Canada and the United States and can further analyze the emissions on a regional basis. This feature can be used to show regional variation as well as allowing the region to be chosen that facilitates the best comparison with the other models. For comparison purposes the model was run for the US average situation, the year 2012, and the 2007 IPCC GWPs. Fifteen percent of the crude oil is sourced from Canada on a weight basis. Forty two percent of this oil is oil sands derived, with 25% being bitumen and 17% being upgraded bitumen (synthetic oil). The summary of the results is shown in the following table.

Table 3-35 GHGenius Petroleum Well to Tank Results

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Crude oil to Gasoline				
Crude oil extraction and processing	10.39	8.27	0.0818	0.0003
Crude Transport	2.04	1.94	0.0034	0.0001
Refining	12.18	11.31	0.0260	0.0007
Distribution and dispensing	1.37	1.30	0.0023	0.0000
Total	25.99	22.83	0.1134	0.0011
Crude oil to Diesel				
Crude oil extraction and processing	10.54	8.41	0.0824	0.0003
Crude Transport	2.08	1.98	0.0035	0.0001
Refining	11.73	10.93	0.0254	0.0005
Distribution and dispensing	1.39	1.32	0.0023	0.0000
Total	25.74	22.64	0.1135	0.0009

The following sections explore each of the stages in more detail.

3.4.1 Crude Oil Production

The crude oil production emissions are calculated using logic similar to that used in the NETL model. There are different values for different countries and the petroleum flow between the producing countries and the consuming countries determines the crude oil production emissions. The average values for conventional crude oil, and mined and in situ bitumen upgraded to synthetic crude oil (SCO) are shown in the following table.

Table 3-36 Crude Oil Emissions – GHGenius

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Conventional oil				
Energy	7.48	6.84	0.0223	0.0003
Venting and Flaring	2.49	1.03	0.0584	0.0000
Total	9.97	7.87	0.0807	0.0003
Mined Bitumen				
Extraction	8.03	7.72	0.0093	0.0003
Upgrading to SCO	9.97	9.40	0.0291	-0.0005
Venting and Flaring	2.38	0.01	0.0948	0.0000
Total	20.38	17.13	0.1332	-0.0003
In Situ Bitumen				
Extraction	8.60	8.21	0.0119	0.0003
Upgrading to SCO	20.53	18.18	0.0889	0.0004
Venting and Flaring	1.81	0.01	0.0721	0.0000
Total	30.94	26.39	0.1728	0.0008

The emissions are provided for a number of different activities, crude oil transportation, feedstock upgrading (where bitumen is processed into synthetic crude oil), land use change associated with bitumen production, co-product credits in the upgrading process, as well as the energy use and venting and flaring emissions. The emissions for these additional stages for the combined US crude oil slate are shown in the following table. The small emissions displaced credit is from the co-products of upgrading bitumen (LPG and naphtha).

Table 3-37 GHGenius Crude Oil Emissions

	Gasoline	Diesel
	g CO_2eq/MJ	
Feedstock transmission	2.04	2.08
Feedstock recovery	7.64	7.77
Feedstock Upgrading	0.30	0.31
Land-use changes, cultivation	0.02	.02
Gas leaks and flares	2.45	2.45
Emissions displaced	-0.01	-0.01
Total	12.44	12.62

3.4.2 Refining

The US refining energy use in GHGenius is based on the EIA data for energy consumed in the refineries. This information is regionalized in the model. The energy use for individual products is allocated to the various products based on the estimated energy use for each product group. The model automatically checks to ensure that the sumproduct of the energy allocated to each product equals the total refinery energy use. Since different regions can have different refinery energy use and different slates of products produced the fraction of energy allocated to each product varies from region to region. Compared to GREET, more energy is allocated to gasoline and diesel fuel in GHGenius.

Table 3-38 GHGenius Refining Energy Use

	Percent Energy Use
Refinery energy efficiency	91.75%
Refinery Energy Use by Type	
Crude oil	0.00
Residual oil	0.20
Diesel fuel	0.60
Gasoline	0.00
Natural gas	18.40
Coal	2.61
Liquefied petroleum gas	0.34
Electricity	6.07
Hydrogen	10.71
Pet coke	15.60
Refinery still gas	41.63
Steam	3.78

The refinery emissions from GHGenius are summarized in the following table. The process emissions are allocated either to all products or just to gasoline and distillates, depending on the process. Compared to GREET, the methane emissions are lower and the N_2O emissions are higher. GHGenius also has some non-energy related process emissions, these amount to 0.8 to 1.2 g CO_2eq/MJ and include CO_2 from blowdown systems, methane emissions and a small quantity of N_2O.

Table 3-39 Refining Emissions - GHGenius

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Gasoline	12.18	11.31	0.0260	0.0007
Diesel	11.73	10.93	0.0254	0.0005

3.4.3 Transportation of Crude and Refined Product

The transportation emissions for crude oil and petroleum products is calculated using a similar logic to GREET, the distance and mode of transportation are the primary inputs and emission factors are used for the various modes of transportation. The crude oil transportation assumptions are shown in the following table. The data was assembled from various sources with most sources reporting data for the 2005 to 2010 period. These include the Association of Oil Pipelines, and the US Army Corps of Engineers. The information is described in more detail in the 2010 US Update report ((S&T)^2, 2011). The ocean tanker distance is calculated by the model based on the source of the crude oil.

Table 3-40 Crude Oil Transportation - GHGenius

	US Crude Oil	
	Share	Distance (kilometres)
Ocean Tanker	52%	10,573
Barge	21%	181
Pipeline	91%	1,747
Rail	3%	100
Truck	4%	50

These input factors produce the following emissions.

Table 3-41 Crude Oil Transportation Emissions

Fuel Type	CO_2	CH_4	N_2O	CO_2eq
	g/MJ			
Gasoline	1.94	0.0034	0.0001	2.04
Diesel	1.98	0.0035	0.0001	2.08

The petroleum product transportation assumptions and emissions are shown in the following tables.

Table 3-42 Petroleum Products Transportation - GHGenius

	US Crude Oil	
	Share	Distance (kilometres)
Ocean Tanker	6%	7,077
Barge	26%	418
Pipeline	80%	455
Rail	20%	300
Truck	100%	60

These input factors produce the following emissions.

Table 3-43 Petroleum Products Transportation Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	g/MJ			
Gasoline	0.99	0.94	0.0017	0.0000
Diesel	1.01	0.96	0.0017	0.0000

3.4.4 Vehicle Use

The vehicle use emissions in GHGenius are calculated slightly differently than the other models. The CO_2eq emissions do not include the carbon in the CO and the VOC that are eventually oxidized to CO_2. This is important for the gasoline pathway but not for the diesel pathway since the emissions of CO and VOCs from diesel vehicles are very low.

Table 3-44 GHGenius Vehicle Emissions

Fuel Type	CO_2eq	CO_2	CH_4	N_2O
	G/MJ			
Gasoline	68.96	67.86	0.0067	0.0031
Diesel	75.21	74.16	0.0046	0.0032

3.4.5 Lifecycle Emissions Summary

The GHGenius results for gasoline and diesel fuel are shown in the following table in the same format as has been presented for the other models.

Table 3-45 GHGenius Petroleum Fuel GHG Results

	GHGenius	
	Gasoline	Diesel
IPCC GWP	2007	
	g CO_2eq/MJ (LHV)	
Crude Oil Extraction (energy)	7.94	8.09
Crude Oil Extraction (VFF)	2.45	2.45
Crude Oil Transport	2.04	2.08
Refining	12.18	11.73
Refined Products Distribution	1.37	1.39
Sub-total	25.99	25.74
Vehicle Use	68.96	75.21
Total	94.95	100.95

3.5 SUMMARY

Each of the four models has been discussed in some detail and now the results for each of the models are presented and discussed below. In most cases the differences in the model results can be explained. The differences are driven not only by data from different time periods, different geographies, and different GWPs (real reasons for variability) but also by decisions and assumptions that have been made by the modellers. There are some differences in system boundaries and allocation approaches used between the models.

3.5.1 Gasoline

The gasoline results are compared in the following table. All of the studies except the JEC assessment used the 2007 GWPs, and the version 3c of the JEC continuing work in this area published in October 2011 switched to the 2007 GWPs. Version 3c was not used for this work because we used the version that was closest to the version used in the BioGrace model. The CA GREET model has the highest emissions. GHGenius does not consider the oxidation of the CO and HC emissions to CO_2 and this is the reason that the GHGenius vehicle use emissions are lower than the other models, which either include this source of CO_2 or calculated the emissions just from the carbon content of the fuel.

Table 3-46 Petroleum Fuels Summary - Gasoline

	BioGrace/JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	2007	2007	2007	2007
	g CO_2eq/MJ (LHV)				
Crude Oil Extraction	3.6	3.2	2.38	11.39	7.94
Crude Oil VFF	0.0	3.6	2.42	inc	2.45
Crude Oil Transport	0.9	1.36	2.97	inc	2.04
Refining	7.0	9.24	10.80	13.72	12.18
Refined Products Distribution	1.0	1.03	0.56	0.36	1.37
Sub-total	12.5	18.43	19.12	26.27	25.99
Vehicle Use	75.2	72.43	73.61	72.91	68.96
Total	87.7	90.98	92.73	99.18	94.95

The stage with the largest difference in results is the crude oil production stage. The two models with the most robust methodology, CA-GREET and GHGenius have the highest emissions. The JEC and GREET crude oil emissions from energy use are based on expert opinion assumptions, whereas the other three models are based on calculations using secondary data. The RFS2 venting, flaring and fugitive emissions have high venting and fugitive emission but low flaring emissions since they assume greater than 99.9% methane destruction in the flares. The CA-GREET energy use in the crude oil stage is influenced by the significant production of thermally enhanced production in California. The JEC analysis either excludes venting flaring and fugitive emissions or has them at such a low rate they are reported as zero.

Crude oil transportation emissions should vary depending on the location of the refinery and the locations of the oil fields. Beyond that there are assumptions that need to be made concerning the size of the tankers and the energy use in the tankers.

There are also large differences in the refining stage between the JEC model and the other models. Some of this may be due to the average vs. marginal approach used for the data, although it is unusual that the marginal emissions are lower than the average emissions. As the emissions from the refining stage are not reported in detail in the JEC report, it is not possible to determine the source of the differences compared to the other models.

The NETL, GREET and GHGenius models all rely on data on fuel consumption in refineries produced by the DOE Energy Information Administration. The models choose data for different years and can use different emission factors. The hydrogen consumed in the refineries can be produced inside the refinery gate or purchased. It is only in the past couple of years that the EIA has been reporting hydrogen purchased and natural gas purchased for hydrogen production. NETL calculated hydrogen production emissions separately from other energy related emissions; they extrapolated hydrogen purchases from some 2003 data. One area of uncertainty is the composition of the refinery still gas, which makes up about 50% of the energy consumed in the refinery. NETL use an emission factor of 60.7 kg CO_2eq/GJ of still gas, GHGenius used 58.7 for US refineries and CA GREET assumes the emissions are the same as natural gas. GREET1_2012 estimates the emissions based on the primary energy consumed to avoid the consumption of still gas.

With GREET and GHGenius it is easy to change the GWPs to determine the impact that they have on the results. This is done in the following table using GHGenius. The difference between the 1995 and 2007 GWPs is relatively small but the 2007 GWPs do produce higher GHG emissions by about 0.45% in these two models.

Table 3-47 Impact of GWP on Gasoline Results

	GHGenius		
	1995 GWP	2001 GWP	2007 GWP
	g CO_2eq/MJ (LHV)		
Crude Oil Extraction	10.07	10.27	10.39
Crude Oil Transport	2.03	2.04	2.04
Refining	12.09	12.14	12.18
Refined Products Distribution	1.36	1.36	1.37
Sub-total	25.55	25.81	25.99
Vehicle Use	68.97	68.95	68.96
Total	94.52	94.76	94.95
% Change		0.25	0.45

3.5.2 Diesel Fuel

The diesel fuel results from the models are presented in the following table. They are similar to the gasoline results. The largest variation is again in the crude oil production stage (combined extraction, VFF, and transport).

Table 3-48 Petroleum Fuels Summary - Diesel

	BioGrace/JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	2007	2007	2007	2007
	g CO_2eq/MJ (LHV)				
Crude Oil Extraction	3.7	2.9	2.38	11.39	8.09
Crude Oil VFF	0.0	3.3	2.42	inc	2.45
Crude Oil Transport	0.9	1.25	2.96	inc	2.08
Refining	8.6	9.02	10.79	11.41	11.73
Refined Products Distribution	1.0	0.83	0.51	0.33	1.39
Sub-total	14.2	17.3	19.06	23.13	25.74
Vehicle Use	75.3	72.44	75.81	74.90	75.21
Total	89.5	89.61	94.87	98.03	100.95

The allocation of the emissions to gasoline, diesel fuel, and other products is different in the various models. The gasoline and diesel emissions are summarized in the following table and the ratio of the emissions is also presented.

Table 3-49 Allocation of Refining Emissions

	BioGrace/JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	2007	2007	2007	2007
	g CO_2eq/MJ (LHV)				
Gasoline Refining	7.0	9.24	10.80	13.72	12.18
Diesel Refining	8.6	9.02	10.79	11.41	11.73
Ratio	0.81	1.02	1.00	1.20	1.04

Again we see a range of results. The JEC work used marginal emission values for the refining emissions. Since these refineries are stressed to maximize diesel production it is not surprising that the marginal diesel emissions are higher than the marginal gasoline emissions. The NETL work involved a very detailed assessment of the emissions for each process unit and the contribution of each process unit to the gasoline and the diesel fuel pools. GREET and GHGenius use allocation approaches. GREET changed their approach to this between versions 1.8 and GREET1_2012. The difference between the values in GHGenius is from non-energy related emissions, which are allocated in a similar manner to NETL, whereas the energy related emissions are allocated similar to the approach used in the new, GREET1_2012. There are also some differences in the allocation of emissions to the other products; this can move the gasoline and diesel fuel emissions up or down, depending on the values used.

3.5.3 Oil Sands

The NETL, GREET and GHGenius all consider the emissions from Canadian oil sands. The results from the three models are discussed here. The data sources that NETL used are not lifecycle emissions, they are site emissions and thus any fuel produced at another site and used for oil sands production does not include the production emissions for that fuel. The NETL also used two single facilities (one for bitumen and one for synthetic) to represent the industry. The GREET emissions are for mined bitumen that is upgraded to synthetic crude oil. The model only uses the upgraded crude oil for further processing at refineries. The GHGenius data is industry average data. The synthetic includes mostly mined production (less energy intensive than in situ production) and the bitumen is mostly in situ production and it includes some primary production (produced without steam assist) so the difference between the two values does not represent the upgrading emissions. Bitumen and synthetic crude oil have different densities so reporting the data on a per barrel basis for comparison is misleading, so a tonne of oil is used as the functional unit here.

Table 3-50 Oil Sands Emissions – per Tonne

	NETL	GREET	GHGenius
	kg CO_2eq/tonne		
Bitumen	518	257	544
Synthetic	962	687	940

Crude oil emissions are sometimes reported on a per barrel basis. This can be misleading since the density and energy content of different crude oils can provide an unequal comparison. Nevertheless the results per barrel are shown below. It is assumed that the bitumen has an API gravity of 8 and the synthetic oil has an API gravity of 32.

Table 3-51 Oil Sands Emissions – per Barrel

	NETL	GREET	GHGenius
	kg CO_2eq/bbl		
Bitumen	81.2	40.3	85.2
Synthetic	176.7	126.2	172.7

The NETL and GHGenius results are quite close but the GREET results are quite a bit lower. Argonne has plans to update the oil sands pathways in GREET this year.

4. NATURAL GAS

Natural gas use as a transportation fuel has received increased attention in recent years as North American gas production has increased and the continent is moving from a gas importer to a gas exporter. Increased natural gas use in the transportation sector would serve to reduce crude oil imports and reduce the need to build LNG facilities to export excess production.

The natural gas pathway for this project is the traditional fossil natural gas production system. The BioGrace and EPA modelling frameworks being studied have a biofuel focus and thus they do not have detailed fossil natural gas pathways. Natural gas is an input into most of the biofuel systems, so both of these models do have some information on natural gas emissions. The limited data is discussed below along with the more detailed information on the other models.

4.1 BIOGRACE

BioGrace is designed to facilitate the calculation of emissions of biofuels and it does not have a natural gas pathway in the model. There are two standard emission values for natural gas production and use in the model, one for Russian gas and another for the EU mix. The emission data for the two sources is shown in the following table, note that the bulk of the emissions are from combustion. The source of the values is reported to be the LBST E3database (2012).

Table 4-1 BioGrace Natural Gas Lifecycle Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Natural gas (4000 km, Russian NG quality)	66.20	61.58	0.1981	0.0002
Natural gas (4000 km, EU Mix quality)	67.59	62.96	0.1981	0.0002

The E3database is a tool for Life-Cycle Analyses and Well-to-Wheel Analyses. It allows identification and comparison of all types of supply chains/pathways; be they energy, products or services. The E3database provides results on energy use, air pollutant and greenhouse gas emissions and costs of pathways. It is a commercial product and is not publicly available.

The JEC version 3c of the Wells to Wheels study reports the following values for NG. This is just for the gas delivery to point of use. If the gas is used as CNG, there are additional emissions associated with the compression and dispensing.

Table 4-2 JEC Natural Gas Extraction and Processing Emissions

	g $CO_{2\text{-}eq}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
NG Extraction and Processing stage				
Energy	1.13	1.13	0.0000	0.0000
CO_2 Venting	0.55	0.55	0.0000	0.0000
Methane losses	2.08	0.00	0.0833	0.0000
Sub Total	3.76	1.68	0.0833	0.0000
Pipeline Transport, 4000 km				
Compression stage				
NG consumption and emissions	4.91	4.83	0.0007	0.0002
Methane losses	2.56	0.00	0.1051	0.0000
Sub total	7.47	4.83	0.1058	0.0002
Total	11.23	6.51	0.1891	0.0002

The JEC study uses a value of 56.4 g CO_2eq/MJ of fuel combusted (assuming complete combustion). This would result in GHG emissions of 67.63 g CO_2eq/MJ, approximately the same value used in BioGrace.

The JEC version 3c report provides the following additional information on the natural gas processing and extraction stage.

> *This process includes all energy and GHG emissions associated with the production and processing of the gas at or near the wellhead. Beside the extraction process itself, gas processing is required to separate heavier hydrocarbons, eliminate contaminants such as H_2S as well as separate inert gases, particularly CO_2 when they are present in large quantities.*
>
> *The associated energy and GHG figures are extremely variable depending a/o on the location, climatic conditions and quality of the gas. The figures used here are reasonable averages, the large variability being reflected in the wide range [Source: Shell]. We have not accounted for any credit or debit for the associated heavier hydrocarbons, postulating that their production and use would be globally energy and GHG neutral compared to alternative sources. The figure of 1% v/v for venting of separated CO_2 reflects the low CO_2 content of the gas sources typically available to Europe. For sources with higher CO_2 content, it is assumed that re-injection will be common at the 2015-20 and beyond horizon. 0.4% methane losses are included [Source: Shell].*

The transmission energy is reported to be the average of several values of existing pipelines. The methane loss from the pipelines is 0.13% for each 1000 km of distance. The source is reported as Wuppertal (2004).

4.2 EPA RFS2

Like BioGrace, the EPA RFS2 framework has a focus on biofuels and not alternative transportation fuels. There was not a complete analysis of the natural gas for vehicles pathway completed as part of this work. Natural gas is used in many biofuel pathways and the EPA framework utilizes emission factors that were extracted from version 1.8c of the GREET model. These are shown below.

Table 4-3 RFS2 Natural Gas Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
NG Production	8.9	4.9	0.185	0.000
NG Use	55.9	55.6	0.001	0.001
Lifecycle	64.8	60.5	0.186	0.001

These emissions are slightly lower than the JEC emissions for both natural gas production and transmission and fuel use.

4.3 GREET

GREET has a full analysis of natural gas production and use as a transportation fuel. There is the potential to model North America natural gas, non-North American natural gas, non-North American flared gas, and renewable natural gas. The results presented here will be for North American natural gas (the default setting in the model). There are two natural gas production systems within GREET, conventional gas and shale gas. Data will be presented on both systems as well as the combined system (72% conventional gas and 28% shale gas). The summary of the results for CNG from the combined production systems is shown in the following table.

Table 4-4 GREET CNG Summary

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
NG Recovery	10.97	2.14	0.3528	0.0000
NG Processing	3.65	2.63	0.0404	0.0000
NG Transmission	4.44	0.57	0.1546	0.0000
NG Compression	5.29	4.94	0.0131	0.0001
Sub Total	24.35	10.28	0.5609	0.0002
Vehicle operation	57.56	56.24	0.0250	0.0023
Grand Total	81.91	66.52	0.5859	0.0025

The compressed natural gas lifecycle emissions are lower than the gasoline lifecycle emissions primarily due to the lower carbon to hydrogen ratio of the fuel resulting in lower emissions per unit of energy produced when the fuel is used. The upstream emissions for compressed natural gas are higher than the similar emission stages for gasoline or diesel fuel in GREET. A large component of these emissions is from methane emissions in the gas recovery and gas transmission stages.

The natural gas pathways were updated in GREET in 2012 and the details are described in a published paper (Burnham et al, 2012).

4.3.1 Natural Gas Production

The natural gas production stage includes the extraction of the gas from the reservoir but does not include the processing of the gas in a gas plant to upgrade the gas to pipeline quality. There is some energy consumed in the process and there are venting and fugitive emissions of methane.

The energy efficiency for this stage of the process is modelled as 95.7%. Early versions of GREET used 97.0%. The energy use has a relatively small impact on the production emissions, accounting for about 1.3 g CO_2eq/MJ. The remainder of the emissions are from flaring or venting operations.

Table 4-5 GREET NG Production Emissions

	g $CO_{2\text{-}eq}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Conv Gas	12.06	2.16	0.3955	0.0000
Shale gas	8.21	2.08	0.2450	0.0000
Combined Systems	10.97	2.14	0.3528	0.0000

Methane contributes most of the GHG emissions in the gas recovery stage. The emission factors used in GREET are derived mostly from the EPA 2009 National GHG Inventory (2011) and the Technical Support Document for the GHG Emission Reporting for the Petroleum and Natural Gas Sectors (2010). The key parameters are summarized in the following table.

Table 4-6 Methane Emission Factors – Gas Recovery

	Conventional Gas	Shale gas
	Methane, % Gas Produced	
Well completion and workovers (venting)	0.03	0.46
Liquid unloadings (venting)	1.20	0.00
Well equipment (leakage and venting)	0.73	0.73
Total	1.96	1.19

The difference between the conventional gas production and the shale gas production is primarily the difference in methane leakage rates, the shale gas systems having a lower emission rate.

4.3.2 Processing

At the surface the gas must be processed to remove water, excess carbon dioxide, hydrogen sulphide and other contaminants. This process generally requires energy and will result in some emissions of carbon dioxide and methane. The emissions are summarized in the following table.

Table 4-7 GREET NG Processing Emissions

	g $CO_{2\text{-}eq}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Conv Gas	3.68	2.63	0.0416	0.0000
Shale gas	3.57	2.63	0.0374	0.0000
Combined Systems	3.65	2.63	0.0404	0.0000

Both production systems have a methane emission rate of 0.15% of natural gas processed and a CO_2 emission rate of 0.832 g/MJ of gas processed. Both emission factors are from the EPA GHG Inventory data. The energy efficiency of this stage of the production process is 97.2%. The energy use accounts for about 1.8 g CO_2/MJ with the rest of the CO_2 being accounted for by the CO_2 released from the gas in the process of meeting the pipeline specifications.

4.3.3 Transportation

The transportation of the gas through the high pressure gas transmission system involves the use of compressors to achieve the pressure to move the gas and from methane losses from the system. The methane loss is 0.67% through the transmission stage.

The energy consumption is calculated based on an assumed distance of 1200 km and an energy intensity for gas turbines and natural gas engines of 330 kJ/tonne-km (456 BTU/ton-mile) (both the same). The emissions from this stage are shown in the following table.

Table 4-8 GREET NG Transmission Emissions

	g CO_{2-eq}/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Conv Gas	4.45	0.57	0.1550	0.0000
Shale gas	4.42	0.57	0.1537	0.0000
Combined Systems	4.44	0.57	0.1546	0.0000

4.3.3.1 Gas Compression

For use as a transportation fuel, the gas must be compressed or liquefied to increase the storage density. Compression of the gas to 4,800 psia from a pipeline pressure of 50 psia is the default case in GREET. The model calculates electric power requirements of 0.27 kWh/kg of gas for an electric drive compressor and 0.71 kWh/kg for a gas engine driven compressor. The default case is 100% electric drive.

The emissions for compression are shown in the following table.

Table 4-9 GREET NG Compression Emissions

	g CO_{2-eq}/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Conv Gas	5.25	4.94	0.0113	0.0001
Shale gas	5.31	4.94	0.0139	0.0001
Combined Systems	5.29	4.94	0.0131	0.0001

The compressor inlet pressure is a major driver of the compression energy requirements. Increasing the inlet pressure to 100 psia reduces the compression emissions by 15%.

4.3.3.2 Gas Liquefaction

Natural gas engines drive the liquefaction of natural gas in the model. The energy efficiency of the liquefaction stage is 91%.

LNG production facilities are located close to the gas fields (80 km) and the LNG is moved 50% (1287 km) by rail and 50% by barge (837 km) to a bulk terminal and then 50 km by truck to the refuelling station. The natural gas transmission emissions will be lower for the LNG cases than the CNG cases as the distances are shorter.

There are some boil off losses included (0.1% per day the production plant, the transportation to the bulk terminal, and at the bulk terminal) and it is assumed that 80% of these losses are recovered and utilized.

Table 4-10 GREET NG Liquefaction Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Conv Gas	10.13	7.27	0.11	0.00
Shale gas	9.73	7.26	0.10	0.00
Combined Systems	10.02	7.27	0.11	0.00

4.3.4 Vehicle Use

The GREET vehicle use emissions are shown in the following table. GREET uses slightly different gas compositions for CNG and LNG, which drives the small difference in vehicle CO_2 emissions.

Table 4-11 GREET NG Vehicle Use Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
CNG	57.56	56.24	0.0250	0.0023
LNG	57.79	56.48	0.0250	0.0023

4.3.5 Lifecycle Emissions Summary and CA GREET

CARB developed pathways for CNG from North American gas (CARB, 2009) and LNG from North American and remote gas sources (CARB, 2009b).

The CA GREET model modifications include the use of the California power mix and there were changes to the methane emission rates in the transmission sector to reflect data from California gas utilities. There will also be differences created by the update of the GREET model since version 1.8b.

The differences in the key parameters for the two models are summarized in the following table for both the CNG and LNG pathways.

Table 4-12 Key Parameters – GREET vs. CA GREET

	CNG		LNG	
	GREET 2012	CA GREET	GREET 2012	CA GREET
NG Recovery				
Process Efficiency	95.7%	97.2%	95.7%	97.2%
Leakage rate	1.74%	0.35%	1.74%	0.35%
NG Processing				
Process Efficiency	97.2%	97.2%	97.2%	97.2%
Leakage rate	0.15%	0.15%	0.15%	0.15%
Transmission				
Pipeline distance	750 miles	1,000 miles	50 miles	1,400 miles
Energy intensity	456 BTU/ton-mile	344 BTU/ton-mile		
Leakage rate	0.67%	0.08%	0.67%	0.08%
CNG Compression				
Efficiency	97.1%	98.0%		
LNG				
Liquefaction efficiency			91%	80%
Transport distance			520 to 800 miles	50 to 250 miles
Transport mode			Barge, Rail, and Truck	Truck

There are significant differences in leakage rates at the recovery stage due to new data being available for the 2012 versions of GREET. CARB used slightly higher efficiency for CNG compression but a lower efficiency for LNG production compared to GREET1 2012. The CARB model also uses California incremental power with a lower carbon intensity.

The GREET 2012 results for CNG and LNG using the blend of conventional and shale gas are shown in the following table and compared to the results from the CA GREET model. The variances in the primary model inputs identified above account for most of the differences seen in the following table.

Table 4-13 GREET and CA GREET NG Summary

	CNG		LNG	
	GREET 2012	CA GREET	GREET 2012	CA GREET
	g CO_2eq/MJ			
NG Recovery	10.97	3.5	10.89	3.5
NG Processing	3.65	3.7	3.62	3.7
NG Transmission	4.44	0.97	0.21	0.97
NG Compression/Liquefaction	5.29	2.14	10.02	16.43
Sub Total	24.35	10.31	24.74	24.63
Vehicle Operation	57.56	57.7	57.79	58.5
Total	81.91	68.0	82.70	83.13

4.4 GHGENIUS

GHGenius has a full analysis of natural gas production and use as a fuel. For this work, the model has been set to the US region and the year 2012. While shale gas can be modelled separately in GHGenius in Canada, when the model is set to the United States there is just the emissions for the total gas supply. The GHGenius natural gas summary is shown in the following table. One difference is that the total of gas leaks and flares is shown as a separate item, rather than the leaks in each stage being reported in the stage that they occurred in as in GREET.

Table 4-14 GHGenius CNG Summary

	NG for Industry	CNG	LNG
	g CO_2eq/MJ (LHV)		
Fuel dispensing/compression/liquefaction	0.00	3.85	9.35
Fuel distribution and storage	4.15	4.62	4.83
Fuel production	1.39	1.39	1.39
Feedstock transmission	0.00	0.00	0.00
Feedstock recovery	5.28	5.29	5.29
Gas leaks and flares	8.21	10.02	8.97
CO_2, H_2S removed from NG	0.87	0.87	0.87
Total	19.88	26.05	30.70
Fuel Use	57.05	59.56	59.59
Grand Total	76.93	85.61	90.29

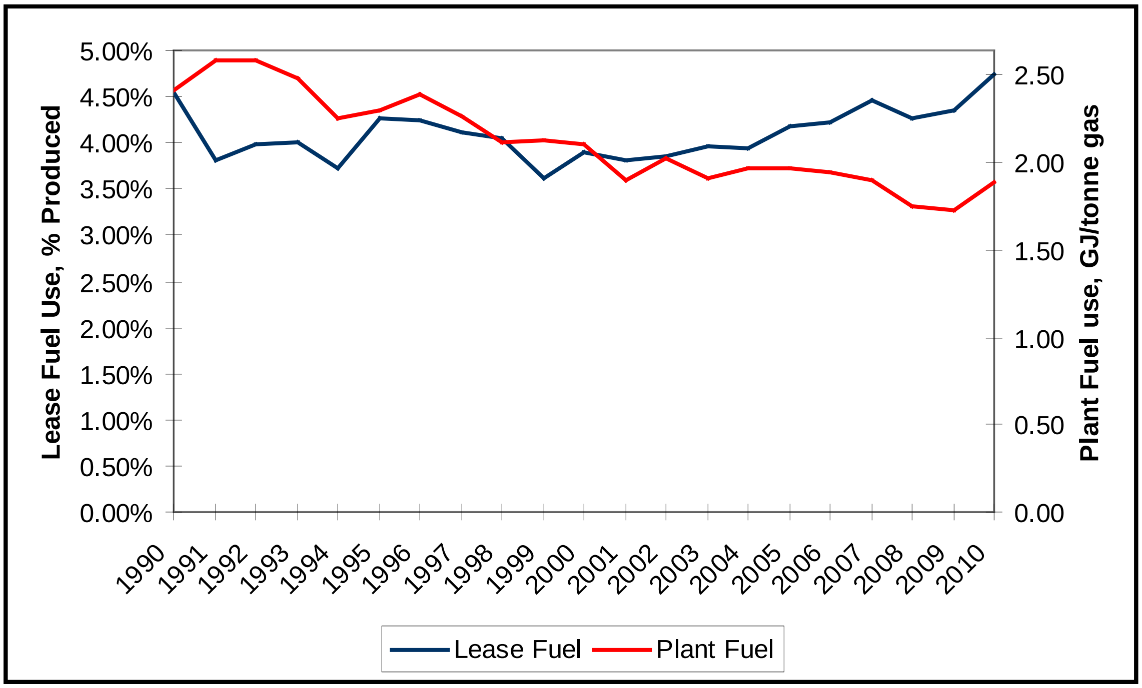
The stages that are reported in the model are different than the standard stages that are being used for reporting here. In the following sections each of the standard stages being used here will be reported on along with the important data sources.

4.4.1 Natural Gas Production

The natural gas production stage includes the extraction of the gas from the reservoir but does not include the processing of the gas in a gas plant to upgrade the gas to pipeline quality. There is some energy consumed in the process and there are venting and fugitive emissions of methane.

The energy use in the gas production sector in the United States has been derived from information from the US EIA, which reports "lease fuel" as part of the annual natural gas supply data and the Energy Outlook. The EIA also reports the natural gas consumption by end use (http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm), and in this data it separates the lease fuel into lease fuel and plant fuel. The historical data is shown in the following figure.

Figure 4-1 Lease and Plant Fuel Consumption US Natural Gas Production



The emissions for the gas production stage in GHGenius are shown in the following table.

Table 4-15 GHGenius NG Production Emissions

	g CO_{2-eq}/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Recovery	5.19	4.24	0.0353	0.0002
Venting and Flaring	4.43	0.00	0.1769	0.0000
Total	9.62	4.24	0.2122	0.0002

Methane contributes about half the GHG emissions in the gas recovery stage. The emission factors used in GHGenius are derived mostly from the EPA 2009 National GHG Inventory (2011). The methane loss rate for this stage is 1.08% for the year 2012.

4.4.2 Processing

At the surface the gas must be processed to remove water, excess carbon dioxide, hydrogen sulphide and other contaminants. This process generally requires energy and will result in some emissions of carbon dioxide and methane. Historical energy use data for the United States processing sector is available from the EIA as noted in the previous section. This data is used in the model for US gas processing. The emissions are summarized in the following table.

Table 4-16 GHGenius NG Processing Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Gas Processing	1.29	1.15	0.0053	0.0000
Venting and Flaring	1.57	0.86	0.0282	0.0000
Total	2.86	2.01	0.0335	0.0000

The methane loss rate in the GHGenius model is 0.174% in 2012. This is developed from the 2009 US National GHG Emission Inventory (2011).

4.4.3 Transportation

The transportation of the gas through the high-pressure gas transmission and distribution system involves the use of compressors to achieve the pressure to move the gas. The methane loss is 0.654% through the transmission and distribution stage. This is developed from the 2009 US National GHG Emission Inventory (2011).

Table 4-17 GHGenius NG Transmission Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Gas Transmission and Distribution	4.29	4.10	0.0069	0.0000
Venting	3.20	0.00	0.1281	0.0000
Total	7.49	4.10	0.1350	0.0000

4.4.3.1 Gas Compression

For use as a transportation fuel, the gas must be compressed or liquefied to increase the storage density. Compression of the gas to 3600 psia from a pipeline pressure of 65 psia is the default case in GHGenius. The model calculates electric power requirements of 0.22 kWh/kg of gas for an electric drive compressor. This is a less severe compression case than is presented in GREET.

The emissions for compression are shown in the following table.

Table 4-18 GHGenius NG Compression Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Gas Compression	3.80	3.67	0.0043	0.0001
Venting	1.61	0.00	0.0644	0.0000
Total	5.41	3.67	0.0687	0.0001

4.4.3.2 Gas Liquefaction

GHGenius can use electricity or natural gas to drive the liquefaction process. Since GREET uses natural gas, this option has been chosen. The energy efficiency of the liquefaction stage is 88%.

There are some boil off losses included (0.5% per transfer, three transfers included) and it is assumed that 50% of these losses are recovered and utilized. These are higher losses with less recovery than are used in GREET. No public data is available on the few operating LNG for transportation facilities in North America.

Table 4-19 GHGenius NG Liquefaction Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
Gas Liquefaction	8.25	8.09	0.0061	0.0000
Venting	1.50	0.00	0.0599	0.0000
Total	9.75	8.09	0.0660	0.0000

4.4.4 Vehicle Use

The GHGenius vehicle use emissions are shown in the following table. They are almost identical for CNG and LNG. These emissions are derived from Mobile 6.2C data in GHGenius. For the post 2004 period, Mobile 6.2C assumed that natural gas and gasoline have the same CAC exhaust emissions.

Table 4-20 GHGenius NG Vehicle Use Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
CNG	59.56	54.75	0.1429	0.0023
LNG	59.59	54.74	0.1443	0.0023

4.4.5 Lifecycle Emissions Summary

The lifecycle emissions for the natural gas pathways in GHGenius are generally similar to those in GREET. The GHGenius CNG summary is shown in the following table. The breakdown of the emissions by stage shown in the following table is not the normal presentation of the data. It is derived by zeroing the methane emissions for all stages but the stage of interest, unfortunately doing it this way results in emissions that are slightly lower than the total due to the iterative nature of the model. The subtotal and grand totals shown below are correct but the subtotal line is slightly higher than the total of the four lines above it.

Table 4-21 GHGenius CNG Emissions

	g $CO_{2\text{-eq}}$/MJ	g CO_2/MJ	g CH_4/MJ	g N_2O/MJ
NG Recovery	9.62	4.24	0.2122	0.0002
NG Processing	2.86	2.01	0.0335	0.0000
NG Transmission	7.49	4.1	0.135	0.0000
NG Compression	5.41	3.67	0.0687	0.0001
Sub Total	26.05	14.12	0.4727	0.0003
Vehicle operation	59.56	54.75	0.1429	0.0023
Grand Total	85.61	68.87	0.6156	0.0026

4.5 SUMMARY

The emissions for natural gas used as an industrial fuel from all four models are shown in the following table. The RFS2 values are based on an earlier version of GREET and had relatively low methane losses. BioGrace and the RFS2 data are similar and both have relatively low methane loss rates. GREET and GHGenius results are also similar and have similar, but higher methane loss rates. The data that is available on methane loss rates from the Canadian natural gas production and distribution system are lower than the US rates. As a result, when GHGenius is set to Canada, the emissions are lower than are shown here. This issue will be discussed in more detail in the variability section.

Table 4-22 Natural Gas as Industrial Fuel Summary

	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA GREET	
GWP	2001	1995	2007	2007	2007
	g CO_2/MJ (LHV)				
NG Production	3.8	4.9	11.0	3.5	9.6
NG Processing	-	-	3.6	3.7	2.9
NG Transportation	7.5	-	4.4	0.97	7.5
NG Combustion	56.4	55.6	57.6	57.7	57.0
Lifecycle	67.7	60.5	76.6	62.4	77.0

Using the natural gas as CNG produces different results, as there is extra energy that must be expended to compress the gas. There is no public reporting of the compression energy required and the different models have different methods of calculating/estimating the emissions.

The CNG results for the two versions of GREET and GHGenius are compared in the following table. As noted earlier CARB has used much lower methane loss rates than are in GREET1_2012 and in GHGenius and a lower amount of compression energy. This results in lower lifecycle emissions. The GREET and GHGenius rates are fairly close, the largest difference is in the transmission and distribution emissions. The GHGenius emissions are calculated from the pipeline energy use reported by the EIA and the reported quantity of gas moved. The transmission distance assumption in GHGenius is 1887 km (1173 mi) and in GREET this distance is assumed to be 1200 km (746 mi).

Table 4-23 CNG as Vehicle Fuel Summary

	GREET	CA GREET	GHGenius
	g CO_2/MJ (LHV)		
NG Production	10.97	3.5	9.62
NG Processing	3.65	3.7	2.86
NG Transportation	4.44	0.97	7.49
NG Compression	5.29	2.14	5.41
NG Use	57.56	57.7	59.56
Lifecycle	81.91	68.0	84.94

The LNG results from the three models are compared in the following table. Like the CNG systems, there is little public data available on the liquefaction energy requirements. GREET chose to locate the LNG plant close to the gas field and had lower natural gas transmission emissions as a result of that. CARB used a much lower liquefaction efficiency than was used in either GREET or GHGenius. The CARB pathway also benefits from the low methane loss rates used in their modelling.

Table 4-24 LNG as Vehicle Fuel Summary

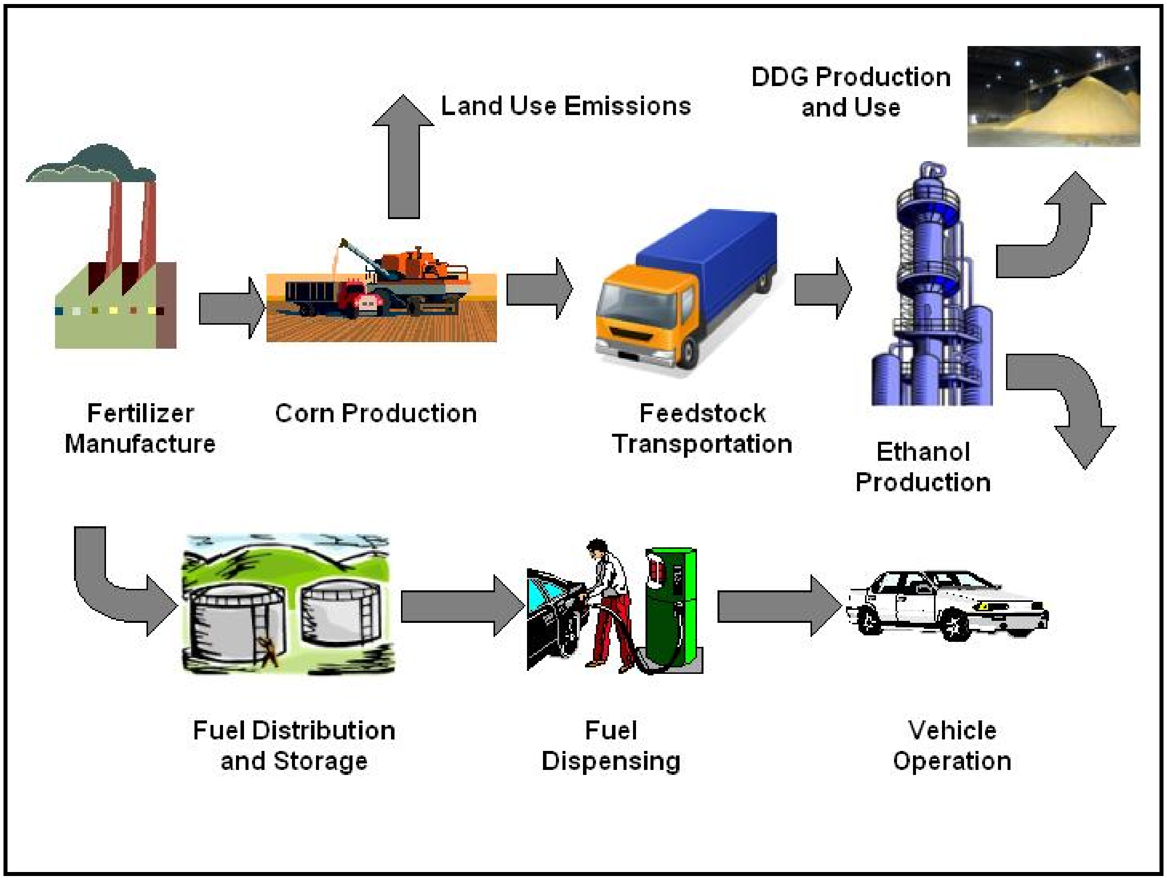
	GREET	CA GREET	GHGenius
	g CO_2/MJ (LHV)		
NG Production	10.89	3.49	9.62
NG Processing	3.62	3.74	2.86
NG Transportation	0.21	0.97	7.49
NG Liquefaction	7.96	15.79	9.75
LNG Transportation	2.06	0.64	0.98
NG Use	57.79	58.5	59.59
Lifecycle	82.53	83.13	90.29

Transportation emissions for a low density fuel like LNG are higher than they are for liquid transportation fuels for the same distance travelled. The quantity of energy moved per kg of truck is lower due to both the lower energy density and the fact that heavier fuel tanks are required for a cryogenic fuel like LNG. The transportation assumptions are therefore more critical for LNG than they are for gasoline or diesel fuel.

5. CORN ETHANOL

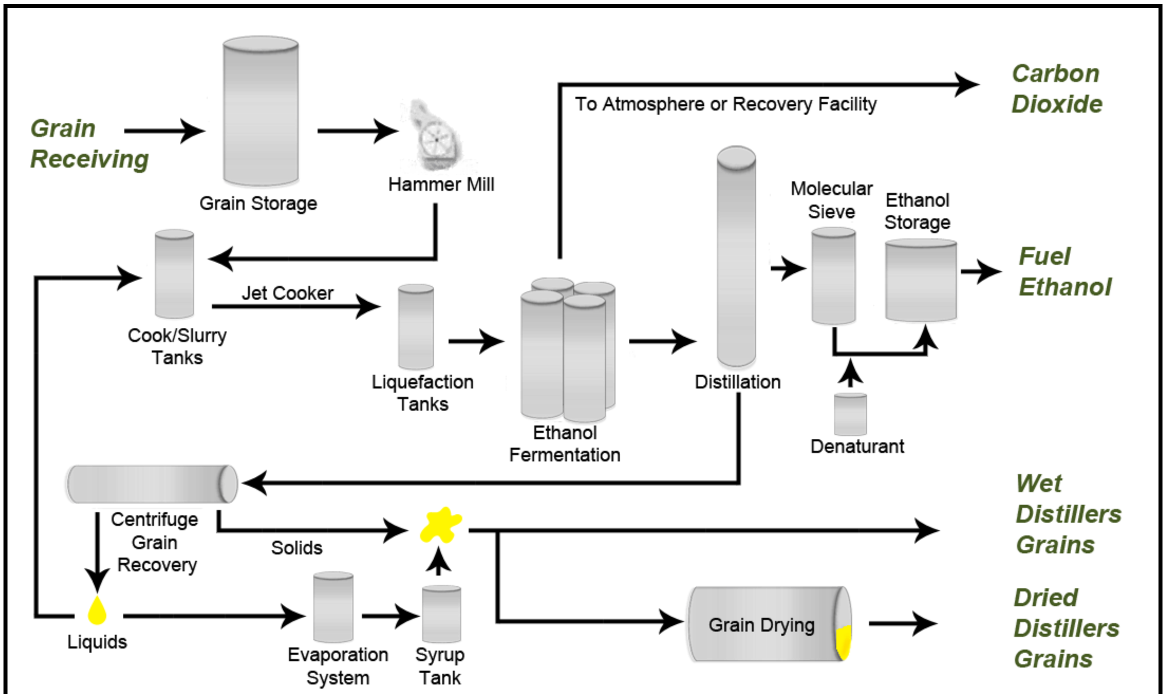
There are five primary stages for the corn ethanol lifecycle, the corn production stage (which will include fertilizer manufacturing and land use emissions), feedstock transportation, ethanol manufacturing, ethanol transportation, distribution and dispensing, and the vehicle use stage. Again the ethanol distribution, storage and dispensing stages are combined, as the contributions are small. The stages are shown in the following figure.

Figure 5-1 General System Boundaries – Corn Ethanol



Most of the corn ethanol is produced in dry mill facilities and all of the models have natural gas fired dry mill pathways, so this will be the focus of the comparison undertaken here. In a dry mill process the entire corn kernel is ground into flour. The starch in the flour is converted to sugar by elevating the temperature of the "mash" in the presence of enzymes and the resulting sugar is converted to ethanol during the fermentation process, creating carbon dioxide and distillers grain. A typical process is shown in the following figure.

Figure 5-2 Dry Mill Ethanol Process



Source: (S&T)[2]

5.1 BioGrace

BioGrace models a corn ethanol pathway with European produced corn and a natural gas fired combined heat and power ethanol plant. The model uses allocation by energy content for the co-product from distillers grains and can use either the 2001 or the 2007 IPCC GWPs. The 2001 values are used in the RED and these will be used here.

The BioGrace results for this pathway are summarized in the following table. BioGrace calculates default values by increasing the expected energy use in the processing stages by 40% as required by the European Union Renewable Energy Directive (RED), a plant that uses actual values would be expected to have lower emissions. In this case, the expected emissions drop from 43.4 to 37.2 g CO_2eq/MJ. BioGrace also does not include any vehicle emissions. The combined heat and power plant produces significant amounts of surplus electricity and this produces a significant GHG benefit.

Table 5-1 BioGrace Corn Ethanol Well to Tank Emissions[11]

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	36.78	23.19	0.030	0.044
Feedstock Transport	0.51	0.51	0.000	0.000
Ethanol Production	86.01	80.13	0.252	0.000
Co-product credit (power)	-46.73	-42.99	-0.140	-0.002
Co-Product credit (DDG)	-34.75	-27.61	-0.064	-0.019
Ethanol Distribution	1.538	1.50	0.001	0.000
Total	43.40	34.72	0.079	0.023

Each of the stages is investigated in more detail in the following sections.

5.1.1 Feedstock Production

The inputs for the corn production are shown in the following table along with the GHG impacts of each of the inputs. The source for these inputs is reported to the GEMIS 4.3 model (JEC RED parameters, 2008c). GEMIS (Global Emissions Model for integrated Systems) is a public domain lifecycle and material flow analysis model and database that IINAS provides freely. GEMIS was first released in 1989, and has been continuously updated and extended since then. It is used by many parties in more than 30 countries for environmental, cost and employment analyses of energy, materials and transport systems.

Table 5-2 BioGrace Corn Production Inputs

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	25.9 litres/t	10.12	0.000	0.000	10.12
N Fertilizer	13.3 kg/t	9.75	4.69	0.014	0.016
K_2O	6.64 kg/t	0.48	0.44	0.001	0.000
P_2O_5	8.88 kg/t	1.12	1.07	0.001	0.000
Pesticides	0.62 kg/t	0.84	0.76	0.002	0.000
$CaCO_3$	412 kg/t	6.65	6.11	0.011	0.001
Seeds	0.00	0.00	0.00	0.000	0.000
N_2O Emissions		7.83	0.00	0.000	0.026
Total		36.78	23.19	0.030	0.044

The two most obvious inputs are the diesel fuel (being high relative to other estimates) and the nitrogen fertilizer (being low relative to other estimates). Looking into the GEMIS model, the data is reported to be representative of German, French, and British practices. The ultimate source is BMU Biomass, 2004 but there is an indirect source identified, AFER, and the data quality is labelled as preliminary.

The N_2O calculations in the JEC work are not transparent and BioGrace uses static values for these emissions rather than calculating them directly (although BioGrace does give users

[11] Includes the 40% increase in processing energy use.

the option of doing this). The effective N_2O emission rate is 1.586% of the nitrogen in the fertilizer applied. This is low when the nitrogen in the crop residue is considered.

The emission factors used in BioGrace for these inputs are summarized in the following table. The nitrogen fertilizer emissions are reflective of ammonium nitrate fertilizers, which have high N_2O emissions. In North America urea and ammonia are more significant sources of nitrogen and they have lower GHG emissions per unit of N.

Table 5-3 BioGrace Production Input Emission Factors

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/kg	g/kg	g/kg	g/kg
Diesel/litre	3,361	3,361	0.00	0.00
N Fertilizer	5,880.6	2,827	8.68	9.6418
K_2O	1,010.7	964.9	1.33	0.0515
P_2O_5	576.1	536.3	1.57	0.0123
$CaCO_3$	129.5	119.1	0.22	0.0183
Pesticides	10,971.3	9,886.5	25.53	1.6814

5.1.2 Fuel Production

The ethanol plant uses natural gas to produce steam and electricity. It produces more electricity than the plant needs and the excess is exported to the grid and the plant receives a GHG credit. The ethanol yield from the corn is 379 litres/tonne (2.54 gal/bushel). The plant parameters for BioGrace modelling are summarized in the following table. There are no enzymes, yeast or other chemicals included in the calculations.

The modelling assumes that steam is used to dry the distillers' grains; this is not a common practice in North America as steam dryers have higher capital and maintenance costs. The higher volume of steam also allows more electricity to be produced, this too increases capital costs. Compared to a North American plant the ethanol yield is lower, and the NG and electricity requirements are higher. The GHG emissions for the expected energy case are 11.22 g/MJ lower than the default case, however, since these emissions are used in the calculation of the co-product credit, the net impact is about 6.2 g CO_2eq/MJ.

Table 5-4 Ethanol Plant Parameters

Parameter	Value		GHG	CO_2	CH_4	N_2O
	Expected	+40%	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Yield	379 l/tonne	379 l/tonne				
NG Cons for steam	10.3 MJ/l	14.4 MJ/l				
Power Consumption	0.19 kWh/litre	0.27 kWh/litre				
Power Credit	0.96 kWh/litre	1.35 kWh/litre				
Total NG			86.01	80.13	0.252	0.000
Power credit			-46.73	-42.99	-0.138	-0.002
Total		26.95 MJ/l	39.28	37.13	0.114	-0.002
Total	19.25 MJ/l		28.06	26.52	0.081	-0.001

The source for the energy input is the 1995 USDA report on the Energy Balance of Corn Ethanol. That source reported the energy requirements for a new dry mill, which would have used gas to dry the distillers' grain and not the steam used in the BioGrace model. Energy requirements of ethanol dry mills have improved significantly since the 1995 report was written. The energy use in the 1995 report was attributed to Katzen, an ethanol plant process developer. The USDA ethanol energy balance report has been updated several times in the past 18 years and now uses data from actual plant surveys.

The distillers grains is provided a credit based on the energy value of the DDG relative to the energy value of both products times the emissions up to and including the ethanol plant. The DDG yield is 41.7% on an as is basis with corn at 15% moisture and the DDG at 10% moisture. The DDG credit is shown in the following table. The lower ethanol yield results in a higher DDG yield, although 41.7% DDG yield is high for a 379 litre/tonne ethanol yield.

Table 5-5 BioGrace DDG Credit

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
DDG Credit (Default)	-34.75	-27.61	-0.064	-0.019
DDG Credit "Actual Values" for energy use	-29.66	-22.79	-0.051	-0.019

5.1.3 Transportation

The corn transportation is assumed to be 50 km between the field and the ethanol plant. The corn is moved by truck and the emissions are shown in the following table.

Table 5-6 BioGrace Corn Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	50 km	0.51	0.51	0.000	0.000

The ethanol transportation is based on 300 km movement by truck. There are also electrical energy requirements at a blending plant and the final dispensing stage. The information is summarized below.

Table 5-7 Ethanol Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	300 km	0.99	0.99	0.000	0.000
Blending electricity	0.0002 kWh/MJ	0.11	0.10	0.000	0.000
Dispensing electricity	0.0009 kWh/MJ	0.44	0.41	0.001	0.000
Total		1.54	1.50	0.001	

5.1.4 Fuel Use

Fuel use is not included in the BioGrace model. The JEC study assumed the same emissions for neat ethanol as they did for gasoline, they are shown below.

Table 5-8 Tailpipe Emissions

	CO_2eq	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Ethanol	1.8	0.0	0.175	0.013

5.1.5 Lifecycle Emissions Summary

The BioGrace model includes a corn ethanol pathway. It is based on European production of corn and a combined heat and power ethanol. A combined heat and power plant can be sized to produce the electricity required and produce supplemental steam, or the steam required with excess electricity. This model assumes the later configuration and maximizes the quantity of steam utilized in the plant, with the net impact of being a significant power producer as well.

In terms of feedstock supply, the nitrogen requirements are low (about the theoretical minimum) with nitrogen applied being about equal to the nitrogen removed in the grain. The diesel requirements are very high compared to North American practices and reflect more aggressive tillage practices.

The co-product credit is higher than other models suggest, as the energy allocation approach for ethanol co-products is known to provide a greater GHG emission benefit. This is one of the reasons that this method was chosen, so that there would be no incentives to burn the DDG rather than use it for feed.

The emissions are summarized again in the following table, this time removing the 40% extra energy to better represent the actual values.

Table 5-9 BioGrace Corn Ethanol Well to Tank Emissions – "Actual Values"

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	36.78	23.19	0.030	0.044
Feedstock Transport	0.51	0.51	0.000	0.000
Ethanol Production	61.43	57.23	0.180	0.000
Co-product (power)	-33.38	-30.71	-0.099	-0.001
Co-Product (DDG)	-29.66	-22.79	-0.051	-0.019
Ethanol Distribution	1.54	1.50	0.001	0.000
Total	37.22	28.93	0.061	0.024

5.2 EPA RFS2

The EPA RFS2 modelling framework is actually a collection of models as shown in Figures 2-3 and 2-5. The FASOM and FAPRI components can only be run on the computer systems of the EPA contractors. For this work we can only extract data from the results reported by the EPA, we cannot run the models. The EPA also reported the results using different stages than we have used for the other models. We have aggregated the EPA results into the standard stages used here, where possible.

There are some differences in the modelling approach used by the EPA for petroleum fuels and for renewable fuels. The petroleum fuels are analyzed using a 2005 baseline whereas the renewable fuels are analyzed using a projection of the emissions in 2022.

The EPA results for a corn ethanol dry mill using natural gas fuel are shown in the following table.

Table 5-10 RFS2 Corn Ethanol Well to Tank Emissions

	g CO_2eq/MM BTU	g CO_2eq/MJ
International Land Use Change	31,797	30.16
Other (fuel and feedstock transport)	4,265	4.05
Domestic Farm Inputs and Fert N_2O	8,281	7.85
Domestic Soil Carbon	-4,033	-3.83
Domestic Livestock	-3,746	-3.55
Domestic Rice Methane	-209	-0.20
International Farm Inputs and Fert N_2O	6,601	6.26
International Livestock	3,458	3.28
International Rice Methane	2,089	1.98
Ethanol Plant	32,369	30.70
Tailpipe	880	0.83
Total	81,752	77.54

The modelling framework used by the EPA forced most land use change outside of the United States. So for comparison purposes these emissions could be removed. The EPA methodology also calculates the impact of incremental demand and the benefits of the co-product, rather than showing up as a separate line, they are incorporated into the other categories. The results could be reclassified as follows. The feedstock and fuel transport emissions have been allocated equally to the two categories here. The soil carbon changes due to land management change are not in BioGrace and we have run GREET and GHGenius without them, so we have presented the results with and without those emissions. This soil carbon change is a large one year only increase in soil carbon. It is not clear what would drive this behaviour.

Table 5-11 Reclassified RFS2 Corn Ethanol

	Without Land Management Change	With Land Management Change
	g CO_2eq/MJ	
Feedstock Production	15.63	11.80
Feedstock Transport	2.86	2.86
Ethanol Production	30.7	30.7
Ethanol Distribution	1.18	1.18
Ethanol Use	0.83	0.83
Total	51.20	47.37

The modelling parameters used in the FASOM model, the ethanol production stage and some of the international emissions are relatively transparent (even if the actual calculations are not) and can be extracted from the documentation and the spreadsheets released by the EPA. The FASOM modelling done for the EPA is documented in the report by Beach et al (2010). These are discussed in the following sections.

5.2.1 Feedstock Production

The domestic emissions are calculated from FASOM and the international emissions are based on production results from the FAPRI model with the emissions calculated by the EPA with additional sources of data and emission factors that are derived from the GREET model.

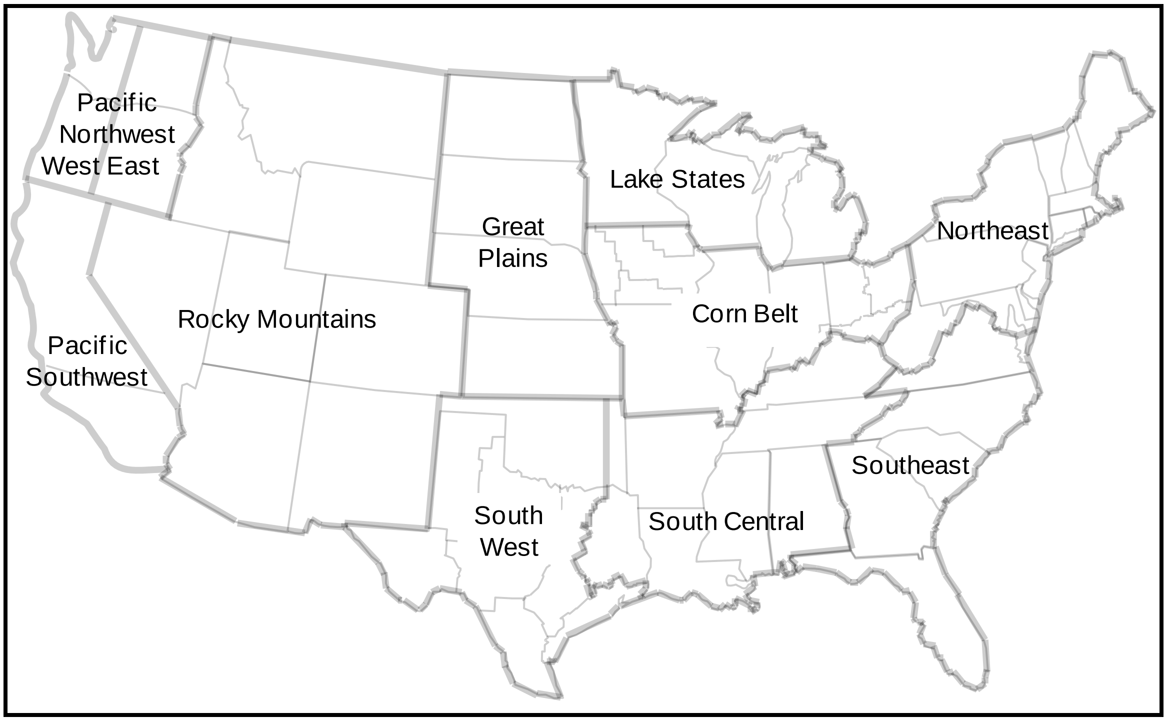
The feedstock production emissions in FASOM are calculated as the difference in agricultural emissions between a control case and the control case without the extra corn ethanol production. Agricultural emissions arise from crop and livestock production, principally from:

- fossil fuel use,
- nitrogen fertilization usage,
- other nitrogen inputs to crop production,
- agricultural residue burning,
- rice production,
- enteric fermentation from digestion of feed by livestock, and
- manure management.

In addition, changes in carbon sequestration are tracked within the model. Agricultural sequestration involves the amount of carbon sequestered in agricultural soils, due principally to choice of tillage and irrigation along with changes to crop mix choice. Sequestration is also considered in terms of grasslands versus cropland/or mixed usage, where cropland can be moved to pasture use or vice versa. The sequestration accounting can yield either positive or negative quantities, depending on the direction of change in tillage between the three available options (conventional, conservation, or zero tillage) and irrigation choices, along with pasture land (grassland)/cropland conversions and movements between agriculture and forestry.

The data that is in FASOM is also regionalized, with different performance in different regions, the emissions can be changed as crop production is shifted from one region to another. The regions are shown in the following figure.

Figure 5-3 FASOM Regions



Most of the changes in corn area in the model happen in the Corn Belt and the Lake States. We will focus on these two regions when comparing the inputs to the corn production system.

The international emissions are calculated in a similar manner in that there is a control case and a corn only case in FAPRI. Based on the difference in production between the two scenarios, the EPA then calculated the emissions related to the difference in production between the two scenarios.

The following table identifies the fertilizer and fuel values used for corn production in the two FASOM regions and the average values used in the international emissions modelling. The FASOM values for the 2000-2004 period and the FAPRI international values for the 2022 period are compared in the following table.

Table 5-12 FASOM Corn Inputs

	Lake States	Corn Belt	International
Yield, (bu/acre)	145	136	118
Nitrogen, kg/tonne corn	16.1	13.6	12.0
P_2O_5, kg/tonne corn	2.8	5.3	4.8
K_2O, kg/tonne corn	7.6	7.2	3.6
$CaCO_3$, kg/tonne corn	27	0	0
Pesticides, kg/tonne corn	0.44	0.37	0.04
Diesel, l/tonne corn	11.3	10.5	17.0

With the exception of the pesticides, the FASOM inputs are in line with the values used in the GREET model, which are derived from USDA surveys.

The international inputs have less confidence. The fertilizer inputs are estimates based on the fertilizer sold in the country with a set of calculations that match that value with the area of each crop and the expected fertilizer applied for each crop. In the case of nitrogen for corn, the range of fertilizer used by the EPA is 1.3 to 51.4 kg/tonne corn. At the low end this is probably not sustainable and the high end represents so much excess nitrogen that the crop production would be un-economic. The lower rate of fertilizer application may be one reason for the low yields. Some countries can be expected to have lower rates because they have a high proportion of soybeans (which fix their own nitrogen from the atmosphere and the high nitrogen content in the residues left after harvest help to fertilize the next crop) to corn production and thus have more nitrogen applied to corn from soybean residues than in the United States. The international pesticide rates are extremely low and could also contribute to the low yields.

The international energy use is based on very coarse data at the country level. 2005 IEA data on the CO_2 emissions in each country is used to arrive at the energy use in the agricultural and forestry sector. This is divided by the agricultural area, and is thus an overestimate because it is the energy used in agriculture and forestry. The quality of this data is uncertain; in some countries the breakdown of energy use by sector is little more than an estimate.

In FASOM, the corn yield is expected to grow at 1.48% annually. That would put the yield at 30% higher in 2022, or 177 to 188 bu/acre. FASOM employs elasticity factors[12] to adjust the inputs as the yield increases. The elasticity factors are shown in the following table. These inputs all increase at a slower rate than the yield, indicating that less input per tonne of corn is required in 2022, than in 2004.

Table 5-13 FASOM Input Elasticities

Parameter	Elasticity
Nitrogen	0.16
Phosphorus	0.16
Pesticides	0.77
Fuel	0.79

While the FASOM model has emission factors for diesel fuel, power, fertilizers and ag chemicals these were not used the EPA. Instead the EPA took the change in fuel and fertilizer usage and multiplied them by emission factors that were developed from GREET 1.8c. They are all lower than used in FASOM. The same emission factors are used in the domestic and international portions of the modelling even though the change in usage of the materials comes from different models.

[12] The elasticity factor times the percentage increase in production produces the percentage increase in the input.

Table 5-14 FASOM and FAPRI Emission Factors

	As applied to changes generated by FASOM and FAPRI models
Diesel/litre	3.32
N Fertilizer, g CO_2eq/kg	3,628
P_2O_5, g CO_2eq/kg	1,238
K_2O, g CO_2eq/kg	818
Herbicides, kg CO_2eq/kg	25.95

The ethanol yield assumption in FASOM is 404 l/tonne (2.71 gal/bu) in the 2000-2004 period and it does not change with time.

The N_2O emissions in FASOM are calculated using the Century model. This model takes into account the soil conditions, precipitation, crops grown and other factors to arrive at the emissions. This model is also used to produce the US national GHG Emission Inventory every year. The N_2O emission factor will be different in different regions of the country and for different crops. The net results will again be the difference between the control case and the corn only case. The international modelling follows the IPCC Tier 1 guidelines and again presents results for the total difference between the two scenarios, not just the emissions for corn production.

5.2.2 Fuel Production

The EPA calculated the fuel production emissions outside of the FASOM model. The energy used in the dry mill ethanol plant and the resulting GHG emissions are shown in the following table.

Table 5-15 Ethanol Plant Energy Use and GHG Emissions

	2012	2017	2022
Natural gas, MJ/l	8.73	8.15	7.57
Electricity, kWh/l	0.206	0.190	0.174
Yield, l/tonne	404	404	404
GHG, g CO_2eq/MJ	35.6	33.1	30.7

The 2012 values are slightly higher than the values used in GREET and the yield is lower than is used in GREET. There are certainly some operating plants that have energy use lower than the values used by the EPA for 2022, and many plants have higher yields (up to 425 l/tonne).

5.2.3 Transportation

The transportation of the feedstock in these calculations includes the transportation of the DDG. The transportation emissions are shown below.

Table 5-16 Transportation Emissions

	Emissions, g CO_2eq/MJ
Feedstock	2.86
Ethanol	1.18
Total	4.04

5.2.4 Fuel Use

The fuel use emissions from the combustion of ethanol are derived from the MOVES model. The results are shown below.

Table 5-17 Tailpipe Emissions

	CO_2eq	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Ethanol	0.83	71,371[13]	0.0121	0.0276

5.2.5 Lifecycle Emissions Summary

The EPA RFS2 modelling of the corn ethanol pathway relies on a number of models. The emissions associated with crop production are derived from the FASOM and FAPRI models, neither of which are particularly transparent.

The FASOM model crop inputs for corn production are similar to those used in the GREET model. The primary difference is in the emission factors for the crop inputs. The FASOM emission factors are low for fuel but are very high for fertilizer and pesticides relative to other models. The overall impact cannot be calculated precisely but the emissions for corn production are likely overstated.

The international modelling uses the changes in crop production from FAPRI, GREET derived emission factors, and quantities of agricultural inputs that have a low quality and high uncertainty. The emission factors used in the domestic modelling are quite different and mostly higher than the international modelling emission factors.

Table 5-18 RFS2 Corn Ethanol

	Without Land Management Change	With Land Management Change
	g CO_2eq/MJ	
Feedstock Production	15.63	11.80
Feedstock Transport	2.86	2.86
Ethanol Production	30.7	30.7
Ethanol Distribution	1.18	1.18
Ethanol Use	0.83	0.83
Total	51.2	47.37

The one advantage that the FASOM and FAPRI modelling have is that they should provide the best estimate of the displacement value of the co-product. They should be considering all

[13] Biogenic, not included in the CO_2eq.

of the emissions (production and use) that change between the base case and the corn ethanol scenarios.

The feedstock production emissions shown in the previous table are the net of the credit for the co-product in both modelling frameworks. Based on the GREET results and what is known of the FASOM inputs, it is likely that at least half of the corn production GHG emissions are displaced by the co-product.

5.3 GREET

GREET offers a number of options for modelling the corn ethanol system. We have set the model to 2012. We have modelled a natural gas fired dry mill that produces dried distillers grains, we have used the displacement allocation method to account for co-product credits, and we have not included indirect land use change emissions. These selections provide the closest comparisons to the BioGrace and GHGenius models.

The following table provides a summary of the emissions for each stage of the lifecycle. Each stage is discussed in more detail in the following sections.

Table 5-19 GREET Corn Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	33.50	13.09	0.0582	0.0633
Feedstock Transport	2.21	2.11	0.0032	0.0001
Ethanol Production	33.74	28.39	0.2035	0.0005
Co-Product (DDG)	-14.52	-6.50	-0.1278	-0.0160
Ethanol Distribution	1.52	1.39	0.0020	0.0000
Total	56.44	38.49	0.1391	0.0479

5.3.1 Feedstock Production

The feedstock production inputs and GHG impacts for corn production in GREET are shown in the following table. These have been updated several times in the model to reflect new information that is made available by the USDA; the most recent update was for version 1.8d released in 2010 (the GREET reference is USDA, “National Agricultural Statistics Service,” accessed August 2010). Most of these parameters show reductions over time due to increasing crop yields. GREET has energy inputs of diesel fuel, gasoline, electricity, natural gas, and LPG. They have been converted to diesel fuel equivalents for this table for comparison purposes.

Table 5-20 GREET Corn Ethanol Production Inputs

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ ethanol	g/MJ ethanol	g/MJ ethanol	g/MJ ethanol
Diesel eq	10.9 l/t	4.12	3.76	0.0123	0.0001
N Fertilizer	16.04 kg/t	8.50	5.79	0.0424	0.0053
P_2O_5	5.76 kg/t	0.42	0.40	0.0008	0.0000
K_2O	6.65 kg/t	0.47	0.44	0.0013	0.0000
$CaCO_3$	44.4 kg/t	2.26	2.25	0.0001	0.0000
Pesticides	0.21 kg/t	0.48	0.45	0.0012	0.0000
N_2O Emissions		17.25	0.00	0.0000	0.0579
Total		33.50	13.09	0.0582	0.0633

The N_2O emissions are calculated based on 1.525% of the nitrogen in the fertilizer and the crop residue. This is an effective EF1 (the emission factor for direct N_2O emissions per kg of nitrogen applied) of 1.2% vs. the IPCC default value of 1.0%. If we calculate the N_2O emissions on the basis of a percent of the nitrogen fertilizer, then the effective rate is 3.2% (compared to the 1.59% in BioGrace).

The large difference will be caused by different quantities of nitrogen in the crop residue and different quantities of residue produced per unit of primary product. These values are not transparent in BioGrace. In GREET the nitrogen in the crop reside is a fixed input value of 141.6 g/bu. The IPCC default value for maize varies with yield but it is approximately 190 g N/bu. This is almost 50% of the nitrogen applied as fertilizer.

The emission factors used in GREET for the agricultural inputs are shown in the following table. The diesel, phosphorus and pesticide values are higher than those used in BioGrace and the other values are lower. There is a large difference in the nitrogen fertilizer, which reflects the different mix of nitrogen fertilizers used in the United States compared to Europe.

Table 5-21 GREET Production Input Emission Factors

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/kg	g/kg	g/kg	g/kg
Diesel/litre	4,060	3,876	5.77	0.13
N Fertilizer	3,530.3	2,513.3	21.2	1.6
P_2O_5	662.9	626.9	1.3	0.0
K_2O	638.9	592.0	1.8	0.0
$CaCO_3$	14.7	14.1	0.0	0.0
Pesticides	21.0	19.6	0.1	0.0

5.3.2 Fuel Production

The ethanol plant energy requirements were also updated in 2010 to reflect the data in the RFS2 modelling and the survey of ethanol plants undertaken by Mueller at the University of Illinois at Chicago (2010). The model inputs are shown in the following table.

Table 5-22 GREET Ethanol Plant Parameters

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Yield	419 l/tonne				
NG	8.38 MJ/l	27.81	22.85	0.1888	0.0004
Power Consumption	0.20 kWh/l	5.93	5.54	0.0147	0.0001
Total		33.74	28.39	0.2035	0.0005

The GHG emissions include the contribution of emissions embedded in the enzymes and yeast usage but the total contribution is very small (~0.7 g CO_2eq/MJ).

The DDG credit calculated based on the displacement of corn (0.776 kg corn/kg DDG), soybean meal (0.304 kg/kg DDG) and urea (0.028 kg/kg DDG). There is also a reduction in methane emissions from cattle that consume the DDG (~16% of the total DDG credit). The net DDG credit is shown in the following table.

Table 5-23 GREET DDG Credit

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
DDG Credit	-14.52	-6.50	-0.1278	-0.0160

5.3.3 Transportation

The corn transportation is assumed to be 16 km (10 miles) between the field and an intermediate storage facility and 64 km (40 miles) from that facility to the ethanol plant. The corn is moved by truck and the emissions are shown in the following table.

Table 5-24 GREET Corn Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	80 km	2.21	2.11	0.0032	0.0001

Moving the ethanol from the plant to a bulk terminal is done 40% by barge (830 km), 40% by rail (1,280 km), and 20% by truck (130 km). All of the ethanol is then moved by truck from the terminal to the retail station, a distance of 50 km. The emissions from these movements are shown in the following table.

Table 5-25 GREET Ethanol Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	920 km	1.52	1.39	0.0020	0.0000

5.3.4 Fuel Use

The emissions from the combustion of E100 produce the non-CO_2 emissions shown in the following table.

Table 5-26 GREET Ethanol Vehicle Emissions

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	0.81	0.00	0.0027	0.0025

5.3.5 Lifecycle Emissions Summary and CA Greet

The corn ethanol pathway in GREET has been updated many times as new information and more recent data becomes available. The comparison of the results for the CA GREET and the latest version of GREET is shown in the following table. The latest model produces 18% lower GHG emissions than the CA GREET version. Both models consider a dry mill ethanol plant using natural gas as the process fuel. There is a difference in the displacement factors for the DDG co-product between the two model versions. The CA GREET model assumes that DDG displaces corn on a one for one mass basis, The GREET1_2012 version has a more detailed co-product displacement method and includes the displacement of corn, soybean meal and urea. It also includes a credit for reduced methane production in ruminants. The results for the two models are compared in the following table.

Table 5-27 CA GREET and GREET1_2012 Corn Ethanol excluding ILUC

	CARB GREET 1.8b	GREET1_2012rev2	% Change
Corn Ethanol Fuel Cycle Components	Dry Mill (g/MJ)	Dry Mill (g/MJ)	
Fuel	Natural Gas	Natural Gas	
Feedstock Production	35.85	33.50	-6.5%
Feedstock Transport	2.22	2.21	-0.5%
Ethanol Production	38.30	33.74	-11.9%
Co-Product (DDG)	-11.51	-14.52	23.0%
Ethanol Distribution	2.70	1.52	-43.7%
Total	67.56	56.44	-16.5%

The input values for corn farming in the two models are shown in the following table. Both versions of the model use 158 bushels/acre as the yield but the newest version of the model uses 25.4% less energy to produce the corn. There are some changes in the types of energy used that will have some impact on the emissions but the difference in the emissions per MJ of ethanol is 27.1%, so the impact of the different fuel mix is minimal. The quantity of ag chemicals used and the emissions associated with the production of these chemicals is compared below. There are large changes in pesticide application rates, but relatively small differences in the other ag chemicals, although everything is lower. This should not be too surprising as there is a long term trend to reduced inputs and greater efficiency in North American agriculture.

Table 5-28 Corn Farming Inputs

	CARB GREET 1.8b	GREET1_2012rev2	% Change
Yield, bu/acre	158	158	0.0
Farming Energy, BTU/bu	12,635	9,421	-25.4%
N, g/bu	420	407	-3.1%
P_2O_5, g/bu	149	145	-2.7%
K_2O, g/bu	174	169	-2.9%
$CaCO_3$, g/bu	1,202	1,127	-6.2%
Herbicide, g/bu	8.1	4.75	-41.4%
Insecticide, g/bu	0.68	0.40	-41.2%
CO_2 from Lime	529	496	-6.2%
GHG emissions, g/MJ EtOH	5.65	4.12	-27.1%
Land Use, g/Bu	195	0	-100.0%

CARB used the default land use emission of 195 g/bushel in GREET, the new version makes it clear that these emissions are land use change emissions and not land use management emissions. For the GREET1_2012 model set up used here, these have been set to zero. They probably should have been set to zero in the CARB modelling as well, since CARB calculates land use change emissions separately.

The production of the ag chemicals is compared in the next table. The nitrogen production emissions have increased (version GREET1_2011) to include the emissions for ammonia production. There was a large drop in emissions association with limestone ($CaCO_3$), it is not clear from the release notes when this happened. Limestone and lime (CaO) are often confused; limestone can be mined in a quarry, whereas lime is calcined at high temperature. CO_2 is released when limestone is applied to a field to neutralize the soil acidity and this is captured elsewhere in GREET. CO_2 is released when lime is produced. The older version of GREET appeared to count these CO_2 emissions twice.

Table 5-29 Ag Chemicals Production

	CARB GREET 1.8b	GREET1_2012rev2	% Change
	g CO_2eq/kg	g CO_2eq/kg	
Nitrogen	2,960	3,530	19.3%
P_2O_5	1,020	660	-35.3%
K_2O	690	640	-7.2%
$CaCO_3$	630	10	-98.4%
Herbicide	21,400	21,000	-1.9%
Insecticide	24,860	24,520	-1.4%

The overall GHG emissions for the ag chemicals are shown in the following table. The overall emissions have declined by about 4%. This is essentially due to better information about each of the pathways. The N_2O emissions are more transparent in the latest version of GREET and they use a higher emission factor (EF1) than before (1.25% vs. 1.0%). This change is described in Wang et al (2012).

Table 5-30 Corn Ag Chemicals Emissions

	CARB GREET 1.8b	GREET1_2012rev2	% Change
	g CO_2eq /bu	g CO_2eq /bu	
Nitrogen	1,241	1,464	18.0%
P_2O_5	152	97	-36.2%
K_2O	119	109	-8.4%
$CaCO_3$	753	17	-97.7%
Herbicide	173	101	-41.6%
Insecticide	17	10	-41.2%
Urea CO_2	139	135	-2.9%
$CaCO_3$, CO_2	529	496	-6.2%
N_2O from N (as CO_2eq)	3,484	3,919	12.5%
Total	6,607	6,348	-3.9%

While there are differences in the credit provided to DDG between the two versions of GREET and the transportation scenarios modelled are different, most of the differences in the models is derived from new data that is used in the 2012 version of the model.

5.4 GHGENIUS

The GHGenius estimate for the emissions from corn ethanol production in the United States is shown in the following table. The model is set to the US and 2012. The plant is a natural gas fired dry mill facility to allow comparison with the other models. There is a very small amount of soil carbon change in the model due to the adoption of reduced and no tillage.

Table 5-31 GHGenius Corn Ethanol Well to Tank Emissions excluding ILUC

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	37.22	12.17	0.0780	0.0775
Feedstock Transport	1.62	1.55	0.0020	0.0001
Ethanol Production	38.26	33.93	0.1667	0.0006
Co-Product (DDG)	-18.87	-2.79	-0.1344	-0.0427
Ethanol Distribution	1.61	1.52	0.0026	0.0001
Total	59.84	46.38	0.1149	0.0355

The inputs and results for each of the stages are discussed below.

5.4.1 Feedstock Production

Data for corn production on yield and fertilizer rates is derived from USDA data. GHGenius uses time series for each of these data sets and the model automatically updates the fertilizer requirements and yield based on the year.

Table 5-32 GHGenius Corn Production Inputs

Parameter	Value
Diesel eq	15.4 leq/tonne
N Fertilizer	17.5 kg/tonne
P_2O_5	5.35 kg/tonne
K_2O	7.18 kg/tonne
$CaCO_3$	0
Pesticides	0.32 kg/tonne

The emission factors for these inputs are summarized in the following table.

Table 5-33 GHGenius Production Input Emission Factors

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/kg	g/kg	g/kg	g/kg
Diesel/litre	3,640			
N Fertilizer	3,603	3,139	17.94	0.05
P_2O_5	711	650	1.43	0.08
K_2O	480	443	1.25	0.02
$CaCO_3$	150	133	0.39	0.03
Pesticides	151	140	0.33	0.01

The composition of the feedstock emissions is shown in the following table. The N_2O emissions contribute two thirds of the total emissions. The N_2O emission factor for US corn in GHGenius is currently 1.5%. Some new data has become available and this value is reduced to 1.25% in the next version of GHGenius (4.03).

Table 5-34 Feedstock Emissions

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Fuel	6.13	4.99	0.0368	0.0007
Fertilizer	9.13	8.03	0.0410	0.0002
N_2O emissions	22.81	0.00	0.0000	0.0076
Soil Carbon	-0.85	-0.85	0.0000	0.0000
Total	37.22	12.17	0.0780	0.0775

5.4.2 Fuel Production

The fuel production parameters used in GHGenius are shown in the following table. When GHGenius is used to produce a carbon intensity for a specific plant for the BC LCFS, these are the primary values that are adjusted.

Table 5-35 GHGenius Ethanol Plant Parameters

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Yield	405 l/tonne				
NG	8.90 MJ/l				
Power Consumption	0.19 kWh/l				
Total		38.26	33.93	0.1667	0.0006

In addition to these inputs there are emissions associated with yeast, enzymes, ammonia, sodium hydroxide, and sulphuric acid. These chemicals contribute 5.9 g CO_2eq/MJ of ethanol produced.

The DDG credit in GHGenius is calculated from the displacement of corn and soybean meal and a methane credit for reduced methane emissions from ruminants. The displacement factors are larger than those in GREET since they haven't been adjusted in a number of years. These are reduced in the next version (4.03). The credits are shown in the following table.

Table 5-36 GHGenius DDG Credit

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
DDG Credit	-18.87	-2.79	-0.1344	-0.0427

5.4.3 Transportation

The corn transportation is assumed to be 100 km between the field and the ethanol plant. The corn is moved by truck and the emissions are shown in the following table.

Table 5-37 GHGenius Corn Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	100 km	1.62	1.55	0.0020	0.0001

The ethanol is transported from the plant by rail and truck. 22% is transported an average of 802 km by rail, and all of it is moved 121 km by truck. The emissions are shown below.

Table 5-38 GHGenius Ethanol Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	298 km	1.61	1.52	0.0026	0.0001

5.4.4 Fuel Use

The emissions from the use of the ethanol are shown in the following table. The CO_2 emissions are not included as the feedstock is biomass. The methane emissions are assumed to be higher than gasoline unlike some of the other models that assume the emissions are the same as gasoline.

Table 5-39 GHGenius Ethanol Vehicle Emissions

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	2.22	0.00	0.0847	0.0001

5.4.5 Lifecycle Emissions Summary

The GHGenius corn ethanol lifecycle emissions are shown in the following table. GHGenius use a higher N2O emission factor than the other models, and it includes the emissions for a number of the chemicals used in the plants that aren't included to the same extent in the other models. Both of these factors lead to higher emissions. Offsetting these two factors is a small credit for increasing soil carbon levels and higher displacement factors for the DDG.

Table 5-40 GHGenius Corn Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	37.22	12.17	0.0780	0.0775
Feedstock Transport	1.62	1.55	0.0020	0.0001
Ethanol Production	38.26	33.93	0.1667	0.0006
Co-Product (DDG)	-18.87	-2.79	-0.1344	-0.0427
Ethanol Distribution	1.61	1.52	0.0026	0.0001
Total	59.84	46.38	0.1149	0.0355

5.5 SUMMARY

The following table summarizes the GHG emissions for the production of corn ethanol from the five models. The BioGrace values are the default values and use 40% more energy in the ethanol plant than the expected average.

Table 5-41 Corn Ethanol Summary excluding ILUC

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement			
	g CO_2eq/MJ (LHV)				
Feedstock Production	36.78	15.63	33.50	35.85	37.22
Feedstock Transport	0.51	2.83	2.21	2.22	1.62
Ethanol Production	86.01	30.7	33.74	38.30	38.26
Co-product (power)	-46.73	-	-	0.00	0.00
Co-Product (DDG)	-34.75	-	-14.52	-11.51	-18.87
Ethanol Distribution	1.54	1.18	1.52	2.70	1.61
Sub total	43.4	50.38	56.44	67.56	59.84
Fuel Use	-	0.83	-	0.80	2.22
Total	43.4	51.21	56.44	68.36	62.16

There is a fair range in the results and it is not possible to directly compare all of the stages as the RFS2 model has no way to break out the co-product credit. The GREET1_2012 model has significantly lower emissions than the CARB model. Most of this is due to more recent data being used in the model, with a small contribution from the different assumptions made concerning the displacement impacts of DDG.

5.5.1 Feedstock Production

There are three primary components to the GHG emissions in the feedstock production stage, the fuel used, the fertilizer and chemicals applied and the N_2O emissions from the decomposition of the nitrogen fertilizer and crop residue. We can extract this data from all of the models, except the RFS2 model.

Table 5-42 Feedstock Production Comparison

	BioGrace	GREET1_2012	CA GREET	GHGenius
Fuel, l /tonne	25.9	10.9	14.6	15.4
Nitrogen, kg/tonne	13.3	16.0	16.5	17.5
N_2O direct emission factor	?	1.25	1.0	1.5
Fuel, g CO_2eq/MJ	10.12	4.12	6.96	6.13
Fertilizer production, g CO_2eq/MJ	18.84	10.55	13.56	8.28
N_2O emissions, g CO_2eq/MJ	7.83	17.25	15.33	22.81
Total feedstock emissions, g CO_2eq/MJ	36.78	33.50	35.85	37.22

There is greater variation in the individual components than there is in the total emissions from this stage. The BioGrace results can partially be explained by the different farming practices in Europe compared to the United States. In addition, the model assumes a high percentage of ammonium nitrate use for N fertilizer and this form of nitrogen fertilizer has high N_2O emissions in the production stage, whereas very little ammonium nitrate is used in North America.

The BioGrace N_2O emissions are very low and unfortunately there is no transparency with respect to how the emissions are calculated. BioGrace does include a sheet where the N_2O emissions can be calculated using the IPCC Tier methodology. When this approach is used the GHG emissions from N_2O emissions increase by 115%, even when the direct N_2O emission factor is just 1%. GHGenius uses a higher N_2O emission rate (1.5% for the direct N_2O emissions) than the other models. It also has a small credit for increases in soil carbon due to land management practices.

Areas of uncertainty and variability include the field fuel use, nitrogen use, fertilizer manufacturing emissions, and the N_2O emissions.

5.5.2 Ethanol Process

The BioGrace model considers a very different process configuration than the other models. It is a full steam plant (including the DG dryers) and has a full co-gen plant. Significant amounts of power are exported and credited with the emissions from a natural gas combined cycle plant (124 g CO_2eq/MJ). In the following table the BioGrace actual values for power and thermal energy consumption are shown. The ethanol plant modeling assumptions are shown in the following table. The RFS2 models a plant in 2022 so its inputs should be lower than models that use average values.

Table 5-43 Ethanol Production Comparison

	BioGrace	EPA RFS2	GREET 1_2012	CA GREET	GHGenius
Ethanol yield, l/tonne	379	418	404	405	405
NG (excluding co gen), MJ/litre	10.3	8.0	8.7	9.0	8.9
Power consumption, kWh/l	0.19	0.17	0.21	0.28	0.19
GHG Emissions, g CO_2eq/MJ	28.0	30.70	35.6	38.3	38.3

There is some variation in the ethanol plant production parameters. The BioGrace results are a function of the co-gen configuration and the source for the energy inputs were from the 1990s. The EPA used estimates for energy use for 2022. The other three models are relatively close, with the primary difference being the inclusion of some process chemicals in GREET1_2012 and more process chemicals in GHGenius.

5.5.3 Co-products

The RFS2 model does not report the co-product credit directly but the results suggests that the co-product credit is worth at least 50% of the feedstock emissions since the feedstock emissions are half of the next lowest model. The GREET and GHGenius models use similar approaches but there are differences in what is displaced by the co-product. These different displacement assumptions and the different emissions for producing corn and soybeans drive the different results.

Table 5-44 Ethanol Co-Product Comparison

	BioGrace	GREET 1_2012	CA GREET	GHGenius
	g CO_2eq/MJ			
Power	46.73			
DDG	34.75	14.16	11.5	18.87
Total	81.48	14.16	11.5	18.87

5.5.4 Indirect Land Use Change

The EPA RFS2 modelling framework has been set to restrict land expansion in the United States and thus the reported International emissions represent the indirect land use change emissions. In Europe and in California they have utilized other models (IFPRI-Mirage in Europe and GTAP in California) to estimate the indirect land use emissions. The ILUC emissions for corn ethanol are added to the direct emissions for those three modelling frameworks below. The EU results use a 20 year amortization period and have been adjusted to a 30 year period to allow comparisons to the other sources in the following table. The BioGrace results also have actual values shown.

Table 5-45 Direct Emissions and Indirect Land Use Emissions – Corn Ethanol

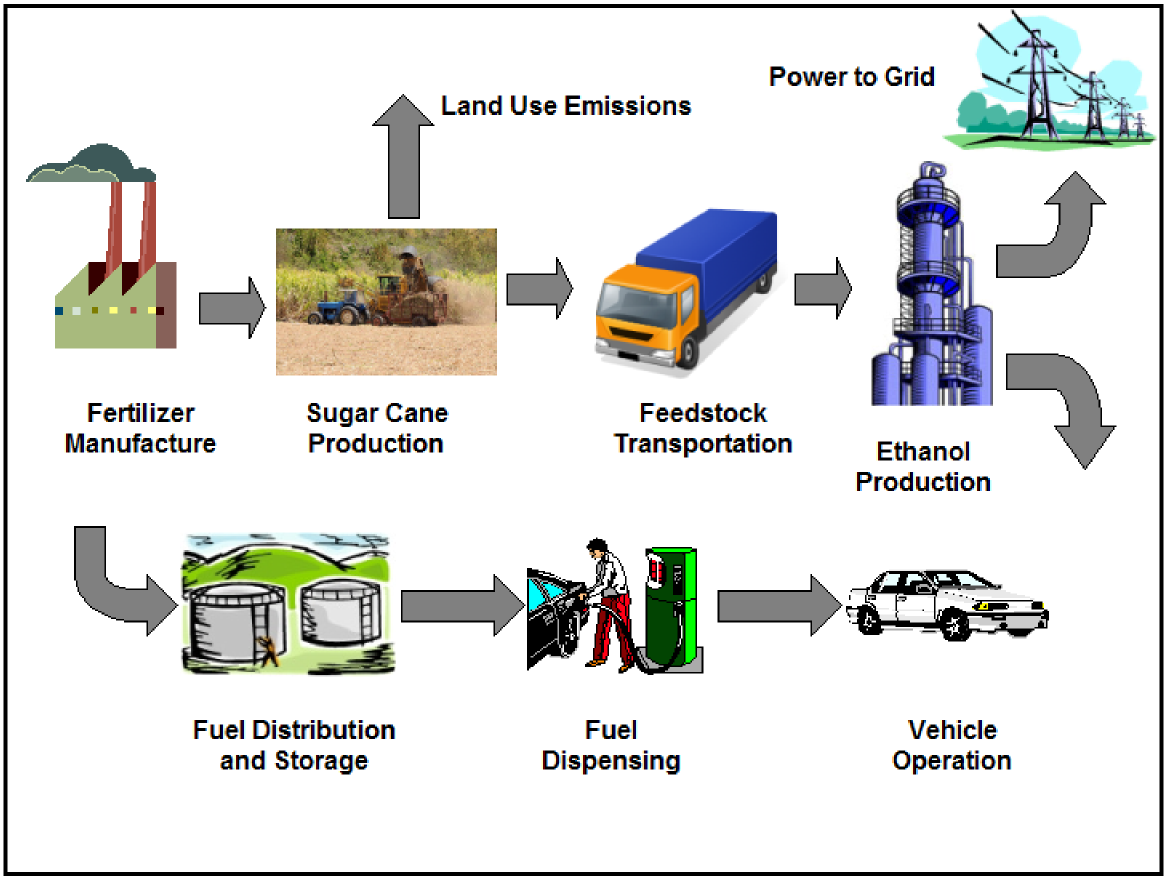
	BioGrace	EPA RFS2	CA GREET
	g CO_2eq/MJ		
Direct Emissions	37.22	47.37	67.56
ILUC	6.67	30.16	30.00
Total	43.89	77.53	97.56

There are significant differences in the ILUC emissions between the European model and the North American models. While the two North American estimates are close there are very large differences in how they are calculated, where the emissions are projected to occur and what is included in the estimates.

6. SUGARCANE ETHANOL

There are five primary stages for the sugarcane ethanol lifecycle, the sugarcane production stage (which will include fertilizer manufacturing and land use emissions), feedstock transportation, ethanol manufacturing, ethanol transportation, distribution and dispensing, and the vehicle use stage. Again the ethanol distribution, storage and dispensing stages are combined, as the contributions are small. The stages are shown in the following figure.

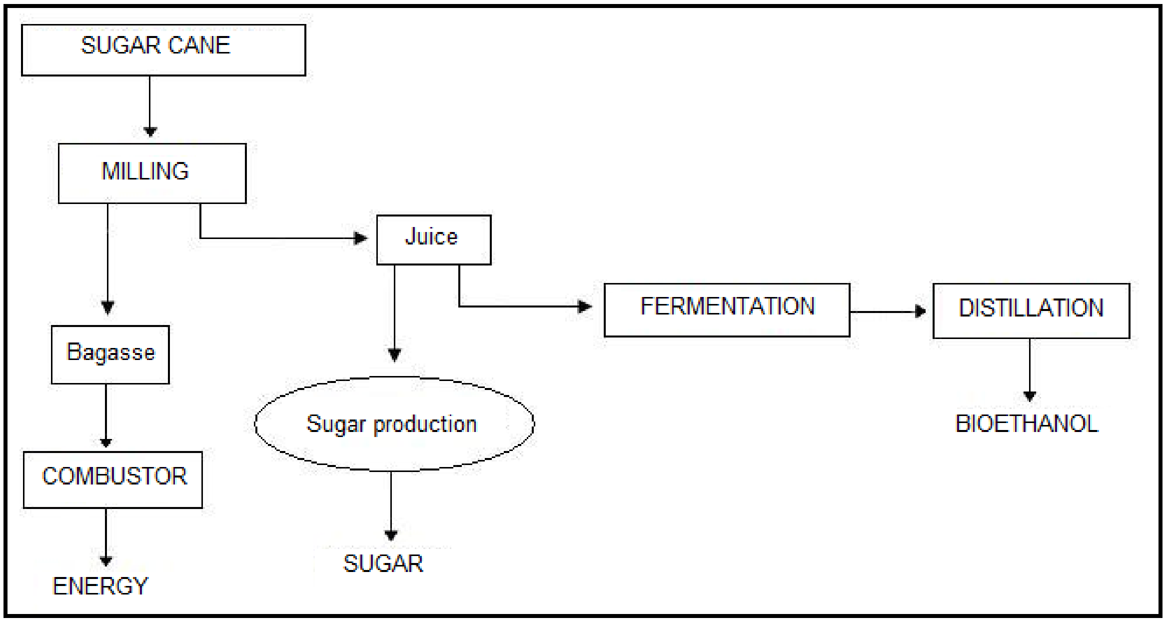
Figure 6-1 General System Boundaries – Sugarcane Ethanol



The traditional approach to sugarcane harvesting in Brazil was to harvest the cane manually. To do this the fields were first set on fire to reduce the biomass from the leaves and to drive snakes and other animals from the fields. Workers then cut the cane stalks manually and loaded the cane onto transport trucks. More recently the trend is to harvest the fields with mechanical harvesting equipment and to avoid the burning of the fields.

The options that are included in some of the models include manual or mechanical harvesting, burning the sugarcane straw and trash or leaving it on the field, and the potential export of electricity. The model variables are described in each section and an attempt has been made to allow the most accurate comparisons possible.

Figure 6-2 Sugarcane Ethanol Process



Source: Di Nicola et al (2011)

6.1 BIOGRACE

BioGrace models a sugarcane ethanol pathway with the ethanol produced in South America and shipped to Europe. The model can use either the 2001 or the 2007 IPCC GWPs. The 2001 values are used in the RED and these will be used here. There are no co-products in the system analyzed. Excess bagasse production is not considered in the default values.

The case modelled by the JEC assumed 80% manual cane harvesting and burning of the fields prior to harvesting. All of the data came from Macedo et al. (2004), a paper that included an average and best practices case in the centre-south region of Brazil with data collected in 2002. The JEC used the best practice case for their source of data, although there were not large differences between the two sets of data for most of the inputs. This is a widely cited source of information on Brazilian sugarcane production information although there have been several more recent publications with updated data.

The model is not complete for this pathway and returns #NA for the emissions from the CHP supply. The emission factors for a CHP plant burning bagasse need to be entered on the "User Defined Standards Value" sheet. We have entered zeros for these emission factors to remove the warning and this also aligns the values with the RED.

The BioGrace results for this pathway are summarized in the following table. BioGrace calculates default values by increasing the expected energy use in the processing stages by 40%, in this case the 40% is applied to biomass inputs, which have no GHG emission factor in the BioGrace model so the results from the default and actual value cases are very similar.

Table 6-1 BioGrace Sugarcane Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	14.11	3.75	0.1525	0.0232
Feedstock Transport	0.84	0.84	0.0001	0.0000
Ethanol Production	0.85	0.83	0.0008	0.0000
Co-product (power)	-	-	-	-
Ethanol Distribution	8.16	8.11	0.0020	0.0000
Total	23.97	13.53	0.1554	0.0232

Each of the stages is investigated in more detail in the following sections.

6.1.1 Feedstock Production

The sugarcane production inputs in the BioGrace model are summarized in the following table. BioGrace uses the same emission profile for all of the fertilizer, pesticides, and process chemicals for all of the pathways. These emission factors were summarized in Table 5-3.

Table 6-2 BioGrace Sugarcane Production Inputs

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	0.80 l/t	1.29	1.29	0.0000	0.0000
N Fertilizer	0.91 kg/t	2.75	1.32	0.0041	0.0045
K_2O	1.08 kg/t	0.32	0.30	0.0009	0.0000
P_2O_5	0.41 kg/t	0.21	0.20	0.0003	0.0000
Pesticides	0.03 kg/t	0.16	0.15	0.0004	0.0000
$CaCO_3$	5.34 kg/t	0.36	0.33	0.0006	0.0001
Filter cake mud	8.73 kg/t	0.00	0.00	0.0000	0.0000
Vinasse	385 kg/t	0.00	0.00	0.0000	0.0000
Seeds	29.11 kg/t	0.02	0.02	0.0000	0.0000
N_2O Emissions		5.49	0.00	0.0000	0.0186
Methane from straw burning		3.37	0.00	0.1463	0.0000
Total		13.97	3.61	0.1525	0.0232

The N_2O calculations are not transparent in the JEC work or in BioGrace. There is nitrogen in the vinasse and the filter cake that should also be included in the calculations. There will also be some N_2O emissions from the field burning of the cane. The rate of N_2O per kg of synthetic nitrogen fertilizer is 2.4%, which would suggest that at least some of these additional sources are included in the calculation.

6.1.2 Fuel Production

The sugarcane ethanol plant burns the bagasse and is self-sufficient in energy in the BioGrace model. The CO_2 from burning bagasse is biogenic, thus is not counted in the GHG footprint of the plant. There is no export of electricity assumed and as noted above, there do not appear to be any methane or N_2O emissions from the combustion of the bagasse. The ethanol plant emissions are a function of the emissions embedded in the chemicals used in the process. These are shown in the following table.

Table 6-3 Ethanol Plant Parameters

Parameter	Value		GHG	CO_2	CH_4	N_2O
	Expected	+40%	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Yield, l/tonne	88.5	88.5				
Pure CaO for processes, kg/MJ	0.000478	0.000670	0.69	0.68	0.0004	0.0000
Cyclohexane, kg/MJ	0.000028	0.000040	0.03	0.03	0.0000	0.0000
Sulphuric acid (H_2SO_4), kg/MJ	0.000427	0.000598	0.12	0.12	0.0003	0.0000
Lubricants, kg/MJ	0.000007	0.000010	0.01	0.01	0.0000	0.0000
Total			0.85	0.83	0.0008	0.0000

There are no co-products in the BioGrace sugarcane ethanol pathway.

6.1.3 Transportation

The sugarcane transportation is assumed to be 20 km between the field and the ethanol plant. The cane moved by truck and the emissions are shown in the following table.

Table 6-4 BioGrace Sugarcane Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	20 km	0.84	0.84	0.0001	0.0000

The ethanol transportation is based on 700 km movement by truck in the country of origin, 10,186 km by ship, and then 300 km by truck in the country of use. There are also electrical energy requirements at the export terminal, the import terminal, the blending plant, and at the service station. The information is summarized below.

Table 6-5 Ethanol Transportation and Blending

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel					
Exporting country	700 km	2.31	2.31	0.0001	0.0000
Importing Country	300 km	0.99	0.99	0.0001	0.0000
Fuel oil					
Ocean transport	10,186 km	4.10	4.10	0.0000	0.0000
Export terminal power[14]	0.005 kWh/l	0.10	0.10	0.0003	0.0000
Import Terminal power	0.005 kWh/l	0.11	0.10	0.0002	0.0000
Blending electricity	0.005 kWh/l	0.11	0.10	0.0002	0.0000
Dispensing electricity	0.020 kWh/l	0.44	0.41	0.0010	0.0000
Total		8.16	8.11	0.0020	0.0000

[14] Different power carbon intensity assumed.

6.1.4 Fuel Use

Fuel use is not included in the BioGrace model. As noted in the corn ethanol section, the JEC assumed that the emissions are the same as gasoline.

6.1.5 Lifecycle Emissions Summary

Most of the data used in the sugarcane ethanol pathways are from a 2002 best case scenario for Brazilian sugarcane production. This is a departure from the data philosophy used in other BioGrace pathways. There are no methane and N_2O emissions from the combustion of the bagasse in the sugarcane mills. The lifecycle results without the 40% extra fuel and chemicals use in the fuel transformation process are shown in the following table. There is relatively little difference between this and the base case since these emissions are so small.

Table 6-6 BioGrace Sugarcane Ethanol Well to Tank Emissions - "Actual Values"

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	14.11	3.75	0.1525	0.0232
Feedstock Transport	0.84	0.84	0.0001	0.0000
Ethanol Production	0.61	0.59	0.0005	0.0000
Ethanol Distribution	8.16	8.11	0.0020	0.0000
Total	23.72	13.29	0.1551	0.0232

6.2 EPA RFS2

The EPA considered 4 sugarcane ethanol cases, one for ethanol produced and dehydrated in Brazil and one where the ethanol was dehydrated in the Caribbean Basin[15], and for both cases there was a marginal vs. average electricity case. The Brazilian ethanol with the marginal power will be considered here, as that is the pathway that achieved a 61% reduction in GHG emissions, which is greater than the 50% reduction required to qualify as an advanced biofuel. This pathway has no collection of the residue for additional power production. The EPA results are shown in the following table.

[15] The Caribbean Basin Initiative (CBI) is intended to facilitate the economic development and export diversification of the Caribbean Basin economies. The CBI currently provides beneficiary countries with duty-free access to the U.S. market for most goods.

Table 6-7 RFS2 Sugarcane Ethanol Well to Tank Emissions

	g CO_2eq/MM BTU	g CO_2eq/MJ
International Land Use Change	4,300	4.08
Other (fuel and feedstock transport)	4,637	4.40
Domestic Farm Inputs and Fert N_2O	0	0.00
Domestic Soil Carbon	1,049	0.99
Domestic Livestock	0	0.00
Domestic Rice Methane	0	0.00
International Farm Inputs and Fert N_2O	37,884	35.93
International Livestock	-128	-0.12
International Rice Methane	485	0.46
Ethanol Plant	-11,027	-10.46
Tailpipe	880	0.83
Total	38,080	36.12

If we remove the international land use emissions and reclassify the emissions into the standard groupings that are used here, the results are shown in the following table. The land management change in the US from expanded Brazilian sugarcane production is not large but it is derived from the FAPRI model. This is the result of FAPRI projection of some land use change in the US with the expansion of sugarcane area in Brazil. This is really an indirect land use change and has also been removed from the table.

Table 6-8 Reclassified RFS2 Sugarcane Ethanol

	Sugarcane Ethanol
	g CO_2eq/MJ
Feedstock Production	37.26
Feedstock Transport	1.69
Ethanol Production	-10.46
Ethanol Distribution	2.71
Ethanol Use	0.83
Total	32.03

6.2.1 Feedstock Production

In the EPA analysis the emissions associated with the feedstock production make up most of the lifecycle emissions. These are calculated from the crop changes projected by the FAPRI model and the energy and emission factors developed by the EPA.

Almost all of the increased sugarcane production happens in Brazil and almost 40% of the new sugar cane area comes from land that was in corn production in Brazil.

The Brazilian sugarcane yield in 2022 is reported as 113 tonnes/ha, this is much higher than the 80 t/ha that has been the highest historical yield in Brazil. It was assumed that only 10% of the cane was burned in the field.

The sugar cane fertilizer application rates that were applied in Brazil were 0.75 kg N/t, 0.39 kg P_2O_5/tonne, and 1.03 kg K_2O/tonne. The energy use in Brazil was reduced compared to the control case but the overall energy use for all crops and all regions was approximately 17 l diesel/ha. The GHG emissions for the various components are shown in the following table.

Table 6-9 GHG Emissions by Feedstock Production Component

	g CO_2eq/MJ
Total N use	0.42
Total P_2O_5 use	0.14
Total K_2O use	0.54
Lime	1.84
Herbicide Use	0.00
Pesticide Use	0.00
N_2O Emissions	27.74
Ag Energy Use	4.88
Int'l Rice CH4	0.46
Sugarcane Residue Burning	0.61
Total	36.64

The N_2O emissions dominate the feedstock production emissions. The EPA used the IPCC Tier 1 default values for these calculations. Seventy-five percent of the N_2O emissions were from the direct emissions from the breakdown of the crop residues. They are therefore very sensitive to the N_2O emission factor and there is little direct evidence of what the emission factors are in Brazil.

6.2.2 Fuel Production

The ethanol plant burns bagasse, a small amount of diesel fuel and produces electricity. The assumptions are shown in the following table.

Table 6-10 Ethanol Inputs

Parameter	Value
Biomass	1.81 kg/litre
Diesel Fuel	0.0006 l/litre ethanol
Power sold	0.45 kWh/l

There are some GHG emissions associated with the biomass combustion and the diesel fuel and a GHG emission credit for the power. The power is credited with a marginal power intensity of 166 g CO_2eq/MJ of power; this is a typical value for a natural gas simple cycle system.

Table 6-11 Fuel Production

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Bagasse and diesel	2.15	0.07	0.0333	0.0044
Power	-12.61	-12.00	-0.0257	-0.0002
Total	-10.46	-11.93	0.0076	0.0042

There are no emissions associated with the use of lime at the ethanol plants.

6.2.3 Transportation

The feedstock and fuel transportation emissions use the same data and emission factors that were in GREET 1.8c.

Table 6-12 RFS2 Sugarcane Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	30 km	1.69	1.64	0.0389	0.0096

The transportation distances that are used for the ethanol transportation and distribution are shown in the following table.

Table 6-13 RFS2 Sugarcane Ethanol Transportation Data

	Pipeline	Rail	Ocean tanker	Barge	Truck
Distance in Brazil, km	805	805	11,823	0	0
% Mode	50	50	100	0	0
Distance in US, km	0	1012	0	540	120
% Mode	0	76.8	0	11.7	100

More recent versions of GREET have updated the transportation modes so that all of the ethanol in Brazil moves by truck instead of rail and pipeline. This is more consistent with the actual practice. The ocean tanker energy use is also for a crude oil super tanker and ethanol is moved from Brazil in much smaller vessels, so the emissions calculated by the EPA will be a significant underestimate of the actual emissions. The resulting transportation emissions are shown below.

Table 6-14 RFS2 Sugarcane Ethanol Transportation Emissions

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	2.71	2.63	0.0689	0.0194

6.2.4 Fuel Use

The fuel use emissions are the same as the EPA used for corn ethanol and discussed in section 5.2.4.

6.2.5 Lifecycle Emissions Summary

The EPA RFS lifecycle emissions for sugarcane ethanol without the land use impacts are summarized in the following table. The feedstock production emissions are dominated by the N_2O emissions from the sugarcane residue left in the field. The emission rate is the IPCC default rate. The ethanol production emissions do not include any chemicals such as lime or cyclohexane, which are used in Brazil. The ethanol distribution emissions are not reflective of current practices where truck is used in Brazil instead of rail and pipelines and the ocean shipments of ethanol use relatively small vessels with higher fuel consumption than is used in this modelling effort.

Table 6-15 Reclassified RFS2 Sugarcane Ethanol

	Sugarcane Ethanol
	g CO_2eq/MJ
Feedstock Production	37.26
Feedstock Transport	1.69
Ethanol Production	2.15
Co-product credit (power)	-12.61
Ethanol Distribution	2.71
Ethanol Use	0.83
Total	32.03

6.3 GREET

The sugarcane ethanol pathway in GREET has been updated several times in the past few years as more data on the actual production system in Brazil has become available. The default emissions in the model are shown in the following table.

Table 6-16 GREET Sugarcane Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	22.30	12.93	0.1059	0.0226
Feedstock Transport	2.31	2.21	0.0033	0.0001
Ethanol Production	2.76	0.02	0.0357	0.0062
Co-product (power)	-1.63	-1.45	-0.0063	-0.0001
Ethanol Distribution	9.09	8.72	0.0122	0.0002
Total	34.83	22.44	0.1508	0.0289

The default conditions that the model chooses when the year 2012 is chosen are summarized in the following table. These represent a mixture of manually harvested burnt fields and mechanically harvested unburned fields. As the year in GREET is increased, more of the fields are mechanically harvested.

Table 6-17 GREET Modelling Assumptions

Parameter	Value
Year	2012
Portion of fields manual cut	44%
Portion of fields burned	44%
Fraction of sugarcane straw left in unburned fields	76%
Share of straw burnt in burnt fields	90%

There is also some surplus power that is produced from the sugarcane mills. This is treated as a co-product and the emissions that are displaced are calculated based on the Brazilian power grid.

6.3.1 Feedstock Production

The sugarcane production parameters used in the latest version of GREET are shown below. They are based on recent reports by Macedo (2008) and Seabra (2011).

Table 6-18 Sugarcane Production Inputs

	GREET1_2012 Rev2
Diesel, litre eq/tonne sugarcane	2.8
N (including vinasse), g/tonne sugarcane	1,041
P_2O_5, g/tonne sugarcane	307
K_2O, g/tonne sugarcane	1,148
$CaCO_3$, g/tonne sugarcane	5,200
Herbicide, g/tonne sugarcane	45
Insecticide, g/tonne sugarcane	2.5

The feedstock production emissions account for almost 65% of the lifecycle emissions for this pathway. The composition of the emissions is shown in the following table.

Table 6-19 GREET Sugarcane Feedstock Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Fuel	4.79	4.29	0.0187	0.0001
Nitrogen	3.47	2.13	0.0113	0.0035
P_2O_5	0.07	0.06	0.0001	0.0000
K_2O	0.22	0.20	0.0007	0.0000
$CaCO_3$	1.39	1.39	0.0001	0.0000
Herbicide	0.40	0.37	0.0011	0.0000
Insecticide	0.03	0.02	0.0001	0.0000
N_2O and straw burning	11.92	4.45	0.0738	0.0189
Total	22.30	12.93	0.1059	0.0226

One half of the feedstock production emissions are from the decomposition of nitrogen fertilizer and crop residues or the burning of the straw. In this category 60% of the emissions are from methane and nitrous oxide. The N_2O emission factor EF_1 for sugarcane is 0.895%, the other emission factors are IPCC defaults. The total emission factor is 1.22% of the nitrogen in the system. This is discussed in a paper comparing the GHG emissions from corn, sugarcane and cellulosic ethanol (Wang et al, 2012). This paper states that the N_2O emission rate was chosen based on two measured results reported by Carmo et al (2012).

The Carmo paper actually has more than 2 measurements. A total of eight scenarios were measured and the lowest emission factor was 0.68% and the highest was 3.03%. The emission rate increased with the application of vinasse and with increasing quantities of crop residues left on the field.

The GREET model includes vinasse applications and straw left on the field so the use of this N_2O emission factor may be too low for the case being modelled.

6.3.2 Fuel Production

The ethanol plant burns bagasse and a small quantity of fuel oil. There are also some non-combustion emissions of VOCs, which in GREET contribute to GHG emissions. There are no other inputs modelled in GREET, although the plants are known to use some lime in the process. The contribution of the non-CO_2 emissions from the biomass combustion are the largest source of emissions at the ethanol plant.

Table 6-20 GREET Sugarcane Ethanol Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Residual fuel	0.04	0.04	0.0000	0.0000
Biomass combustion	2.64	-0.10	0.0356	0.0062
Non-combustion process emissions	0.09	0.09	0.0000	0.0000
Co-product credit	-1.63	-1.45	-0.0063	-0.0001
Total	1.14	1.14	0.0293	0.0061

The quantity of power that is produced is 0.55 kWh/litre. The credit is based on the average Brazilian grid, which is dominated by hydropower. The credit is 16.3 g CO_2eq/MJ of power, about 10% of the value used by the EPA RFS2 modelling.

6.3.3 Transportation

The sugarcane is transported 19.3 km from the fields to the mill. The emissions for this short movement are relatively high as the cane has a high moisture content and some straw is moved to the mill for fuel use.

Table 6-21 GREET Sugarcane Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	19.3 km	2.31	2.21	0.0033	0.0001

The transportation of the ethanol to the United States uses a combination of truck and ship transport. This version uses truck transport in Brazil and has included a smaller sized ocean vessel for moving the product to the United States. These revisions overcome the shortcomings of earlier versions of GREET.

Table 6-22 GREET Ethanol Transportation and Blending

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel					
Exporting country	691 km	3.57	3.42	0.0052	0.0001
Importing Country	209 km	1.08	1.02	0.0016	0.0000
Fuel oil					
Ocean transport	11,930 km	4.37	4.21	0.0055	0.0001
Electricity		0.06	0.06	0.0000	0.0000
Total		9.09	8.72	0.0122	0.0002

6.3.4 Fuel Use

The fuel use emissions are the same for all sources of ethanol and were discussed in section 5.3.4.

6.3.5 Lifecycle Emissions Summary and CA GREET

CARB modelled three sugarcane ethanol pathways, an average scenario, a mechanized harvest scenario, and a case with the export of some power. The three scenarios are shown in the following table.

Table 6-23 CARB Sugarcane Ethanol Scenarios

	Average	Mechanized plus power export	Power Export
	g CO_2eq/MJ		
Feedstock Production	19.0	11.0	19.0
Feedstock Transport	2.0	2.0	2.0
Ethanol Production	2.1	2.1	2.1
Co-product (power)	0.0	-7.0	-7.0
Ethanol Distribution	3.5	3.5	3.5
Total	26.6	11.6	19.6

The mechanized option ignores any change in N_2O emissions from the increased crop residues; we will discuss the average case compared to the latest GREET results. The inputs are compared in the following table.

Table 6-24 Sugarcane Production Inputs

	CARB GREET 1.8b	GREET1_2012 Rev2
Diesel, litre eq/tonne	2.8	2.8
N, g/tonne	1,092	1,041
P_2O_5, g/tonne	149	307
K_2O, g/tonne	194	1,148
$CaCO_3$, g/tonne	5,338	5,200
Herbicide, g/tonne	8.1	45
Insecticide, g/tonne	2.2	2.5

Other than the potash, the results are not that different. There have been some changes in the emission intensity for the chemicals, as shown in the following table.

Table 6-25 Ag Chemicals Production – Sugar Cane

	CARB GREET 1.8b	GREET1_2012rev2
	g CO_2/g	g CO_2/g
Nitrogen	2.96	5.04
P_2O_5	1.02	0.38
K_2O	0.69	0.33
$CaCO_3$	0.63	0.02
Herbicide	21.4	21.28
Insecticide	24.86	24.86

There is a large difference in the transportation emissions. The CARB assumptions are the same ones used by the EPA. The difference is shown below.

Table 6-26 Ethanol Transportation Assumptions

	CARB GREET 1.8b	GREET1_2012rev2
Pipeline distance, miles	500	0
Pipeline fraction	0.50	0
Rail distance, miles	500	0
Rail fraction	0.50	0
Truck distance, miles	0	500
Truck fraction	0	1.0

CARB used the GREET defaults at the time, assuming that half of the ethanol was shipped from the plant to the port by pipeline and the other half by rail. GREET1_2012 has been changed to reflect the reality that 100% moves by truck. This increases the emissions by over 6 grams/MJ.

The ocean transport distance is 7,416 miles in both cases and the shipping energy is 65 BTU/mile-tonne round trip. This is a very low number and the latest version of GREET increases this to 146 (from 38), reflecting the fact that these shipments tend to be smaller and use smaller, less efficient ships.

6.4 GHGENIUS

We have set GHGenius to the same fraction of manually harvested, burned fields as used by GREET. The model is also set to the United States and the year 2012. The excess power displaces natural gas simple cycle power. The results are shown in the following table.

Table 6-27 GHGenius Sugarcane Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	28.93	13.79	0.1368	0.0393
Feedstock Transport	2.31	2.21	0.0033	0.0001
Ethanol Production	5.81	0.72	0.0789	0.0105
Co-product (power)	-4.26	-3.74	-0.0188	-0.0002
Ethanol Distribution	11.04	10.57	0.0147	0.0003
Total	43.83	23.54	0.2149	0.0500

6.4.1 Feedstock Production

A number of sources of information on fertilizer application rates were identified in the last update of the sugarcane ethanol pathway in GHGenius. The International Fertilizer Association (2009) published estimates for the years 2006/07 and 2007/08 on fertilizer use by crop and by country. This data can be matched with the FAO data on crop area to arrive at an application rate. Information is also supplied by Seabra et al (2011), Macedo et al (2008), and Macedo et al (2004). This information is summarized in the following table.

Table 6-28 GHGenius Sugarcane Fertilizer Application Rates

	Nitrogen	Phosphate	Potassium	Lime
	Kg N/ha	Kg P_2O_5/ha	Kg K_2O/ha	Kg CaO/ha
IFA	84.2	43.1	112.2	-
Seabra	67.4	21.6	85.0	450
Macedo (2008)	80.0	45.0	114.6	1,900
Macedo (2004)	71.6	40.8	120.0	366
Average	75.8	37.6	108	905

The fertilizer requirements used for the model are summarized in the following table. The nitrogen and lime rates are increased compared to the previous version and the phosphorus and potassium rates are similar.

Table 6-29 Fertilizer Assumptions for the GHGenius

Nutrient	Application Rate		Application Rate
	GHGenius 3.2	GHGenius 4.01	GHGenius 4.01
	kg/ha		kg/tonne of cane
Nitrogen	58.3	84	1.077
Phosphorus	36.7	45	0.577
Potassium	100	115	1.474
Lime	366.7	900	11.538

Sugarcane cultivation employs herbicides, insecticides, fungicides and other chemicals. The application rates from the literature are summarized in the following table.

Table 6-30 Chemical Application Rates

	Herbicides	Insecticides	Fungicides	Other
	Kg /ha			
Seabra	3.8	0.26	0	0.083
Macedo (2008)	2.2	0.16	-	-
Macedo (2004)	2.2	0.19	-	-
Average	2.7	0.20	-	-

The Seabra results were based on a top down approach and are believed to be more accurate than the earlier estimates. A value of 4 kg/ha, or 0.05 kg/tonne of cane is used in the model. This is not significantly different than that used previously.

Diesel fuel is required for the application of fertilizer and agricultural chemicals and for the movement of the collection trucks in the field. The Macedo et al (2004) data is used for the energy use information for manual harvesting. This is summarized in the following table.

Table 6-31 Energy Requirements for Manual Sugarcane Production

	Energy Consumed	
	litres/tonne of Cane	litres/ha
Agricultural operations	0.80	64

Mechanical harvesting is rapidly becoming the standard practice in many regions of Brazil. There are both State and Federal decrees that are driving the change. The goal is to reach 100% mechanized harvest by 2018. The default assumption in GHGenius is that 44% of the cane is mechanically harvested.

There are a variety of estimates for fuel usage in mechanized harvest systems, as shown in the following table. The diesel fuel for transportation to the mill is included in the Macedo and Seabra analysis.

Table 6-32 Energy Requirements for Mechanized Sugarcane Production

Source	% Mechanized	Energy Consumed
		litres/ha
Macedo (2008)	50	230
Seabra (2011)	48	274
Galdos (2010)	100	75

This data would suggest that the diesel fuel consumption for a 100% mechanized harvest system would be about 250 l/ha. This is about 3.1 l/tonne of cane (3.2 l/tonne in 2004). It will be assumed that this value, when expressed on a per tonne of cane basis, is reduced by 1% per year. This would result in only a small increase per hectare as yields increase in the future.

An important question is what are the emission factors for N_2O that are applied in the calculation? Almost all of the literature uses the 0.01 EF_1 value, which is the IPCC default value. Some analyses do also factor in the emissions for the material that is leached from the site and the indirect N_2O from the volatilization of the nitrogen, also using the IPCC defaults.

Sugarcane has a high need for moisture and there is the possibility that the N_2O emission factor should be higher due to high levels of precipitation. Renouf et al (2010), in a study of Australian sugarcane production, use an average value of 0.04 for EF_1 and report a range of 0.01 to 0.07. Thorburn et al (2010) modeled the N_2O emissions from sugarcane production systems in Australia and determined a range of N_2O emissions from 3-5% of fertilizer applied. Denmard et al (2010) measured N_2O emissions at two sites in Australia and found a range of emissions from 2.8 to 21% of nitrogen in applied fertilizer. The Australian national GHG inventory applies a value of 1.25% for EF_1 but it is not clear if this is a Tier 2 value, or simply the Tier 1 value from the 1995 IPCC guidelines.

Lisboa et al (2011) looked at this issue for sugarcane production. In addition to the data from Australia they also found data for Hawaii. They determined that the average N_2O emission rate was 3.87%, however while they compare this value to the IPCC EF_1 value, they are not comparable. The 3.87% is the total N_2O emissions based just on the nitrogen applied with synthetic fertilizer. It does not include the nitrogen applied from residue or other sources, nor does it include the N_2O from nitrogen leached from the site. Including these would lower the emission factor.

De Figueiredo et al (2010) undertook a detailed estimate of GHG emissions (including methane and N_2O) associated with sugarcane production in Brazil using data from one mill, but follow the IPCC guidelines for all of the emission factors. This report also does not consider the emissions embedded in the fertilizer or lime.

Based on the previous discussion, an emission factor for EF_1 of 0.0125 has been chosen for GHGenius, as most of the data supports a higher emission factor for sugarcane than the IPCC default value.

The GHG emissions for feedstock production in GHGenius are summarized in the following table.

Table 6-33 Sugarcane Production Emissions – GHGenius

Source	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel fuel	4.49	4.00	0.0052	0.0012
N_2O, Straw Burning, Liming	19.53	5.44	0.1134	0.0378
Fertilizer manufacture	4.90	4.35	0.0182	0.0003
Total	28.93	13.79	0.14	0.04

6.4.2 Fuel Production

Sugarcane mills burn the bagasse (the sugar free portion of the cane) to produce steam and electricity. More electricity is produced than is needed to run the mills and many mills can also produce more steam than is required.

The bagasse yield reported by Seabra from 74 mills was 234 kg/tonne of cane. Since a tonne of cane will produce 80 litres of ethanol, the amount of bagasse burnt will be 2.92 kg/litre of ethanol. The combustion of the bagasse will have some N_2O and methane emissions that must be accounted for.

There are some process chemicals required in the ethanol plant. Seabra (2011) reports that some lime and sulphuric acid are used. The quantities are summarized in the following table.

Table 6-34 Process Chemicals

	GHGenius 4.00	Seabra	GHGenius 4.01
Sulphuric acid, kg/litre ethanol	0.00905	0.0074	0.0074
Lime, kg/litre ethanol	0.010	0.011	0.011
Caustic	0.0	0.0021	0.0021
Diesel	0.0008	0	0.0008

While Seabra does not report any diesel fuel for the ethanol mill, just a small quantity of lubricants, the mills do have a number of vehicles that are used for a variety of tasks, forklifts, tractors for bagasse piles, plant trucks, etc., so some small amount of fuel will be required. The 0.0008 litres/litre of ethanol is typical of the fuel use in North American ethanol plants.

Sugar mills in Brazil have been rapidly increasing the quantity of electricity that they produce. At one time sales of power to the grid were not allowed, but that is no longer the case.

Seabra reports that the power sales for 124 mills averaged 10.7 kWh/tonne of cane or 0.134 kWh/litre of ethanol. The previous value in GHGenius was 0.06 kWh/litre. The new value is used.

The process emissions from an ethanol plant are relatively minor in most situations. GHGenius includes VOC and particulate matter emissions from ethanol plants but other ethanol plants have no process related GHG emissions. That may not be the case for all sugarcane ethanol plants.

It was noted earlier that some nitrogen containing stillage, filter cake and boiler ashes are returned to the soil as fertilizer. From these nitrogen containing materials, the N_2O emissions were calculated. The stillage also contains phosphorus and potassium fertilizer and organic material. Seabra reports that the quantity of stillage produced and reused is 11 litres/litre of ethanol based on data from 85 mills. A variety of methods are employed to return this material to the fields, but one method is through the use of open drainage channels. In these channels it has been reported that the stillage goes anaerobic and methane is generated.

This issue was raised by Galdos et al (2010) who recommended further investigation and by Lisboa et al (2011) who made some estimates of the emission rates:

> *First measurements in Brazil show that CH_4 is produced and emitted during the transport of vinasse in open channels to application sites. CH_4 emissions from open channels are approximately in the 0–10 mg CH_4-C m^{-2} h^{-1} range. If one assumes that the share of open irrigation channels per ha sugarcane field is approximately 1% and that vinasse is applied at 30 days yr^{-1} the total CH_4 emission would be in maximum 720 g CH_4-C ha^{-1} sugarcane yr^{-1}.*

This methane emission rate would be approximately 5 grams methane/GJ of ethanol or 120 g CO_2eq/GJ. This is relatively small but it is based on a low rate of methane emissions.

Boddey (2009), in a presentation on the unknowns with respect to the GHG emissions from sugarcane ethanol, reported methane emissions at various points in the distribution channels. The emissions were 4.5 g CH_4/m^2/hour close to the mill where the temperature was 60°C, but they increase as the temperature of the effluent decreased, at 37°C they were 20.9 g CH_4/m^2/hour and at 25°C they had increase to 185.5 g CH_4/m^2/hour. This information would suggest that the emissions could be considerably higher than 120 g CO_2eq/GJ.

Oliveira et al (2011) reported that the average methane emissions were 2.23 kg CO_2eq/m^3 of vinasse. This is equivalent to 1,030 g CO_2eq/GJ for the mill studied. Not all mills distribute the vinasse through open ditches that can go anaerobic.

When estimating the methane emissions from anaerobic digestion, the IPCC has an emission factor of 0.21 t CH_4 per tonne of COD. The COD of the vinasse can range from 20,000 to 60,000 mg/litre. With vinasse production of 11 litres/litre of ethanol, the maximum methane emission rate could be as high as 3,900 g CH_4/GJ of ethanol or 97,000 g CO_2eq/GJ. This is not to suggest that this is the typical emission rate but this is clearly an issue that requires more research and data. These emissions have not been added to the model as the values are speculative and clearly more work is required to quantify them.

The GHGenius emissions for the fuel production stage are summarized in the following table.

Table 6-35 Sugarcane Ethanol Fuel Production – GHGenius

Source	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Plant Emissions	5.81	0.72	0.0789	0.0105
Co-product	-4.26	-3.74	-0.0188	-0.0002
Fuel Production	1.55	-3.02	0.0601	0.0103

6.4.3 Transportation

The sugarcane is transported from the field to the sugar mill an average of 20 km by truck. This is supported by the 21 km reported by Seabra et al in their 2011 paper. They do expect some increase in the future as mills get larger and transportation distances must increase.

The product transportation assumptions in GHGenius are 400 km by truck, 12,558 km by ship, and 2% shipped 63 km by rail and 34% shipped an average distance of 137 km by barge. The transportation emissions are shown in the following table.

Table 6-36 GHGenius Transportation Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock	2.31	2.21	0.0033	0.0001
Ethanol	11.04	10.57	0.0147	0.0003

6.4.4 Fuel Use

The fuel use emissions for ethanol in GHGenius are the same as they are for corn ethanol and discussed in section 6.4.4.

6.4.5 Lifecycle Emissions Summary

The lifecycle GHG emissions for sugarcane ethanol from GHGenius are shown in the following table.

Table 6-37 GHGenius Sugarcane Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	28.93	13.79	0.1368	0.0393
Feedstock Transport	2.31	2.21	0.0033	0.0001
Ethanol Production	5.81	0.72	0.0789	0.0105
Co-product (power)	-4.26	-3.74	-0.0188	-0.0002
Ethanol Distribution	11.04	10.57	0.0147	0.0003
Total	43.83	23.54	0.2149	0.0500

GHGenius has the most complete accounting of the emissions of the models considered. It also has the highest emissions from the four models. It includes some non-combustion emissions at the ethanol plant that none of the other models include. It also has the highest N_2O emission factor of the models.

6.5 SUMMARY

The results for sugarcane ethanol from the five models are shown in the following table. The results range from 24 to 44 g CO_2eq/MJ. There is a large variation in the results for almost all of the stages of the lifecycle.

Table 6-38 Sugarcane Ethanol Summary excluding ILUC

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy		Displacement		
	g CO_2eq/MJ (LHV)				
Feedstock Production	14.11	37.26	22.30	19.0	28.93
Feedstock Transport	0.84	1.69	2.31	2.0	2.31
Ethanol Production	0.85	2.27	2.76	2.1	5.81
Co-product (power)	0.0	-13.29	-1.63	0.0	-4.26
Ethanol Distribution	8.16	2.71	9.09	3.5	11.04
Total	23.97	32.03	34.83	26.6	43.83

The EPA RFS2 modelling produces the highest emissions for the feedstock production stage, but they have the lowest rate of burning and thus the highest quantity of residues left in the field. BioGrace has the lowest field emissions but it is not transparent how the N_2O emissions were calculated and it may be that there is no N_2O from the field burning of the crop residues. The components of sugarcane production in the different models are compared in the following table.

Table 6-39 Sugarcane Ethanol Feedstock Summary

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation		Displacement			
	g CO_2eq/MJ (LHV)				
Diesel Fuel	1.29	4.88	4.79	1.8	4.49
Fertilizer	3.80	2.94	5.58	5.7	4.90
N_2O emissions	5.49	27.74	11.92	3.5	11.26
Other	3.53	1.70	-	8.0	8.28
Total	14.11	37.26	22.30	19.0	28.93

BioGrace also has the lowest transport emissions but they have a similar transportation distance so their truck efficiency must be higher.

The ethanol plant emissions range from less than 1 to almost 6 g CO_2eq/MJ. BioGrace excludes the methane and N_2O emissions from the bagasse combustion. The RFS2 and GREET have no chemical related emissions for the production process and only GHGenius also includes some non-combustion process emissions.

BioGrace and the CARB base case do not consider any power exports. The EPA and GREET use different kinds of power to displace (average vs. marginal production). GHGenius uses a similar assumption about the type of displaced power but uses a current estimate of quantity vs. a forecast of the quantity in 2022.

The most important uncertain parameter is the N_2O emission factor.

6.5.1 Indirect Land Use Change

The EPA RFS2 modelling framework has been set to restrict land expansion in the United States and thus the reported International emissions represents the indirect land use change emissions. In Europe and in California they have utilized other models (IFPRI-Mirage in Europe and GTAP in California) to estimate the indirect land use emissions. The ILUC emissions for sugarcane ethanol are added to the direct emissions for those three modelling frameworks below. The EU results use a 20-year amortization period and have been adjusted to a 30-year period to allow comparisons to the other sources in the following table. The BioGrace results also have actual values shown, although for sugarcane ethanol there is very little difference between the two approaches as there is almost no fossil energy used in the ethanol processing stage.

Table 6-40 Direct Emissions and Indirect Land Use Emissions – Sugarcane Ethanol

	BioGrace	EPA RFS2	CA GREET
	g CO_2eq/MJ		
Direct Emissions	23.72	31.04	26.6
ILUC	8.9	4.1	46
Total	32.62	35.14	72.6

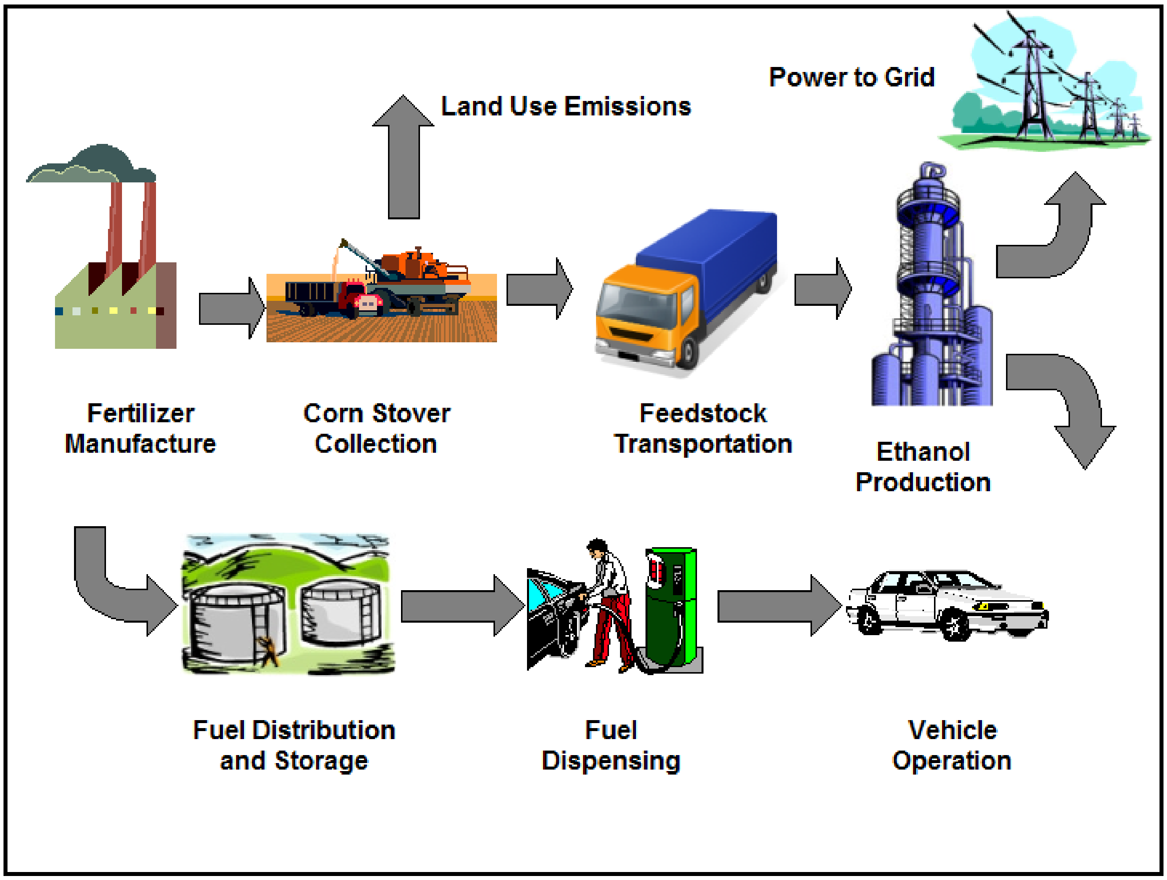
There are significant differences in the ILUC emissions between the European model and the North American models. With the North American models, the ILUC emissions are very different, unlike the case with corn ethanol where they were quite close.

7. Cellulosic Ethanol

The pathway specifics that have been chosen are to use corn stover as the feedstock and enzymatic hydrolysis as the conversion process. This was the basis for the RFS2 work and this pathway exists in both GREET and in GHGenius.

There are five primary stages for the cellulosic ethanol lifecycles, the corn stover recovery stage (which will include fertilizer manufacturing and land use emissions), feedstock transportation, ethanol production, ethanol transportation, distribution and dispensing, and the vehicle use stage. Again the transportation distribution, storage and dispensing stages will be combined, as the contributions are small. The stages are shown in the following figure.

Figure 7-1 General System Boundaries – Cellulosic Ethanol



7.1 BioGrace

There is no cellulosic ethanol pathway in BioGrace. The version 3 of the JEC wells to wheels study includes a wheat straw to ethanol process modelled with information from Iogen. The source is cited as "Iogen plant data supplied by Groves, A., Shell: evaluation of ethanol from lignocellulose; July 2003". This is not a public report and Iogen was at a relatively early stage of development in 2003. This is an enzymatic process but utilizes wheat straw instead of corn stover. The emissions from this report are shown in the following table.

Table 7-1 JEC Wheat Straw to Ethanol

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	3.08	3.0	0.00	0.00
Feedstock Transport	0.62	0.6	0.00	0.00
Ethanol Production	3.43	3.3	0.00	0.00
Ethanol Distribution	1.54	1.5	0.00	0.00
Total	8.7	8.4	0.01	0.00

Very little detail is available in the JEC reports on this pathway but the JEC WTW report version 3c states:

> *A biomass credit is given for electricity export again based on the Altenstadt wood-burning power station (the straw-burning power plant at Sanguesa in Spain has a similar efficiency). Of the chemicals inputs, Iogen only specified sulphuric acid consumption, which is lower than for the wood-to-ethanol process because of a more favourable composition. We assumed that the other chemicals (e.g. for neutralization) mentioned by [Wooley 1999] are also needed by the straw process, in proportion to the lower sulphuric acid requirements.*
>
> *The yield calculation applied to wood gives about the wood-to-ethanol yields claimed in [Wooley 1999]. Furthermore, we used the same procedure for the straw-to-SSCF part of process, and came up with energy and emissions figures almost the same as for a commercial state-of-the art straw-to-ethanol process.*

The detail data in version 3c is shown in the following table. It does not appear to include the collection of the feedstock nor the distribution of the ethanol to the service stations. The ethanol production emissions are similar in the two reports (versions 3 and 3c) but the other stages are different.

Table 7-2 Emissions from JEC WTW Report version 3c

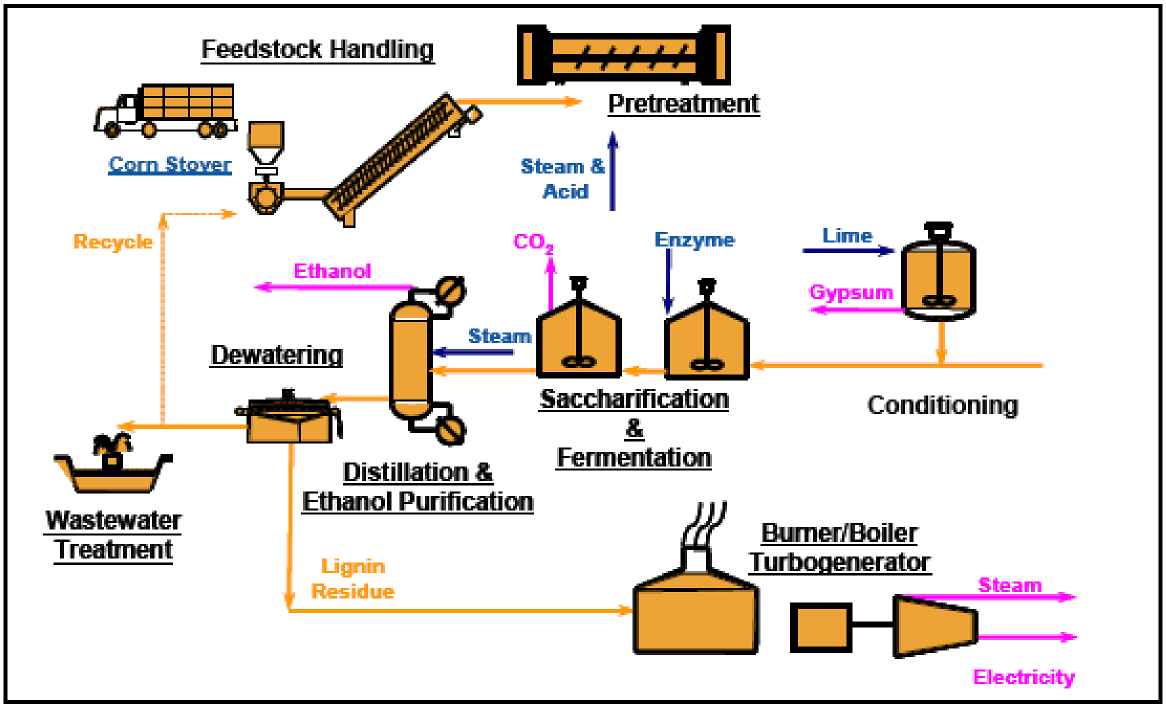
	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total Fertilizer	1.31	1.23	0.0030	0.0000
Transport of straw	0.22	0.22	0.0000	0.0000
Credit for straw-to-electricity	-0.07	0.00	-0.0014	-0.0001
H_2SO_4	0.87	0.81	0.0023	0.0000
CaO	2.59	2.54	0.0020	0.0000
Total	4.92	4.8	0.0059	-0.0001

7.2 EPA RFS2

The EPA considered several cellulosic ethanol pathways in their analysis, the corn stover to ethanol via hydrolysis and fermentation is considered here as it can be compared to similar pathways in other models.

The EPA relied on data from NREL (2008) to model the pathway. The process schematic is shown in Figure 7-2. This is a conventional process and NREL have been developing and refining the process for more than a decade.

Figure 7-2 NREL Corn Stover Ethanol Process Schematic



Source: NREL

For this analysis, NREL chose to purchase enzymes. Electricity and steam are produced from the portion of the feedstock that is not converted to ethanol and some excess electricity is available for sale to the grid. In the EPA modelling, the electricity is given a credit for the average grid carbon intensity.

Table 7-3 RFS2 Corn Stover Ethanol Well to Tank Emissions

	g CO_2eq/MM BTU	g CO_2eq/MJ
International Land Use Change	0	0.00
Other (fuel and feedstock transport)	2,418	2.29
Domestic Farm Inputs and Fert N_2O	1,660	1.57
Domestic Soil Carbon	-10,820	-10.26
Domestic Livestock	9,086	8.62
Domestic Rice Methane	434	0.41
International Farm Inputs and Fert N_2O	0	0.00
International Livestock	0	0.00
International Rice Methane	0	0.00
Ethanol Plant (includes electricity credit)	-32,628	-30.95
Tailpipe	880	0.83
Total	-28,969	-27.48

This data has been reclassified into the standard stages and the results are shown in the following table.

Table 7-4 Reclassified RFS2 Corn Stover Ethanol

	Without Land Management Change	With Land Management Change
	g CO_2eq/MJ	
Feedstock Production	10.60	0.34
Feedstock Transport	1.11	1.11
Ethanol Production	-30.95	-30.95
Ethanol Distribution	1.18	1.18
Ethanol Use	0.83	0.83
Total	-17.23	-27.49

7.2.1 Feedstock Production

The components that are included in the feedstock production emissions are shown in the following table.

Table 7-5 Feedstock Production Emissions

Component	g CO_2eq/MJ
Domestic Farm Inputs and Fert N_2O	1.57
Domestic Soil Carbon	-10.26
Domestic Livestock	8.62
Domestic Rice Methane	0.41
Total	0.34

The EPA modelling has a significant build in soil carbon. The unusual aspect is that this happens in year zero with very small increases or decreases each year after that. It is not clear from the data that have been released what would drive the build of soil carbon in the first year.

There are changes in fuel and fertilizer use between the control case and the corn stover ethanol cases. There is an increase in cropped acres of 587,000 acres. There are increases in fertilizer use and electricity but decreases in diesel fuel, natural gas, and gasoline use with the corn stover collection scenario. The emissions for the fuel and fertilizer are shown in the following table.

Table 7-6 FASOM Fuel and Fertilizer Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total Fertilizer	2.95	2.70	0.0037	0.0011
Fuel	-1.09	-1.01	-0.0034	0.0000
N_2O emissions	-0.30	0.00	0.0000	-0.0010
Total	1.56	1.69	0.0003	0.0001

It is surprising that there is a reduction in agricultural fuel use with an increase in corn stover collection. The model is obviously projecting more cropping changes than just collecting corn stover from existing cornfields. This is also apparent from an increase in livestock methane emissions and rice emissions. This would suggest that more meat and rice are being consumed. Those emissions are shown in the following table.

Table 7-7 FASOM Livestock and Rice Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Domestic Livestock	8.62	0.00	0.4104	0.0000
Rice Methane	0.41	0.00	0.0196	0.0000
Total	9.03	0.00	0.4300	0.0000

7.2.2 Fuel Production

The fuel production parameters are a yield of 385 litre/dry tonne in 2022 and an electricity export rate of 0.95 kWh/litre. Both values are higher than are used in other models. No enzymes or other chemicals are considered from a GHG perspective. There are emissions from the combustion of the lignin and a credit for the sale of power. The credit provided is the US average electricity rate in 2022, projected to be 208.5 g CO_2eq/MJ.

The fuel production emissions are shown below.

Table 7-8 Fuel Production Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Plant Emissions	2.66	0.00	0.0029	0.0084
Co-product	-33.60	-32.55	-0.0439	-0.0004
Total	-30.94	-32.55	-0.0410	0.008

7.2.3 Transportation

The emissions from the transportation of the stover from the field to the ethanol plant and from the ethanol plant to the market are calculated by the EPA using emission factors from GREET. The emissions for the two transportation stages are shown below.

Table 7-9 Transportation Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock	1.11	1.08	0.0001	0.0000
Fuel	1.19	1.15	0.0001	0.0000
Total	2.30	2.23	0.0003	0.0001

7.2.4 Fuel Use

The fuel use emissions for cellulosic ethanol are the same as for the other sources of ethanol. These were discussed in section 5.2.4.

7.2.5 Lifecycle Emissions Summary

The lifecycle emissions for this pathway are shown in the following table.

Table 7-10 EPA RFS2 Cellulosic Ethanol Summary

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Fertilizer	2.95	2.70	0.0037	0.0011
Farm Fuel	-1.09	-1.01	-0.0034	0.0000
N_2O emissions	-0.30	0.00	0.0000	-0.0010
Feedstock transportation	1.11	1.08	0.0001	0.0000
Domestic Livestock	8.62	0.00	0.4104	0.0000
Rice Methane	0.41	0.00	0.0196	0.0000
Domestic Soil Carbon	-10.26	-10.26	0.0000	0.0000
Plant Emissions	2.66	0.00	0.0029	0.0084
Co-product credit (power)	-33.60	-32.55	-0.0439	-0.0004
Fuel transportation	1.19	1.15	0.0001	0.0000
Fuel use	0.83	0.00	0.0121	0.0276
Total	-27.48	-38.89	0.4016	0.0357

There are a number of surprising findings with this analysis. First, there is the large one time increase in soil carbon in the first year of the modelling, which results in a large CO_2 credit. There is also the decrease in farm fuel requirements with the increase in corn stover collection. The plant modelling assumes a rapid progress in the plant yield and performance by the year 2022. The power available for sale to the grid increases as the quantity of mass combusted decreases. There are also no emissions calculated for the purchased chemicals for the plant.

7.3 GREET

GREET has several cellulosic ethanol pathways; we have chosen the corn stover to ethanol via hydrolysis and fermentation pathway. The model is set to the year 2012 and the land use change emissions have been excluded from the modelling. The summary of the emissions is shown in the following table.

Table 7-11 GREET Corn Stover Ethanol

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	10.32	8.56	0.0322	0.0032
Feedstock Transport	1.05	1.01	0.0015	0.0000
Ethanol Production	8.19	4.57	0.0295	0.0097
Co-Product (Power)	-17.11	-15.98	-0.0424	-0.0002
Ethanol Distribution and storage	1.52	1.46	0.0020	0.0000
Total	3.97	-0.39	0.0228	0.0127

The total lifecycle emissions are very low but this is the result of a high credit for the excess electricity produced. Each of the stages is discussed in more detail below.

7.3.1 Feedstock Production

The feedstock portion of the lifecycle includes diesel fuel required to collect the corn stover from the field and the emissions from the production or manufacture of additional fertilizer that is required to be used to replace the nutrients in the stover that is removed. The contribution of the various components is shown in the following table.

Table 7-12 GREET Corn Stover Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Fuel	2.62	2.52	0.0038	0.0000
Nitrogen	6.46	4.89	0.0251	0.0032
P_2O_5	0.18	0.17	0.0004	0.0000
K_2O	1.06	0.98	0.0029	0.0000
Total	10.32	8.56	0.0322	0.0032

There are no additional N_2O emissions as the quantity of nitrogen applied in the crop residue and synthetic sources is the same, with or without, stover removal. The actual model inputs for these parameters are shown in the following table.

Table 7-13 Corn Stover Inputs

Parameter	Model Value
Fuel	5.55 litres/t
Nitrogen	7.7 kg/t
P_2O_5	2.0 kg/t
K_2O	12.0 kg/t

7.3.2 Fuel Production

The fuel production process parameters are shown in the following table. The plant is self-sufficient in steam and has excess power for sale back to the grid. This power is given an emissions credit based on the grid carbon intensity. The only inputs from a modelling perspective are cellulase enzymes and yeast.

Table 7-14 Corn Stover Ethanol Inputs

Parameter	Model Value
Yield	340 litres/t
Excess power production	225 kWh/t
Excess power production	0.66 kWh/litre
Cellulase enzyme	10 kg/t stover
Yeast	2.5 kg/t stover

The emissions from this stage are shown in the following table.

Table 7-15 GREET Corn Stover Ethanol Production Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	0.22	0.21	0.0003	0.0000
Biomass combustion	2.61	-0.01	0.0030	0.0085
Cellulase enzymes	4.40	3.55	0.0209	0.0011
Yeast	0.91	0.77	0.0053	0.0000
Non Combustion emissions	0.04	0.04	0.0000	0.0000
Power Credit	-17.11	-15.98	-0.0424	-0.0002
Total	-8.93	-11.42	-0.0129	0.0094

The emissions per unit of enzymes and yeast used in GREET are summarized in the following table. These are emission intensive inputs. These emission estimates were calculated by the GREET team (Dunn, et al., 2012) and are not based on primary data from enzyme or yeast manufacturing facilities. There are few other estimates in the literature and none are based on primary data.

Table 7-16 GREET Corn Stover Ethanol Production Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/kg	g/kg	g/kg	g/kg
Cellulase enzymes	3,573	2,965	15.10	0.77
Yeast	2,918	2,522	15.31	0.05

7.3.3 Transportation

The corn stover is transported an average distance of 61.5 km from the field to the ethanol plant. The emissions for this stage are shown in the following table.

Table 7-17 Corn Stover Transportation Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Corn Stover transportation	1.05	1.01	0.0015	0.0000

The corn stover ethanol transportation distances are identical to the corn ethanol distances and modes. Moving the ethanol from the plant to a bulk terminal is done 40% by barge (830 km), 40% by rail (1,280 km), and 20% by truck (130 km). All of the ethanol is then moved by truck from the terminal to the retail station, a distance of 50 km. The emissions from these movements are shown in the following table.

Table 7-18 GREET Ethanol Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	920 km	1.52	1.39	0.0020	0.0000

7.3.4 Fuel Use

The fuel use stage is identical for all types of biomass ethanol and the results were shown in section 5.3.4 and Table 5-38.

7.3.5 Lifecycle Emissions Summary and CA GREET

The cellulosic ethanol via fermentation pathway that has been published using CA GREET uses farmed wood as the feedstock rather than corn stover. Nevertheless, the results are very similar to the results from the latest version of GREET using corn stover. The two pathways are compared in the following table.

Table 7-19 CA GREET vs. GREET1_2012 Cellulosic Ethanol

	CA GREET	GREET1_2012
	g CO_2eq/MJ	
Feedstock	Farmed Trees	Corn Stover
Feedstock Production	4.44	10.32
Feedstock Transportation	2.10	1.05
Ethanol Production	2.56	8.19
Co-product (power)	-10.2	-17.11
Ethanol Transportation	2.70	1.52
Total	1.60	3.97

The difference in the feedstock emissions is from the different fertilizer needs of the two crops. These are compared in the following table.

Table 7-20 CA GREET vs. GREET1_2012 Feedstock Fertilizer

	CA GREET	GREET1_2012
	g/dry ton	
Feedstock	Farmed Trees	Corn Stover
Nitrogen	709	7,700
P_2O_5	189	2,000
K_2O	331	12,000
Herbicide	24	0
Pesticide	2	0
Diesel	6.5 litres/ton	5.7 l/ton
Electricity	3.92 kWh/ton	0

The CA GREET model does not include the cellulase enzymes and yeast as process inputs. This accounts for most of the difference in the two models. There is no commercial cellulosic ethanol plant in operation so the process inputs are based on computer simulations or pilot plant data. Most of these techno-economic assessments have had more chemical inputs than are included in the GREET model and there are GHG embedded in these chemicals that are therefore not included in the GREET modelling. Both the CA GREET and the GREET1_2012 likely underestimated the emissions for this process as a result of the lack of many of the chemicals being included in the model. In addition, the first commercial plants may not operate as well as predicated by the process models, at least initially. Yields may be lower and the power and energy requirements may be higher.

7.4 GHGENIUS

GHGenius has an enzymatic cellulosic pathway that has default data from The US National Renewable Energy Laboratory recently released report (NREL, 2011) that has detailed information on one variation of the biochemical process. The process is conceptually the same as modelled by the EPA and by GREET with the exception that GHGenius includes the emissions associated with most of the chemicals that are used in the process. The emissions for this pathway are summarized in the following table. The model is set to the United States, the year 2012, and the 2007 IPCC GWPs.

Table 7-21 GHGenius Cellulosic Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	10.52	9.31	0.0319	0.0014
Feedstock Transport	2.48	2.37	0.0030	0.0001
Ethanol Production	33.14	24.20	0.1683	0.0159
Co-product (power)	-15.84	-13.91	-0.0698	-0.0006
Ethanol Distribution	2.25	2.13	0.0034	0.0001
Total	32.55	24.10	0.1368	0.0169

Each stage is discussed in more detail in the following sections.

7.4.1 Feedstock Production

For materials like corn stover, GHGenius includes the replacement of the nutrients in the stover with synthetic fertilizers. There are no incremental N_2O emissions, as the amount of nitrogen applied to the land remains constant. There are additional fuel requirements to collect the stover from the field.

Table 7-22 Corn Stover Production Parameters

	2012
	kg/tonne
Nitrogen	9.40
P_2O_5	1.38
K_2O	10.33
Sulphur	0.0
Pesticides	0.0
Seeds	0.0
Diesel fuel, L	7.70

The emissions for the feedstock production stage are summarized in the following table.

Table 7-23 GHGenius – Corn Stover Production Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock recovery	4.80	4.29	0.0056	0.0013
Fertilizer manufacture	5.72	5.03	0.0264	0.0001
Total feedstock production	10.52	9.31	0.0319	0.0014

7.4.2 Fuel Production

The ethanol yield is modelled as 329 litres/tonne (79 gal/ton) and the process produces surplus power of 0.50 kWh/litre for sale to the grid. It is assumed that this power displaces natural gas single cycle power.

The chemical input data for this biochemical process, as detailed in the NREL report, is summarized in the following table. One of the attributes of GHGenius is that it has the ability to include many different process chemicals. It does not have corn steep liquor or the last four chemicals in this list but all of the other chemicals on this list can be included in the modelling. Note that the process requires 0.38 kg of process chemicals for every litre (0.79 kg) of ethanol produced.

Table 7-24 Process Chemicals Biochemical Process

Input	Kg/litre ethanol
Glucose	0.088
Caustic	0.082
Sulphuric acid	0.072
Corn steep liquor	0.048
Ammonia	0.043
Lime	0.033
Diammonium phosphate	0.005
Yeast	0.004
Host nutrients	0.002
Sorbitol	0.002
Sulphur dioxide	0.001
Boiler chemicals	0.000

The GHG emissions for this stage are summarized in the following table. It can be seen that the largest contribution is from the process chemicals, which are often ignored or only partially considered in other LCA models.

Table 7-25 Fuel Production Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Plant Emissions, biomass comb + fossil fuels	6.52	0.14	0.0757	0.0151
Process Chemicals	26.62	24.07	0.0900	0.0000
Co-product	-15.84	-13.91	-0.0698	-0.0006
Total	17.3	10.30	0.0959	0.0145

7.4.3 Transportation

The feedstock and fuel transportation emissions are shown in the following table. The feedstock transportation distance is an average of 100 km, all by truck. The cellulosic ethanol transportation emissions are higher than corn ethanol as it is assumed that more is moved by rail (45% vs. 22%) and the trucking distance is 225 km instead of 121 km).

Table 7-26 GHGenius Transportation Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock	2.48	2.37	0.0030	0.0001
Fuel	2.25	2.13	0.0034	0.0001
Total	4.73	4.50	0.0064	0.0002

7.4.4 Fuel Use

The fuel use emissions are the same for all ethanol; these were discussed in section 5.4.3.

7.4.5 Lifecycle Emissions Summary

The lifecycle emissions for cellulosic ethanol from GHGenius are shown in the following table. While these emissions are the highest of the four models, almost all of the increase is accounted for by the emissions from producing the process chemicals. These emissions are partially included in GREET1_2012, but are excluded from the other models.

Table 7-27 GHGenius Cellulosic Ethanol Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock recovery	4.80	4.29	0.0056	0.0013
Fertilizer manufacture	5.72	5.03	0.0264	0.0001
Feedstock Transport	2.48	2.37	0.0030	0.0001
Plant Emissions, biomass comb + fossil fuels	6.52	0.14	0.0757	0.0151
Process Chemicals	26.62	24.07	0.0900	0.0000
Co-product (power)	-15.84	-13.91	-0.0698	-0.0006
Ethanol Distribution	2.25	2.13	0.0034	0.0001
Total	32.55	24.10	0.1368	0.0169

7.5 SUMMARY

There is a very wide range in the emissions for this pathway. That is perhaps not too surprising given that there are no commercial operations and thus the data quality for this pathway is quite low. Nevertheless there are also some fundamental differences to what is included (or not included) in the models. The results are compared in the following table.

Table 7-28 Cellulosic Ethanol Summary

	RFS2	GREET		GHGenius
		2012_rev2	CA-GREET	
IPCC GWP	1995	2007	2007	2007
Feedstock	Stover	Stover	Wood	Stover
	g CO_2eq/MJ (LHV)			
Feedstock Production	0.34	10.32	4.44	10.52
Feedstock Transport	1.11	1.05	2.10	2.48
Ethanol Production	2.66	8.19	2.56	33.14
Co-Product (Power)	-33.60	-17.11	-10.2	-15.84
Ethanol Distribution and storage	1.18	1.52	2.70	2.25
Total	-28.31	3.97	1.60	32.55

The EPA RFS2 modelling is the simplest; it does not include any inputs into the system other than the biomass. It has the most optimistic estimates of yield and power available for sale to the grid. This modelling also has a one-time increase in soil carbon at the beginning of the time period and some changes in the domestic livestock sector resulting in increased emissions.

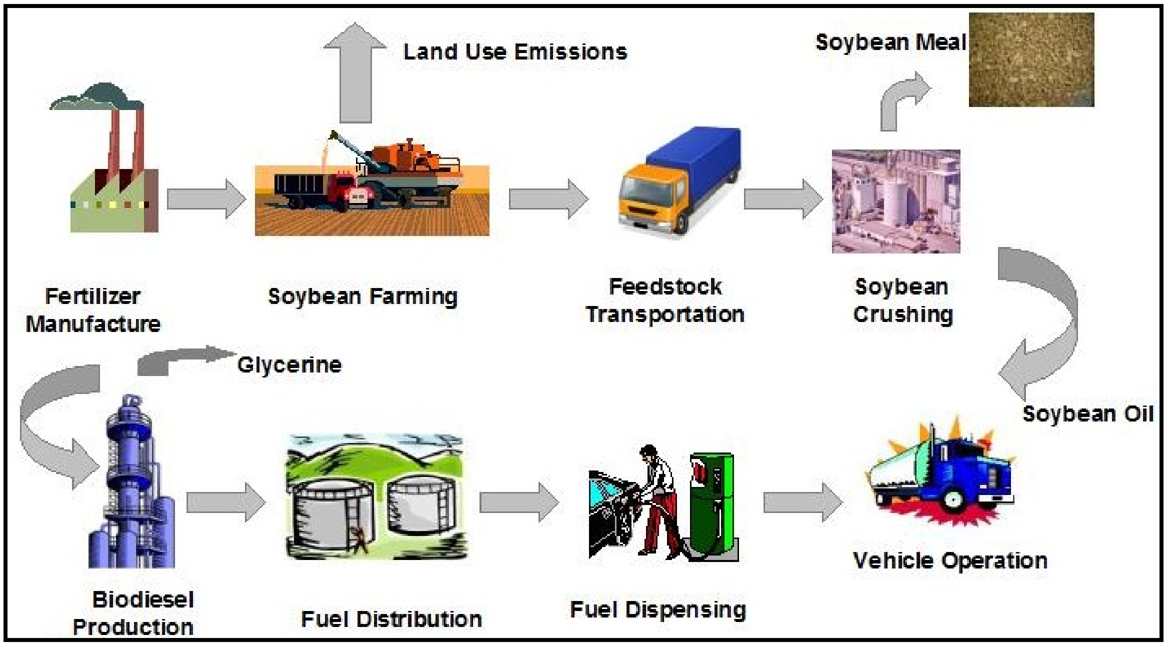
The GREET1_2012 model includes the emissions associated with enzymes and yeast but none of the other chemicals that are included in most cellulosic ethanol processes. The CA GREET model includes no process chemicals. It does include the emissions from the combustion of the biomass and a small amount of diesel fuel.

GHGenius has the most complete accounting of process chemicals and the highest emissions. The process information that is included as the defaults has a large quantity of chemicals including potentially emission intensive chemicals like sodium hydroxide. These chemicals account for most of the emissions difference between GREET and GHGenius.

8. SOYBEAN BIODIESEL/RENEWABLE DIESEL

There are six primary stages for the soybean biodiesel/renewable diesel lifecycles, the soybean production stage (which will include fertilizer manufacturing and land use emissions), feedstock transportation, soybean crushing to produce oil and meal, biodiesel or renewable diesel manufacturing, biodiesel transportation, distribution and dispensing, and the vehicle use stage. Again the soybean oil and biodiesel/renewable diesel distribution, storage and dispensing stages are combined, as the contributions are small. The stages are shown in the following figure.

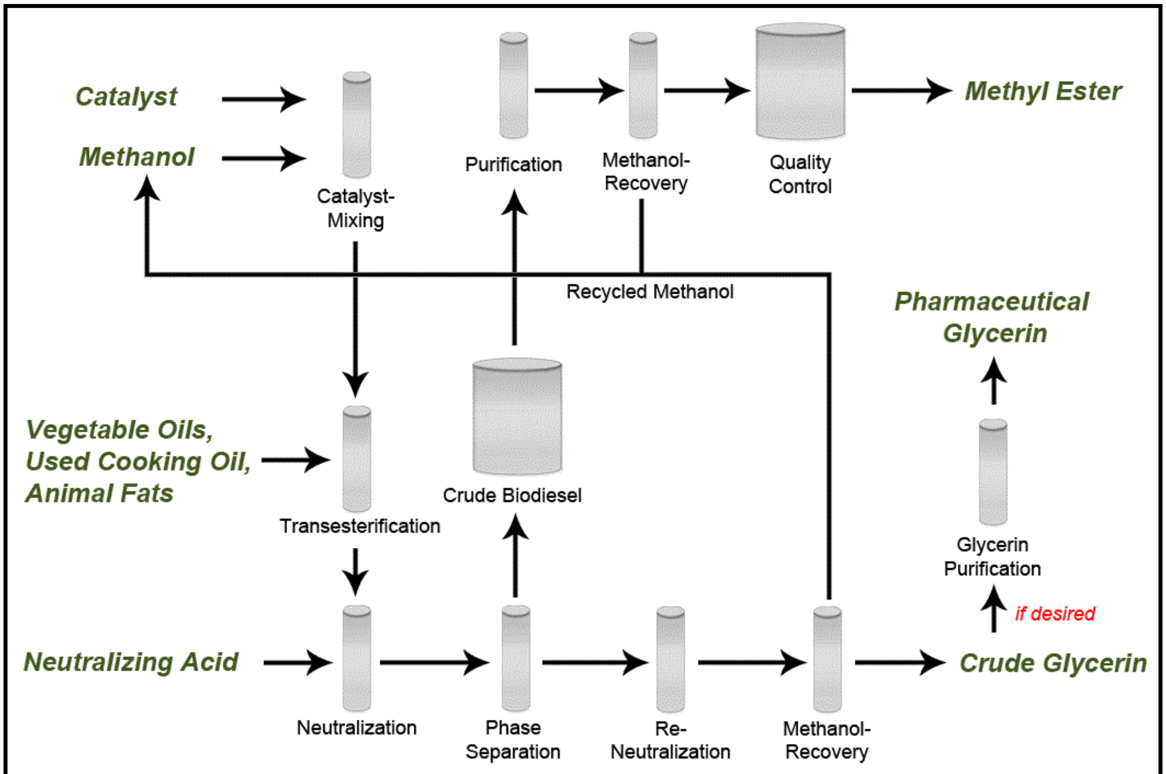
Figure 8-1 General System Boundaries – Soybean Biodiesel



The primary options available to the modellers are the approach to allocation of the emissions to the meal and glycerine co-products. The model variables are described in each section and an attempt has been made to allow the most accurate comparisons possible.

The biodiesel manufacturing process can have many small variations. A typical process is shown in the following figure.

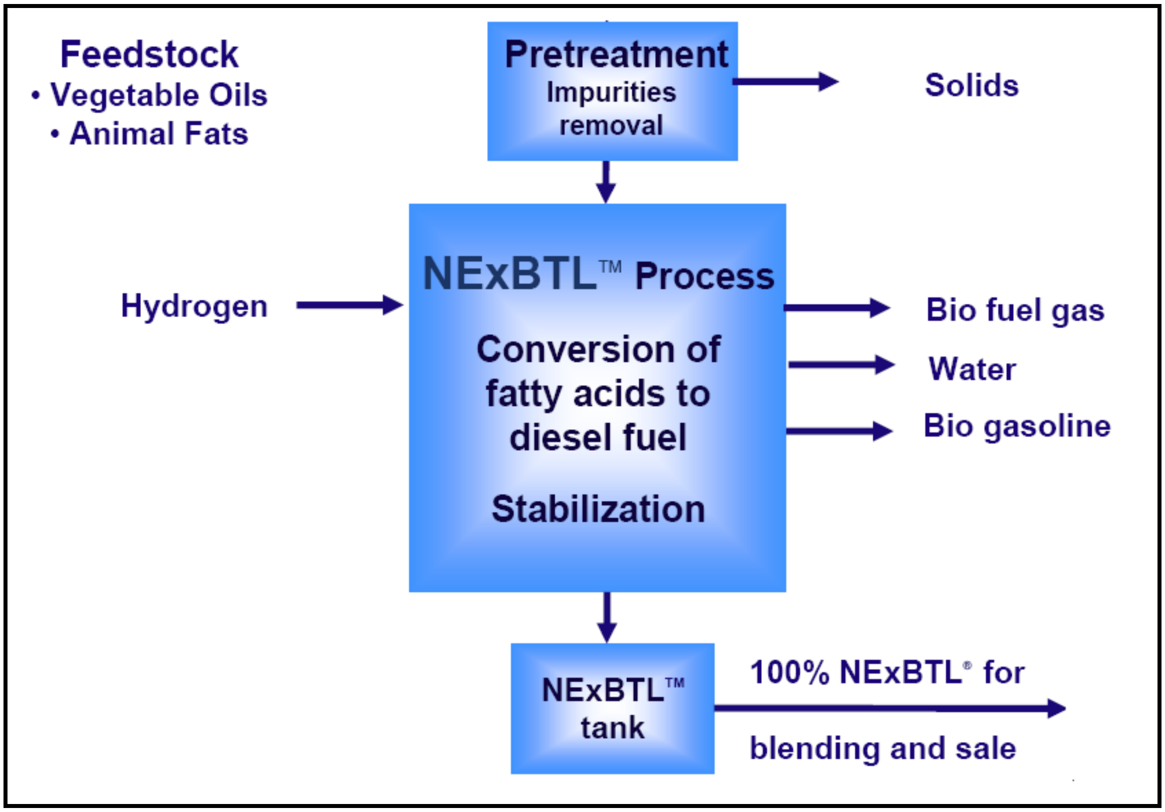
Figure 8-2 Biodiesel Production Process



Source: (S&T)[2]

Renewable diesel production involves reacting the oils and fats with hydrogen rather than methanol and it produces a hydrocarbon rather than an ester. A typical process is shown in the following figure.

Figure 8-3 Renewable Diesel Process



Source: Neste Oil

8.1 BIOGRACE

The soybean biodiesel pathway in BioGrace models Brazilian soybean production and the transport of the soybeans to Europe. The oil is extracted from the soybeans in Europe and converted to biodiesel there. Like all BioGrace pathways, allocation of the emissions between the oil, meal, glycerine, and biodiesel is done by energy allocation. The model assumes that the glycerine is upgraded to technical grade; otherwise no credit is given for crude glycerine as that is considered a waste product. The soybean oil is refined before it is transesterified into biodiesel. The summary of the pathway emissions is shown in the following table.

Table 8-1 BioGrace Soybean Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	56.21	18.17	0.0178	0.1271
Feedstock Transport	35.95	35.60	0.0010	0.0011
Oilseed Crushing	24.13	22.46	0.0652	0.0006
Fuel Production	17.51	16.28	0.0502	0.0002
Co-products meal	-77.31	-50.48	-0.0544	-0.0864
Co-products glycerine	-0.81	-0.75	-0.0023	0.0000
Biodiesel Distribution	1.26	1.22	0.0013	0.0000
Total	56.94	42.50	0.0788	0.0426

BioGrace does not have a renewable diesel pathway that uses soybean oil but it does have pathways using rapeseed oil, sunflower oil, and palm oil. We have added the renewable diesel from soybean oil to the BioGrace model using the same data that is used for the other pathways.

8.1.1 Feedstock Production

The production of the soybeans is assumed to take place in Brazil. The production inputs are shown in the following table.

Table 8-2 BioGrace Soybean Production Inputs

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	20.9 litres/t	10.12	10.12	0.0000	0.0000
N Fertilizer	2.86 kg/t	2.59	1.24	0.0038	0.0042
K_2O	22.16 kg/t	1.96	1.83	0.0054	0.0000
P_2O_5	23.59 kg/t	3.67	3.50	0.0048	0.0002
Pesticides	0.0.96 kg/t	1.63	1.47	0.0038	0.0002
Seeds	0.00	0.00	0.00	0.0000	0.0000
N_2O Emissions		36.24	0.00	0.0000	0.1224
Total		56.21	18.17	0.0178	0.1271

The fuel use is from a German fuel use estimate for rapeseed production. Brazil is a significant adopter of no till agriculture and thus will use much less fuel than is used in the very tillage intensive production systems used in Europe. The source of data for the fertilizer input is the FAO fertilizer use by crop series. The data is from 2002.

Soybeans fix their own nitrogen and thus they have very low nitrogen requirements as evidenced in the table. The N_2O emissions are not transparent. The sources are identified as the 2006 IPCC Guidelines and personal communications with J Edwards of the JRC. Since there is little nitrogen applied, the largest contributor to the emissions is the decomposition of the crop residues. The IPCC uses a default value for soybean crop residue nitrogen of 21.7 kg N/tonne of soybeans produced. The total nitrogen in the system would be 24.6 kg/tonne of soybeans. The direct N_2O emission factor would be about 1.78% of the fertilizer and crop residue nitrogen based on these assumptions.

8.1.2 Feedstock Transportation

The feedstock transportation emissions are significant in the scenario modelled. The beans are transported 700 km by truck in Brazil and then 10,186 km by ocean transport, the same assumption used for sugarcane ethanol from Brazil. There is no transport of the beans in Europe as the assumption is that the crusher is located at a port, a reasonable assumption. The emissions are summarized in the following table.

Table 8-3 Soybean Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel					
Exporting country	700 km	8.76	8.75	0.0005	0.0000
Fuel oil					
Ocean transport	10,186 km	27.19	26.85	0.0005	0.0011
Total		35.95	35.60	0.0010	0.0011

These emissions are very high and reflect the low oil content of the soybeans. A portion of these emissions are allocated to the meal (65.6%) and the glycerine (1.5%), but a different transportation scenario would produce quite different results, for example if the beans were crushed close to where they were grown and the oil transported to Europe this emission category would almost disappear but the oil transportation emissions (which are zero in this scenario) would increase. The BioGrace model does not allow this scenario to be modelled, as there is no provision for transport of the oil between the crusher and the biodiesel plant.

8.1.3 Oilseed Crushing

The crushing of the beans and refining of the oil takes place in Europe in the scenario modelled. The inputs and the emissions from this stage are shown in the following table. The energy and chemicals are increased by 40% from the expected values.

Table 8-4 Soybean Crushing

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Crushing	188 kg oil/t soybeans				
Natural Gas	1,554 MJ/t soybeans	10.5	14.92	0.0476	0.0003
Electricity	84 kWh/t soybeans	6.43	6.01	0.0147	0.0003
Hexane	0.98 kg/t soybeans	0.54	0.54	0.0001	0.0000
Refining					
Natural Gas	45.1 MJ/t oil	0.87	0.81	0.0026	0.0000
Electricity	8.4 kWh/t oil	0.14	0.13	0.0003	0.0000
Fullers earth	8.4 kg/t oil	0.05	0.05	0.0000	0.0000
Total		24.13	22.46	0.0652	0.0006

The data for both of these processes is based on a 1999 report on rapeseed crushing and refining from the German Environment Agency (Krause et al, 1999). It is increased by 40% as per the RED methodology.

The co-product credit for the meal is based on the relative energy contents of the meal and the oil. As shown in Table 8-1, this is a very large credit and it includes the transportation emissions in the calculations.

8.1.4 Fuel Production

The process parameters and the GHG emissions for the components of the biodiesel production stage are shown in the following table.

Table 8-5 Biodiesel Production

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Yield	0.92 kg oil/l biodiesel				
Natural Gas	3.69 MJ/l	7.59	7.04	0.0224	0.0001
Electricity	0.038 kWh/l	0.78	0.73	0.0018	0.0000
Phosphoric acid	0.0021 kg/l	0.19	0.18	0.0006	0.0000
Hydrochloric acid	0.0249 kg/l	0.57	0.54	0.0008	0.0000
Sodium carbonate	0.0031 kg/l	0.11	0.10	0.0006	0.0000
Sodium Hydroxide	0.0084 kg/l	0.12	0.11	0.0003	0.0000
Methanol	1.29 l/l	8.15	7.59	0.0237	0.0000
Total		17.51	16.28	0.0502	0.0002

The source of this data is reported as Dreier, T., Geiger, B., Institute for Energy and Power Plant Technology, Technical University of Munich (IfE) Saller, A., Research Institute for Energy (FfE): Holistic process chain analysis for the production and use of bio-fuels; study commissioned by Daimler Benz AG, Stuttgart and Bavarian Center for Applied Energy Research (ZAE), May 1998. Commercial biodiesel production did not really start until the mid 1990s so it is not clear how much of this data was based on theoretical or laboratory work and how much might have been based on commercial experience. There is a difference between the natural gas value in BioGrace and the value in the JEC spreadsheets that are supposed to duplicate the results for the RED. The gas use in BioGrace is about double that in the JEC spreadsheet. The natural gas and methanol components account for the majority of the emissions.

The treatment of methanol in the model is questionable since there is a stoichiometric reaction involved, so if 40% extra methanol is used then it must come out somewhere else in the process. For example, it could be used as fuel in the process and the current treatment could be considered double counting of these emissions. The standard value for the production and oxidation of methanol is 99.57 g CO_2eq/MJ of methanol.

The glycerine credit is quite small and may be less than the extra energy that is required at the plant to produce technical grade glycerine (> than 98% purity). Plants may have a better carbon footprint if they sell the crude glycerine for feed or fuel than if they upgrade it to technical grade, although the economics may not be as attractive. This is a problem when the energy value of a product is very different from its value as a chemical and, since the production of glycerine through the Farben process is very energy intensive, this is a problem here.

8.1.5 Transportation

The biodiesel is assumed to be transported 300 km by truck to the filling station. There is also some electricity consumption at the storage depot and the filling station. These emissions are shown in the following table.

Table 8-6 Biodiesel Transportation and Blending

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Truck	300 km	0.71	0.71	0.0000	0.0000
Terminal power	0.008 kWh/l	0.11	0.10	0.0002	0.0000
Dispensing electricity	0.031 kWh/l	0.44	0.41	0.0010	0.0000
Total		1.26	1.22	0.0012	0.0000

8.1.6 Fuel Use

Fuel use is not included in the BioGrace model.

8.1.7 Renewable Diesel

The renewable diesel pathway results are compared to the biodiesel results in the following table. The primary difference is in the fuel production stage, where the renewable diesel has an advantage. The co-products from the renewable diesel production process are some electricity and steam from natural gas. The soybean oil is not refined in the case of the renewable diesel. In the default case both the hydrogen and the co-products are increased by 40% from the expected values.

Table 8-7 BioGrace Soybean Biodiesel vs. Renewable Diesel

	Biodiesel	Renewable Diesel
	GHG	GHG
	g CO_2eq/MJ	g CO_2eq/MJ
Feedstock Production	56.21	55.44
Feedstock Transport	35.95	35.46
Oilseed Crushing	24.13	22.76
Fuel Production	17.51	10.47
Co-products meal	-77.31	-74.56
Co-products glycerine (BD) or Power (RD)	-0.81	-1.14
Biodiesel Distribution	1.26	1.15
Total	56.94	49.58

The key modelling parameters for the renewable diesel process are summarized in the following table. In the default case both the hydrogen and the co-products are increased by 40% from the expected values.

Table 8-8 BioGrace Renewable Diesel Modelling Parameters

Parameter	Expected Value	Model Value
Yield, kg RD/kg soybean oil	0.80	0.80
Hydrogen consumption, MJ H_2/kg RD	3.77	5.28
Co-product electricity, kWh/kg RD	0.018	0.025
Co-product natural gas, MJ/kg RD	0.495	0.544

This modelling data is based on the Neste process as modelled in 2006 by IFEU (Reinhardt et al, 2006). This work was done before the first of the refinery-integrated plants was constructed and the data was supplied by Neste.

8.1.8 Lifecycle Emissions Summary

The BioGrace soybean biodiesel production system is based on the production of soybeans in Brazil and all of the processing of the soybeans takes place in Europe. This pathway has very high transportation emissions as a result. It is difficult to verify the quality of the data used in the model, as an example fuel consumption data from one crop and country has been used for a different crop in a different county. Similarly, the energy requirements for crushing soybeans are based on the energy requirements for processing rapeseed.

The biodiesel processing data has a few values that appear to be inconsistent with the assumptions that have been made. For example, the biodiesel yield is quite low considering that refined soybean oil is the feedstock; a value of 4-5% higher would be more consistent with the feedstock quality. The biodiesel processing energy is also quite high compared to what is used in other models.

In the following table the BioGrace results for soybean biodiesel and soybean renewable diesel without using the extra 40% energy in the default case are shown. The actual value for the biodiesel is 12.7% less than the default and the actual renewable diesel is 9.9% less than the default value.

Table 8-9 BioGrace Soybean Biodiesel vs. Renewable Diesel- "Actual Values"

	Biodiesel	Renewable Diesel
	GHG	GHG
	g CO_2eq/MJ	g CO_2eq/MJ
Feedstock Production	56.21	55.44
Feedstock Transport	35.95	35.46
Oilseed Crushing	17.24	16.25
Fuel Production	12.50	7.48
Co-products meal	-72.89	-70.29
Co-products glycerine (BD) or Power (RD)	-0.58	-0.84
Biodiesel Distribution	1.26	1.15
Total	49.69	44.65

8.2 EPA RFS2

The full collection of models is employed in the EPA modelling of soybean biodiesel. The emissions are summarized in the following table.

Table 8-10 RFS2 Soybean Biodiesel Well to Tank Emissions

	g CO_2eq/MM BTU	g CO_2eq/MJ
International Land Use Change	42,543	40.35
Other (fuel and feedstock transport)	3,461	3.28
Domestic Farm Inputs and Fert N_2O	106	0.10
Domestic Soil Carbon	-8,896	-8.44
Domestic Livestock	-2,100	-1.99
Domestic Rice Methane	-7,950	-7.54
International Farm Inputs and Fert N_2O	5,402	5.12
International Livestock	-6,436	-6.10
International Rice Methane	2,180	2.07
Biodiesel Plant	13,153	12.47
Tailpipe	700	0.66
Total	42,161	39.99

If we remove the international land use emissions we can reclassify the EPA results into the categories that are used for the other models. The results for this are shown in the following table. The oilseed crushing emissions and the credit for the meal are included in the FASOM model and thus it is not possible to extract the data for those stages. Like the FASOM results for corn and corn stover, there is a large one year increase in soil carbon in the FASOM results for soybeans.

Table 8-11 Reclassified RFS2 Soybean Biodiesel

	Without Land Management Change	With Land Management Change
	g CO_2eq/MJ	
Feedstock Production	-8.35	-16.78
Feedstock Transport	2.52	2.52
Oilseed Crushing	-	-
Biodiesel Production	12.47	12.47
Co-products meal	-	-
Co-products glycerine	-	-
Biodiesel Distribution	0.76	0.76
Total	7.41	-1.03

8.2.1 Feedstock Production

The feedstock production emissions in the EPA modelling are negative. There are several possible explanations for this. The first is that the credit for the soybean meal is included in the feedstock production emissions. This likely accounts for a large portion of the feedstock emissions offset. The other explanation is that an increase in soybean area means that there is a reduction in the production area of other crops. Since soybeans fix their own nitrogen from the air and do not require significant quantities of nitrogen fertilizer, this will result in less nitrogen fertilizer being used in the soybean only case compared to the control case.

The international agricultural emissions are also close to zero, although the response of the individual components (livestock, rice, farm inputs) is not the same in the FASOM and FAPRI models.

In the domestic model, the largest increase in soybean acres is found in Arkansas, Indiana, Michigan, Minnesota, Ohio and North Dakota. These states are in four different regions in the model. We have shown the agricultural inputs for the Lake States and the Corn Belt.

Table 8-12 FASOM Soybeans Inputs

	Lake States	Corn Belt	International
Yield, (bu/acre)	42.6	46.2	42.6
Nitrogen, kg/tonne	1.4	2.8	2.7
P_2O_5, kg/tonne	3.0	2.4	20.1
K_2O, kg/tonne	8.8	7.6	17.4
$CaCO_3$, kg/tonne	0.0	79.5	-
Pesticides, kg/tonne	0.7	0.7	0.2
Diesel, l/tonne	19.8	18.3	6.1

The FASOM values are slightly higher than the GREET values for these inputs.

The international inputs have less confidence. The fertilizer inputs are estimates based on the fertilizer sold in the country with a set of calculations that match that value with the area of each crop and the expected fertilizer applied for each crop. In the case of nitrogen for soybeans the range of fertilizer used by the EPA is 1.1 to 47.8 kg/tonne. The high end of the range cannot be explained. However, almost 85% of the incremental soybean production occurs in Brazil so it is the Brazil values that drive the overall results.

The energy use is based on very coarse data at the country level. IEA data on the CO_2 emissions in each country from 2005 is used to arrive at the energy use in the agricultural and forestry sector. This is divided by the agricultural area, and is thus an overestimate because it is the energy used in agriculture and forestry. The quality of this data is uncertain; in some countries the breakdown of energy use by sector is little more than an estimate.

In FASOM, the soybean yield is expected to grow at 0.43% annually. That would put the yield in 2022 at 45.3 bu/acre. FASOM employs elasticity factors to adjust the inputs as the yield increases. The elasticity factors are shown in the following table.

Table 8-13 FASOM Input Elasticities - Soybean

Parameter	Elasticity
Nitrogen	0.8
Phosphorus	0.8
Pesticides	1.69
Fuel	1.66

While the inputs used for soybean production in FASOM and FAPRI are higher than those used in other models, it is the relative values of these inputs compared to the inputs for the crops that soybeans replace that will drive the overall results. The value of soybean meal replacing other crops will also influence the results.

The difference in the input quantities per tonne of soybeans produced between the control case and the soybean only case are shown in the following table.

Table 8-14 FASOM Soybean Inputs

Parameter	Value
Total N use, kg/tonne	-4.7
Total P_2O_5 use, kg/tonne	0.5
Total K_2O use, kg/tonne	2.0
Total Lime Use, kg/tonne	7.7
Herbicide Use, kg/tonne	0.1
Pesticide Use, kg/tonne	0.1
Total Diesel Fuel use, l/tonne	-2.0
Total Gasoline use, l/tonne	-7.7
Total Electricity Use, kWh/tonne	1.7
Total Natural Gas Use, GJ/tonne	-0.49

The soybeans also benefit from a large one time increase in soil carbon in FASOM, as did the corn and corn stover cases.

The overall results from FASOM are summarized in the following table. Note that these results are the difference between model runs with and without soybean biodiesel. The negative results for fuel and fertilizer suggest that less fuel and fertilizer are used on US farms when soybean area is expanded and the area in other crops is decrease.

Table 8-15 FASOM Soybean Domestic Emission Results

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Domestic farm fuel	-10.65	-9.42	-0.0557	-0.0002
Domestic fertilizer	-0.41	0.05	-0.0000	-0.0015
Domestic N_2O	11.15	0.18	0.0000	0.0354
Domestic soil carbon	-8.44	-8.44	0.0000	0.0000
Domestic livestock	-1.99	0.00	-0.0949	0.0000
Domestic rice methane	-7.54	0.00	-0.3591	0.0000
Total	-17.88	-17.63	-0.5097	0.0337

The international results from FAPRI are shown in the following table.

Table 8-16 FAPRI Soybean International Emission Results

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
International Farm Input GHG	5.12	3.06	0.0021	0.0065
International Livestock	-6.10	0.00	-0.2173	-0.0050
International Rice Methane	2.07	0.00	0.0984	0.0000
Total	1.09	3.06	-0.1168	0.0015

8.2.2 Oilseed Crushing

The oilseed crushing energy use should be included in the FASOM results. There is no indication in any of the documentation that was found for the EPA FASOM model of how much energy is used in the crushing process. One would think that there is some natural gas and electricity but the natural gas shows a reduction between the control case and the soybean case.

8.2.3 Fuel Production

The biodiesel production emissions are calculated by the EPA outside of the FASOM and FAPRI models. The inputs used by the EPA are shown in the following table. The energy requirements are higher than they are in GREET even though these are supposed to represent the 2022 projections.

Table 8-17 Biodiesel Production Energy

Parameter	Value
Natural Gas, BTU/lb biodiesel	2,556
Electricity, BTU/lb biodiesel	433
Other Inputs, kg/gal biodiesel	0.373

The feedstock requirements are 7.4 lb. soybean oil/gal of biodiesel production. A typical value for the use of refined soybean oil, but we can’t tell if the refining energy is included in the FASOM model.

The EPA provided a credit for the glycerine based on the avoided combustion emissions for fuel oil. This is a small credit but the EPA did not consider the fact that some of the carbon in the biodiesel/glycerine system is fossil based and must be accounted for either in the biodiesel emissions or in the glycerine use emissions. On the other hand, a credit for the fuel use of glycerine is probably low compared to the other petrochemical uses for the product. The emissions are shown in the following table.

Table 8-18 EPA RFS Biodiesel Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Biodiesel production	17.83	16.74	0.0476	0.0003
Glycerine credit	-5.35	-5.23	-0.0055	-0.0000
Total	12.47	11.51	0.0421	0.0002

8.2.4 Transportation

The transportation emissions in the EPA modelling are also calculated outside of the main FASOM and FAPRI modelling systems. The EPA uses data from GREET for these calculations. The EPA used the same emission factor for a bushel of corn and a bushel of soybeans, even though a soybean bushel weighs 60 lb. And a corn bushel is 56 lbs. The corn transportation distance is 80 km.

Table 8-19 EPA RFS2 Soybean Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	690 km (total)	2.52	2.44	0.0027	0.0001

Moving the biodiesel from the plant to a bulk terminal is done 5% by barge (835 km), 45% by rail (1,290 km), and 50% by truck (80 km). All of the biodiesel is then moved by truck from the terminal to the retail station, a distance of 50 km. The emissions from these movements are shown in the following table.

Table 8-20 EPA RFS2 Biodiesel Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	712 km (total)	0.77	0.74	0.0008	0.0000

8.2.5 Fuel Use

The fuel use emissions for biodiesel are the sum of the methane and nitrous oxide emissions from the MOVES model. There is no allowance for any of the carbon in the biodiesel being of fossil origin.

Table 8-21 RFS2 Vehicle Emissions

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	0.66	0.00	0.0005	0.0211

8.2.6 Lifecycle Emissions Summary

The lifecycle emission summary for the EPA modelling of soybean biodiesel is shown in the following table.

Table 8-22 RFS2 Soybean Biodiesel Summary

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Domestic farm fuel	-10.65	-9.42	-0.0557	-0.0002
Domestic fertilizer	-0.41	0.05	-0.0000	-0.0015
Domestic N_2O	11.15	0.18	0.0000	0.0354
Domestic soil carbon	-8.44	-8.44	0.0000	0.0000
Domestic livestock	-1.99	0.00	-0.0949	0.0000
Domestic rice methane	-7.54	0.00	-0.3591	0.0000
International feedstock	1.09	3.07	-0.0557	-0.0002
Feedstock transportation	2.52	2.44	0.0027	0.0001
Biodiesel production	17.83	16.74	0.0476	0.0003
Glycerine	-5.35	-5.23	-0.0055	-0.0000
Biodiesel transportation	0.77	0.74	0.0008	0.0000
Vehicle emissions	0.66	0.00	0.0005	0.0211
Total	-0.36	0.13	-0.5193	0.0550

The results are extremely low but there are several aspects that we have not been able to examine. The most important is the issue of the energy use in soybean crushing. These emissions are supposed to be accounted for in FASOM but no detail for the energy use for crushing oilseeds could be found in the available documentation. Like the other FASOM pathways there is a relatively large one time build in soil carbon that positively impacts the domestic results.

Both models would suggest that the co-product credit available for the soybean meal essentially offsets all of the emissions of producing and crushing the soybeans themselves.

The EPA did not consider a renewable diesel pathway using soy oil feedstocks. The only renewable diesel pathway considered by the EPA was the marginal impact of co-processing yellow grease in an existing petroleum refinery.

8.3 GREET

The GREET model versions 1.8d (August 2010) and GREET1_2011 both had updates to the soybean pathways in the model. Both of these were done after the base model that CARB used for their work, although CARB did adjust some of the model parameters from the base 1.8b model based on some of the same information that Argonne used to do their two updates.

GREET has a large number of options for dealing with the co-products. There is only one option that does not allocate some of the emission reductions to the feedstock production and transportation stage and that is the process level displacement approach for meal and glycerine. This allows for a proper comparison of the feedstock and crushing emissions. We will show the impact of different allocation systems later. In the following table the base case results are shown.

Table 8-23 GREET Soybean Well to Tank Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	20.76	11.78	0.032	0.027
Feedstock Transport	2.96	2.82	0.004	0.000
Oilseed Crushing	22.74	20.06	0.092	0.000
Fuel Production	7.48	6.41	0.042	0.000
Co-products meal	-22.40	-13.79	-0.034	-0.026
Co-products glycerine	-34.75	-32.62	-0.079	0.000
Biodiesel Distribution	0.71	0.67	0.001	0.000
Total	-2.52	-4.67	0.058	0.002

8.3.1 Feedstock Production

The components that make up the soybean production emissions are shown in the following table.

Table 8-24 GREET Soybean Production Emissions

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	17.9 litres/t	9.06	8.44	0.0204	0.0002
N Fertilizer	1.14 kg/t	0.81	0.55	0.0040	0.0005
K_2O	4.17 kg/t	0.41	0.39	0.0008	0.0000
P_2O_5	7.72 kg/t	0.74	0.68	0.0020	0.0000
Pesticides	0.56 kg/t	1.84	1.71	0.0048	0.0000
Seeds	0.00	0.00	0.00	0.0000	0.0000
N_2O Emissions		7.90	0.00	0.0000	0.0265
Total		20.76	11.77	0.0320	0.0272

The farm energy and fertilizer inputs are based on the 2011 study by Pradhan et al that used the USDA 2006 data on soybean production. The only deviation from this data was that Pradhan reported some lime use, whereas GREET assumes no lime. The USDA lime usage data is considered unreliable, as the survey question that is used to get the data is not specific about which year the lime was applied, it just asks if lime has ever been applied to this field. This group has published three similar reports on soybean biodiesel energy balance using data from 1990, 2002, and 2006 and the energy use and fertilizer consumption has decreased with each analysis. There was a 2012 USDA survey for soybean production; the data will probably be available in 2014.

The N_2O emissions are based on 1.325% of the nitrogen applied and the nitrogen in the crop residues. This is a lower rate than GREET uses for corn ethanol and is equivalent to an EF_1 of 1.0%. The nitrogen in the crop residue is 200.7 grams per bushel (7.37 kg/tonne compared to the 21.7 kg/t used in BioGrace), a fixed number in the model. This should be a combination of the quantity of residue and the residue nitrogen content. This is only one third of the IPCC default value for soybean nitrogen content, which may also be too low as it is from a single reference from the 1920s.

8.3.2 Oilseed Crushing

The oilseed crushing parameters that are used in the GREET model are summarized in the following table. The ultimate source of the data was a National Oilseed Processors Association survey undertaken in November 2008. GREET uses data that is representative of the production of crude soybean oil, not refined oil as with BioGrace.

Table 8-25 GREET Soybean Crushing

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Oil yield	185 kg/tonne				
Natural Gas	888 MJ/tonne	9.91	8.15	0.0683	0.0002
Coal	438 MJ/tonne	6.55	6.29	0.0094	0.0001
Electricity	51.5 kWh/tonne	5.16	4.82	0.0128	0.0001
Hexane	0.56 kg/tonne	0.34	0.32	0.0005	0.0000
Total		22.74	20.35	0.0921	0.0003

The input values used in GREET are quite similar to the actual values in BioGrace, with the exception that some of the facilities use coal instead of natural gas. This will lead to higher GHG emissions.

8.3.3 Fuel Production

The process parameters for biodiesel production in GREET are summarized in the following table. The ultimate source of this data was a survey of biodiesel producers undertaken by the National Biodiesel Board in 2009. Compared to the BioGrace inputs, the natural gas is much lower.

Table 8-26 GREET Biodiesel Production

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Yield	0.92 kg oil/l biodiesel				
Natural Gas	0.73 MJ/l	1.73	1.42	0.0119	0.0000
Electricity	0.03 kWh/l	0.62	0.57	0.0015	0.0000
Hydrochloric acid	0.038 kg/l	0.00	0.00	0.0000	0.0000
Sodium methoxide	0.0205 kg/l	0.00	0.00	0.0000	0.0000
Sodium Hydroxide	0.0001 kg/l	0.00	0.00	0.0000	0.0000
Methanol	0.102 l/l	5.14	4.42	0.0284	0.0000
Total		7.48	6.42	0.0418	0.0001

Changing the quantity of sodium methoxide, sodium hydroxide and hydrochloric acid do not change the GHG emissions for biodiesel. The quantity of glycerine produced in GREET is 0.214 kg/kg of biodiesel produced. This is about double the theoretical yield and leads to higher co-product credits than should be calculated.

8.3.4 Transportation

The soybean transportation is assumed to be 16 km between the field to an intermediate storage facility and 64 km from that facility to the crushing plant. The soybeans are moved by truck and the emissions are shown in the following table. The soybean oil moves by barge, rail and truck to the biodiesel plant, the combined distance is 610 km.

Table 8-27 GREET Soybean Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Diesel	690 km (total)	2.96	2.82	0.0043	0.0001

Moving the biodiesel from the plant to a bulk terminal is done 8% by barge (830 km), 29% by rail (1,280 km), and 63% by truck (130 km). All of the biodiesel is then moved by truck from the terminal to the retail station, a distance of 50 km. The emissions from these movements are shown in the following table.

Table 8-28 GREET Biodiesel Transportation

Parameter	Value	GHG	CO_2	CH_4	N_2O
		g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	570 km (total)	0.71	0.68	0.0010	0.0000

8.3.5 Fuel Use

Greet also makes no allowance for fossil diesel in the combustion of the biodiesel. The emissions from the combustion of B100 produce the non-CO_2 emissions shown in the following table.

Table 8-29 GREET Soybean Vehicle Emissions

Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	0.88	0.00	0.0006	0.0029

8.3.6 Alternative Allocation Approaches

As mentioned earlier, GREET has a large number of alternative approaches to allocating the emissions between the fuel product and the co-products. When these alternative approaches are used, the credit for the co-products is distributed throughout the stages, so the emissions shown for feedstock production are those that are just allocated to the oil, not the full emissions associated with that stage. Some of the alternative approaches are shown in the following tables.

Table 8-30 Alternative GREET Co-Product Approaches

Overall	Process Level Allocation/ Displacement			
Meal	Displacement	Energy	Market	Mass
Glycerine	Displacement	Energy	Energy	Energy
	g CO_2eq/MJ (LHV)			
Feedstock Production	20.76	8.07	8.79	4.00
Feedstock Transport	2.96	1.15	1.25	0.57
Oilseed Crushing	22.74	22.74	22.74	22.74
Biodiesel Production	7.48	7.48	7.48	7.48
Co-Product meal	-22.40	-13.49	-12.73	-17.79
Co-Product glycerine	-34.75	-0.71	-0.71	-0.71
Biodiesel Distribution and storage	0.71	0.71	0.71	0.71
Total	-2.52	25.93	27.52	16.98

The use of the displacement approach for glycerine has a very large impact on the results. The glycerine production method that is displaced is the Farben approach. This was the dominant glycerine production method until the large expansion in the biodiesel market in the past decade. The method involves the chlorination of propylene and is both energy and emission intensive. In the following table, using the system level approach, the impact of changing the approach for each of the co-products is shown.

Table 8-31 Alternative GREET Co-Product Approaches

Overall	Process Level Allocation/ Displacement	System Level Energy-Based Allocation	System Level Market Value-Based Allocation	System Level Mass-Based Allocation
Meal	Displacement	-	-	-
Glycerine	Energy	-	-	-
	g CO_2eq/MJ (LHV)			
Feedstock Production	18.78	8.39	10.20	4.10
Feedstock Transport	2.67	1.19	1.45	0.58
Oilseed Crushing	22.74	22.74	22.74	22.74
Biodiesel Production	7.48	7.48	7.48	7.48
Co-Product meal	-22.44	-13.55	-11.57	-18.25
Co-Product glycerine	-0.71	-4.45	-3.80	-6.00
Biodiesel Distribution and storage	0.71	0.71	0.71	0.71
Total	29.23	22.50	27.20	11.37

8.3.7 Renewable Diesel

GREET has two renewable diesel processes in the model. RD I is modelled after the NRCan SuperCetane process, which involved hydrogenation of the lipids, and the second RD II is modelled after a UOP HDO process. We present the results for the type II (UOP) process here. The following table compares the results for the biodiesel product and the renewable diesel product. The same allocation approach is used for both.

Table 8-32 Comparison of Biodiesel and Renewable Diesel in GREET

	Soybean Biodiesel	Soybean Renewable Diesel
	g CO_2eq/MJ	g CO_2eq/MJ
Feedstock Production	18.78	20.00
Feedstock Transport	2.67	2.85
Oilseed crushing	22.74	21.91
Biodiesel/Renewable Diesel Production	7.48	5.24
Co-Product meal	-22.44	-21.58
Co-Product glycerine/fuel	-0.71	-
Fuel Distribution and storage	0.71	0.60
Total	29.23	29.02

Using the process energy allocation system, the results for the two pathways are very similar. The renewable diesel process parameters are summarized in the following table.

Table 8-33 GREET Renewable Diesel Modelling Parameters

Parameter	Value
Yield, kg RD/kg soybean oil	0.855
Hydrogen consumption, MJ H_2/kg RD	3.69
Co-product electricity, kWh/kg RD	0.0
Co-product LPG, MJ/kg RD	2.56

Compared to the BioGrace model, the product yield is higher and more fuel co-product is produced. Like the BioGrace model, the data is not from an operating plant but from pilot plant work.

8.3.8 Lifecycle Emissions Summary and CA-GREET

The CA GREET model is based on GREET 1.8b and thus it did not have the updates that were included in version 1.8d and GREET1_2011. The CA GREET results are shown in the following table and compared to the GREET results. CARB presented the results for each stage net of the co-product credits. They used mass allocation for the meal and energy allocation for the glycerine. We have used the closest co-product approach in GREET1_2012 for comparison. The vehicle emissions in the CARB model are 0.78 g/MJ for the methane and nitrous oxide and 3.67 for the fossil carbon in the fuel.

Table 8-34 Comparison of Soybean Biodiesel in GREET1_2012 and CA-GREET excluding ILUC

	Soybean Biodiesel	
	GREET1_2012	CA-GREET
	g CO_2eq/MJ	g CO_2eq/MJ
Feedstock Production	4.00	5.42
Feedstock Transport	0.57	0.53
Biodiesel Production	22.74	26.00
Co-Product	7.48	-15.60
Biodiesel Distribution and storage	-17.79	2.13
Sub Total	-0.71	16.80
Vehicle Emissions	0.71	4.45
Grand Total	16.98	21.25

The vehicle emissions in the CARB model are 0.78 g/MJ for the methane and nitrous oxide and 3.67 g/MJ for the fossil carbon in the fuel. The fossil carbon in the fuel arises because a portion of the carbon in the biodiesel arises from the methanol and that is of fossil origin. This also means that a portion of the carbon in the glycerine is biological in origin and if the use of the glycerine is within the system boundary and the glycerine replaces a fossil product (such as a fuel or synthetic glycerine) there should be an equal and offsetting credit for the co-product. That is not considered in the CARB analyses.

The difference in the farming inputs between the two versions of GREET are shown in the following table. All of the inputs are lower in the new version of GREET.

Table 8-35 Soybean Farming Inputs

	CARB GREET 1.8b	GREET1_2012rev2	% Change
Farming Energy, BTU/bu	22,087	16,560	-25.0
N, g/bu	61.2	30.9	-49.5
P_2O_5, g/bu	186.1	113.4	-39.1
K_2O, g/bu	571.5	210.0	-63.3
$CaCO_3$, g/bu	0	0	0.0
Herbicide, g/bu	43.02	15.0	-65.1
Insecticide, g/bu	0.43	0.37	-14.0
CO_2 from Lime	0	0	0.0
N content of residue, g/bu	200.7	200.7	0.0

In contrast, there is not a large difference in the soybean crushing emissions between the two versions, as CARB updated their values from those in GREET 1.8b. The two sets of data are compared in the following table.

Table 8-36 Soybean Crushing

	CARB GREET 1.8b	GREET1_2012rev2	% Change
	BTU/Lb Soy Oil		
Energy	3,533	3,576	1.2
Natural Gas	2,800	2,058	-26.5
Coal	0	1,013	
Electricity	551	445	-19.2
Hexane	182	58	-68.1

There are some small differences in the biodiesel energy and chemical use between the two models as shown in the following table.

Table 8-37 Biodiesel Production

	CARB GREET 1.8b	GREET1_2012rev2	% Change
	BTU/lb. biodiesel		
Energy	2,116	1,844	-12.9
Natural Gas	889	373	-58.0
Electricity	47	55	17.0
Methanol	865	785	-9.2
Sodium hydroxide	42	7	-83.3
Sodium methoxide	209	315	50.7
Hydrochloric acid	63	310	392.1

The following table compares the renewable diesel pathways between the two versions of GREET.

Table 8-38 Comparison of Soybean Renewable Diesel in GREET1_2012 and CA-GREET excluding ILUC

	Soybean Renewable Diesel	
	GREET1_2012	CA-GREET
	g CO_2eq/MJ	g CO_2eq/MJ
Feedstock Production	4.02	5.19
Feedstock Transport	0.57	0.50
Renewable Diesel Production	32.04	11.86
Co-Product	-17.48	inc
Biodiesel Distribution and storage	0.60	1.83
Total	19.76	1.83

8.4 GHGENIUS

The GHGenius model has been set to the US region for 2012 for comparison purposes. The emissions for each of the main stages are shown in the following table.

Table 8-39 GHGenius Soybean Biodiesel

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Feedstock Production	61.65	10.94	0.0477	0.1662
Feedstock Transport	2.20	2.11	0.0027	0.0001
Biodiesel Production	34.01	30.98	0.1090	0.0010
Co-product (meal and glycerine)	-64.22	-19.81	0.0399	-0.1524
Biodiesel Distribution	1.15	1.09	0.0019	0.0001
Total	34.80	25.31	0.2011	0.0150

Each of these stages is discussed in more detail in the following sections.

8.4.1 Feedstock Production

The GHGenius model inputs for soybean production in 2012 are shown in the following table. The data is derived primarily from USDA sources adjusted to the model year by the trends developed from the time series of data used in the model.

Table 8-40 GHGenius Soybean Production Inputs

Parameter	Value
Diesel eq, l eq/tonne	17.4
N Fertilizer, kg N/tonne	1.79
P_2O_5, kg P_2O_5/tonne	5.32
K_2O, kg K_2O/tonne	8.49
$CaCO_3$	-
Pesticides, kg AI /tonne	0.5

The feedstock production emissions in GHGenius are higher than they are in GREET but are similar to the BioGrace emissions. There are two reasons for this, the first is that the N_2O emission factor is set to 1.5% and the second is that GHGenius uses a higher nitrogen content for the below ground residue. The feedstock production emissions are shown in the following table.

Table 8-41 GHGenius Soybean Production Emissions

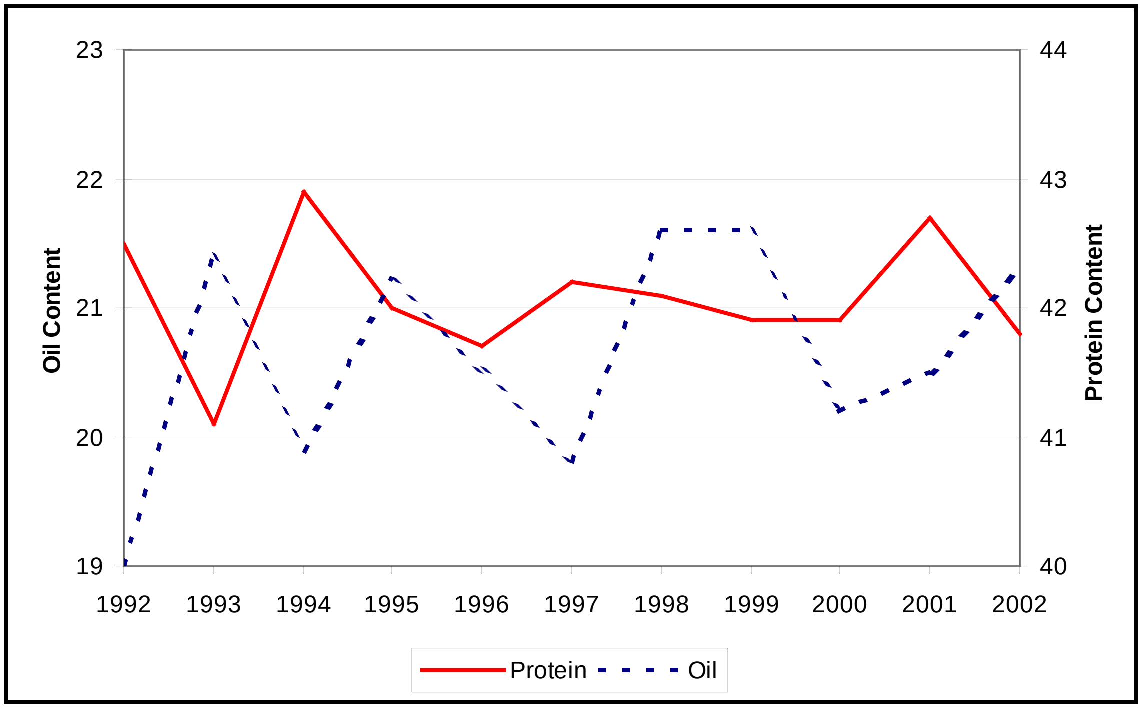
Parameter	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Fuel	10.34	9.27	0.0188	0.0020
Fertilizer	6.62	6.00	0.0205	0.0003
N_2O emissions	48.82	0.00	0.0000	0.1638
Soil Carbon	-4.12	-4.33	0.0083	0.0000
Total	61.65	10.94	0.0477	0.1662

The below ground biomass nitrogen content is a source of significant uncertainty. The IPCC uses a low value in their guidelines but quote a single reference from the 1920s to support the value. Others have calculated a larger value by measuring the field emissions and then calculating the value by using the IPCC methodology to determine what the nitrogen content must be to equal the measured emissions. Direct measurement of the residues is difficult as the nitrogen is found in the root nodules formed by the nitrogen fixing bacteria.

8.4.2 Oilseed Crushing

The oil content of soybean seeds will vary from 18 to 20% (as is basis) depending on location and year. Historical data for Ontario soybeans is shown in the following figure (Canada Grains Commission). This data shows oil content on a moisture free basis, which accounts for the slightly higher values.

Figure 8-4 Soybean Oil Content



The soybeans required to produce one litre of soybean oil can be calculated based on an average of 18% oil content (as is basis) and 95% oil extraction efficiency. The requirement is 5.11 kg/litre.

The National Oilseed Processors Association published an energy survey of their members in 2009. That data is summarized in the following table.

Table 8-42 Soybean Crushing Energy Requirements

	Per tonne of Soybeans crushed	Per tonne of Oil produced
Electricity Purchased, kWh	55.2	289
Natural Gas Purchased, GJ	1.20	6.29
Total Energy, GJ	1.40	7.33

Oilseed crushers also have some small losses of hexane. The US EPA reports that an average of 0.89 USG hexane per ton (2.8 kg/tonne) of soybeans is lost in the process. Lurgi report the hexane consumption as 0.7 kg/tonne. GHGenius uses 0.018 l/kg of oil (2.6 kg/tonne).

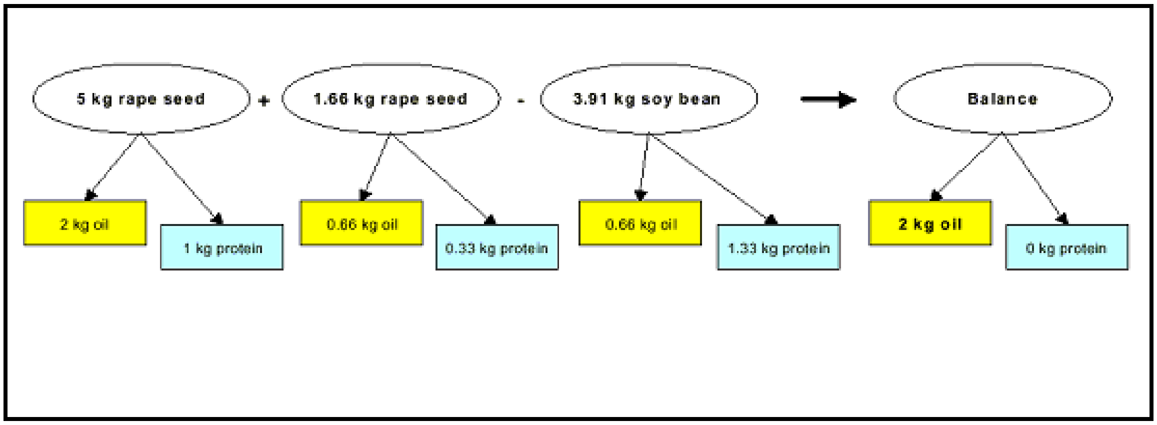
The emissions for this stage are shown in the following table.

Table 8-43 Soybean Crushing Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Soybean Crushing	19.21	17.19	0.0718	0.0007
Meal credit	-46.53	-2.12	0.0399	-0.1524
Total	-27.32	15.07	0.1116	-0.1516

The meal credit is larger than the crushing emissions as it also considers the emissions from the growing of the soybeans. GHGenius uses a system expansion approach using canola and soybean data to calculate the allocation between the oil and the meal. The approach is shown in this figure.

Figure 8-5 Oil and Meal System Expansion



8.4.3 Fuel Production

The low free fatty acid process technology is used for vegetable oil transesterification in GHGenius.

In 2009, the National Biodiesel Board (NBB) conducted the most comprehensive survey of the actual energy used by commercial biodiesel production plants in the world and released the data for public use.

This survey found that for biodiesel produced from virgin vegetable oils, 0.88 kg of oil was used to produce one litre of biodiesel.

The energy consumption data for virgin vegetable oils from the NBB survey is summarized in the following table.

Table 8-44 Biodiesel Energy Use

	Units	NBB
Electricity	kWh/litre	0.032
Natural Gas	L NG/litre biodiesel	20.2

The conversion process is highly efficient and yields of biodiesel per gallon of feedstock can reach 99.5%. The input value in GHGenius has been set to provide a 98% yield.

The co-product from the process is glycerine. This provides a credit for the avoided emissions of producing synthetic glycerine via the Farben process. Most biodiesel plants produce crude glycerine, which still needs to be refined to produce technical grade or higher product. The credit that is provided is therefore just for the materials used in the Farben process and not for the final product.

The emissions for the biodiesel production are shown in the following table.

Table 8-45 Soybean Biodiesel Production Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Biodiesel production	14.80	13.78	0.0373	0.0003
Glycerine credit	-18.34	-17.72	0.0006	-0.0021
Total	-3.54	-3.93	0.0378	-0.0018

8.4.4 Transportation

In GHGenius the feedstock emissions will include the transportation of the soybeans to the crusher and the oil from the crusher to the biodiesel plant if they aren't co-located. The transportation assumptions are shown below.

Table 8-46 Feedstock Transportation Assumptions

	Mode	Distance
Soybeans	Truck	100 km
Soybean oil	Truck	50 km

The emissions for the feedstock transportation are shown in the following table.

Table 8-47 Soybean Biodiesel Feedstock Transportation Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	2.20	2.11	0.0027	0.0001

The movement of the biodiesel from the plant to the market is by a combination of rail and truck. The assumptions are shown below.

Table 8-48 Biodiesel Transportation Assumptions

	Mode	Fraction	Distance
Biodiesel	Rail	0.22	802 km
Biodiesel	Truck	1.00	121 km

The GHG emissions from the fuel transportation and dispensing are summarized in the following table.

Table 8-49 Biodiesel Transportation Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	1.15	1.09	0.0019	0.0001

8.4.5 Fuel Use

The emissions from the combustion of biodiesel in GHGenius are shown in the following table.

Table 8-50 Biodiesel Combustion Emissions

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Total	1.07	0.0	0.0005	0.0033

8.4.6 Lifecycle Emissions Summary

The GHGenius soybean biodiesel results are shown in the following table. They are disaggregated as much as possible.

Table 8-51 GHGenius Lifecycle Emissions Summary

	GHG	CO_2	CH_4	N_2O
	g CO_2eq/MJ	g/MJ	g/MJ	g/MJ
Farm Fuel	10.34	9.27	0.0188	0.0020
Fertilizer	6.62	6.00	0.0205	0.0003
N_2O emissions	48.82	0.00	0.0000	0.1638
Soil Carbon	-4.12	-4.33	0.0083	0.0000
Feedstock transportation	2.20	2.11	0.0027	0.0001
Soybean Crushing	19.21	17.19	0.0718	0.0007
Meal credit	-46.53	-2.12	0.0399	-0.1524
Biodiesel production	14.80	13.78	0.0373	0.0003
Glycerine credit	-17.69	-17.72	0.0006	-0.0021
Fuel distribution	1.15	1.09	0.0019	0.0001
Fuel use	1.07	0.0	0.0005	0.0033
Total	35.87	25.27	0.2023	0.0161

8.5 SUMMARY

The soybean biodiesel results are summarized in the following table. The combustion emissions are not shown in the table.

Table 8-52 Soybean Biodiesel Summary excluding ILUC

	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement	Displacement	Mass/energy	Displacement
	g CO_2eq/MJ (LHV)				
Feedstock Production	56.21	-16.78	20.76	5.42	61.65
Feedstock Transport	35.95	2.52	2.96	0.50	2.20
Oilseed Crushing	17.24	-	22.74	20.53	19.21
Biodiesel Production	12.50	17.83	7.48	5.47	14.80
Co-products meal	-72.89	-	-22.40	-15.33	-46.53
Co-products glycerine	-0.58	-5.35	-34.75	-0.27	-17.69
Biodiesel Distribution	1.26	0.76	0.71	0.75	1.15
Total	49.69	-1.03	-2.52	17.06	34.80

There is a very wide range in the results. The BioGrace results are impacted by the soybean transportation scenario selected. Soybeans are not a significant crop in Europe so the pathway was built using soybeans imported from Brazil and this adds significant emissions that are only partially offset by the soybean meal credit. GREET has very low emissions for soybean production, the primary driver being very low N_2O emissions compared to BioGrace and GHGenius.

The emission credit for glycerine varies widely as well. The energy allocation provides a small credit, as does the displacement of energy. Glycerine production by the Farben process is very energy and emission intensive, so if the biodiesel glycerine displaces Farben produced product there is a much larger co-product credit.

There is also a variation between the models on how the fossil carbon in the methanol is treated. The biodiesel production process sees methanol being added to the oil and biodiesel and glycerine being produced. The fossil carbon in the methanol ends up in the biodiesel and an equivalent amount of biogenic carbon from the oil ends up in the glycerine. In BioGrace the oxidation of the fossil carbon from methanol is included in the biodiesel production emissions, in CA GREET, the oxidation of the carbon is added to the vehicle emissions. In GHGenius it is assumed that the glycerine from the process displaced fossil glycerine and only the difference in the emissions is needed to be included.

The soybean renewable diesel results are shown in the following table. The EPA did not do a rigorous assessment of this pathway so no results are shown. Many of the same factors that apply to the biodiesel pathway also apply here. Only BioGrace has lower emissions for renewable diesel than biodiesel. Their yield is better for renewable diesel, which positively impacts all of the stages of the pathway. The other pathways have lower yields.

Table 8-53 Soybean Renewable Diesel Summary

	BioGrace/JEC	GREET		GHGenius
		2012_rev2	CA-GREET	
IPCC GWP	2001	2007	2007	2007
Allocation	Energy	Energy		Displacement
	g CO_2eq/MJ (LHV)			
Feedstock Production	55.44	4.02	5.19	64.08
Feedstock Transport	35.46	0.57	0.50	2.29
Oilseed Crushing	16.25	21.91	-	19.69
Fuel Production	7.48	10.13	11.86	3.37
Co-products meal	-70.29	-16.93	-	-47.69
Co-products fuel	-0.84	-0.55		-3.77
Biodiesel Distribution	1.15	0.60	1.83	0.97
Total	44.65	19.76	19.38	38.94

8.5.1 Indirect Land Use Change

The EPA RFS2 modelling framework has been set to restrict land expansion in the United States and thus the reported International emissions represents the indirect land use change emissions. In Europe and in California they have utilized other models (IPFRI-Mirage in Europe and GTAP in California) to estimate the indirect land use emissions. The ILUC emissions for soybean are added to the direct emissions for those three modelling frameworks below. The EU results use a 20-year amortization period and have been adjusted to a 30-year period to allow comparisons to the other sources in the following table. The BioGrace results also have actual values shown for the direct emissions.

Table 8-54 Direct Emissions and Indirect Land Use Emissions – Soybean Biodiesel

	BioGrace	EPA RFS2	CA GREET
	g CO_2eq/MJ		
Direct Emissions	49.7	-1.3	21.2
ILUC	37.2	40.3	62.0
Total	86.9	40.0	83.2

There are significant differences in the ILUC emissions between the European model and the North American models. With the North American models, the ILUC emissions are very different, unlike the case with corn ethanol where they were quite close. The CARB emissions for soybean biodiesel are under review, the latest values that CARB presented had the land requirements reduced from 0.63 ha/1000 gal to 0.18 ha/1000 gal (Tyner, 2011) and some of the previous problems with soybean modelling had been addressed. While Tyner did not present the emissions, only the land change, this land change would result in emissions of about 25 g CO_2/MJ.

9. ASSESSMENT OF VARIABILITY

There is a wide range of results for the different pathways from the different models. Many of the reasons for the differences are described in the sections on each of the pathways. In the following two sections many of the differences are classified as variability in the results or uncertainty in the results. Both concepts are defined and discussed in a more rigorous way in the following sections.

9.1 VARIABILITY

One of the earliest discussions of variability and uncertainty as it is applied to lifecycle assessment was the work by Huijbregts (1998). He divided uncertainty into three categories:

(1) parameter uncertainty,
(2) model uncertainty, and
(3) uncertainty due to choices,

while variability covers:

(4) spatial variability,
(5) temporal variability, and
(6) variability between objects and sources.

We will consider these three primary sources of variability in each of the pathways and any other sources that might be unique to specific pathways. Spatial variability and variability between sources can be considered real variability, whereas temporal variability and variability between objects that are not identical are more artificial, but of course can still cause confusion.

Variability is not an issue when a company calculates the carbon footprint or environmental impact of a product from a single production facility. The developed carbon footprint should use primary data from the facility and aggregated data for the inputs to their supply chain to develop a report that is specific to the product produced at that facility. Variability becomes more of an issue when considering that the product could be produced at multiple facilities within a company, or by different companies in the same region, or by companies in different regions. In the latter case there can be spatial variability, temporal variability, and process variability.

Policy makers looking at the “big picture” need to understand all of the categories of variability when designing policy and regulation to meet specific objectives. Failure to properly account for variability will result in either a failure to achieve the desired goals or surpassing of the desired goals with potentially negative economic consequences to society.

BioGrace, GREET and GHGenius are process based models. The concept behind each model is similar with the model inputs being a physical input (either mass or energy based) and this physical parameter is matched with an emission factor to arrive at the emissions for a stage of a pathway. GREET and GHGenius link the pathways and have some loops within pathways that require iteration to resolve, whereas BioGrace is simpler and consists of a set of linear equations. In these three models, changes in a single parameter produces similar responses in output. The changes in model output are directionally always the same and the only difference in magnitude of the response is due to the different emission factors that are used in the different models.

FASOM and FAPRI are more statistical or mathematical models. Changes in output resulting from a change in an input are not always predictable. Several examples of this were identified in the various pathways studied. Some aspects of the EPA modelling framework do utilize process models, the N_2O emission calculations or the biofuel plant emissions for example. The proprietary nature of the EPA modelling framework means that it can't be used to assess variability in the fuel pathways.

Since the structure of the other three models is similar and they respond in a similar fashion to changes in input parameters, we have used GHGenius to illustrate some aspects of parameter variability in this section. The primary reason for choosing GHGenius for this is that the model already has a built-in flexible sensitivity analysis tool. This allows any input parameter to be varied and the resulting impact on any other cell in the model to be determined and automatically graphed. Where this tool is used in the report, all three of the process based models respond in a similar fashion.

Of the three process models, GHGenius is also the only model that has the capacity to easily model the same pathway in different regions. This capacity has been used to demonstrate the spatial variability of some of the pathways.

9.2 Petroleum Fuels

The model results for gasoline are shown in the following table. These are the same results shown earlier for this pathway.

Table 9-1 Petroleum Fuels Summary - Gasoline

	BioGrace/JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	2007	2007	2007	2007
	g CO_2eq/MJ (LHV)				
Crude Oil Extraction	3.6	3.2	2.38	11.39	7.94
Crude Oil VFF	0.0	3.6	2.42	inc	2.45
Crude Oil Transport	0.9	1.36	2.97	inc	2.04
Refining	7.0	9.24	10.80	13.72	12.18
Refined Products Distribution	1.0	1.03	0.56	0.36	1.37
Sub-total	12.5	18.43	19.12	26.27	25.99
Vehicle Use	75.2	72.43	73.61	72.91	68.96
Total	87.7	90.98	92.73	99.18	94.95

There is significant variability between the results from the models investigated. Several methodological issues where identified.

1. The JEC/BioGrace petroleum values use marginal energy use and emissions for the petroleum refinery (separate values for gasoline and diesel). The other models use average values for refinery energy use. There are differences in the allocation of emissions between gasoline, diesel and other products in the other models.
2. The version of the JEC/BioGrace model examined by this work excludes venting and flaring emissions for crude oil production.
3. The inclusion of the oxidation emissions of CO and VOC. The gasoline pathway has the highest emissions of CO in all of the pathways and thus the impact of including or excluding these emissions is most notable here.

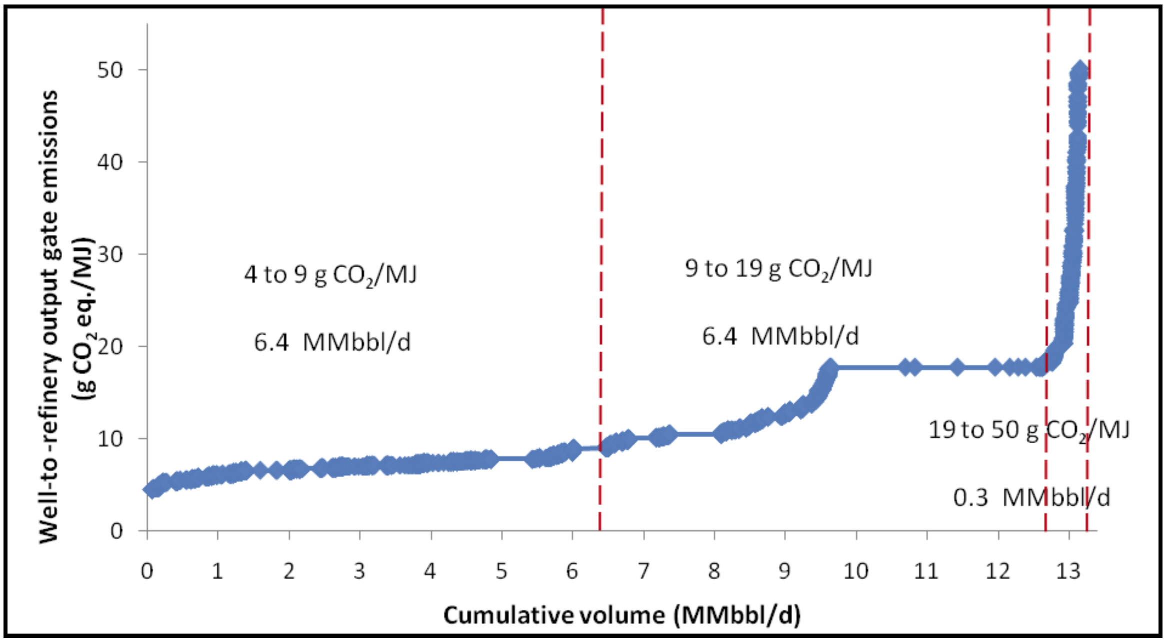
It is not apparent that the marginal approach used in the JEC modelling is the reason for the lower refining emissions, as this stage is particularly opaque in the JEC documentation. It does seem counterintuitive that the marginal emissions are lower than the average emissions, suggesting that perhaps other issues are involved.

Beyond these methodological issues there are other issues that can impact the results that fall within the variability category. These are discussed below.

9.2.1 Spatial

The NETL work and GHGenius have different GHG emission values for crude oil produced in different regions of the world. The CA GREET model, using the OPGEE model inputs has similarly varying emissions for different crude oils. This spatial variation has been reported by others as well, for example the work performed by Energy Redefined LLC for the ICCT (Energy Redefined, 2010). Their field by field emission analysis of the crude oils delivered to Europe up to the refinery output stage is shown in the following figure.

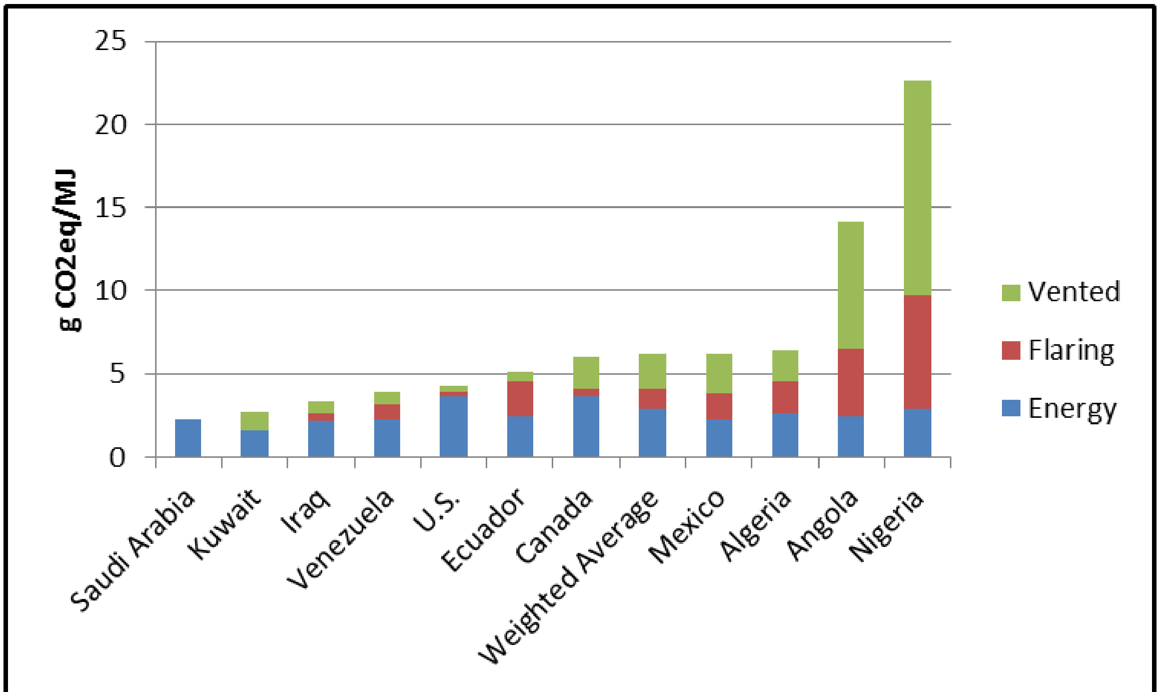
Figure 9-1 Energy Redefined LLC Crude Oil Emission Profile



Source: Energy Redefined LLC

The NETL work reported separate emissions for each of the major crude oil exporters. These crude oil only emissions were shown in Table 3.12 and are shown graphically in the following figure.

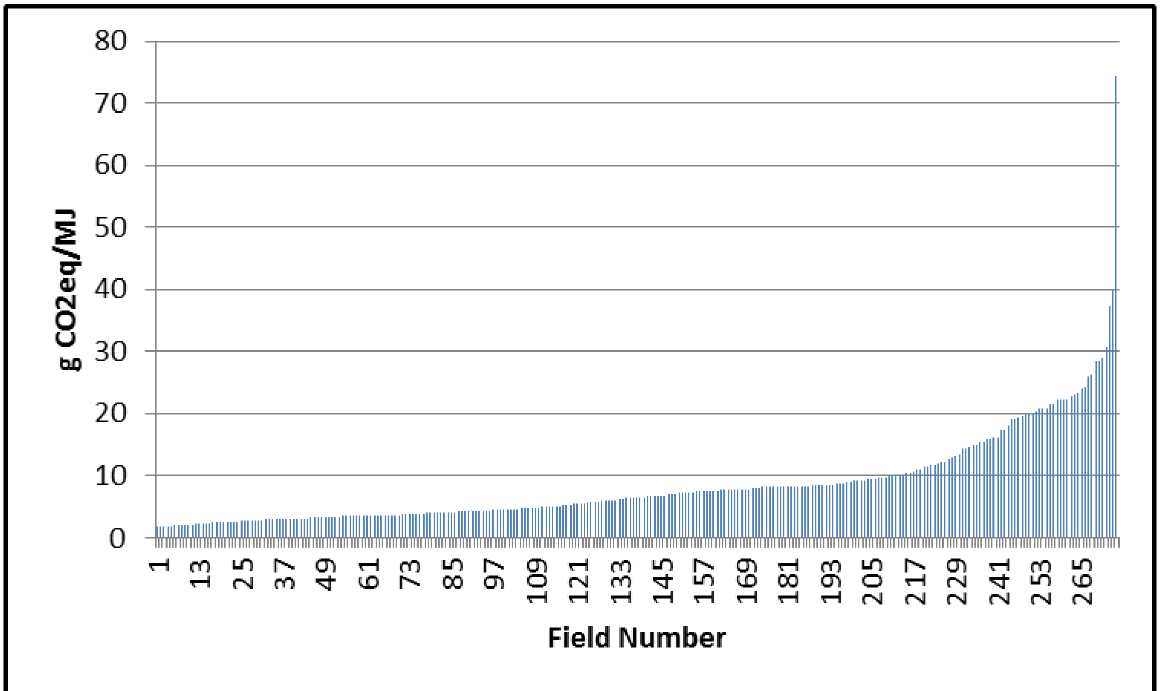
Figure 9-2 NETL Regional Crude Oil Emissions



Source: (S&T)[2] from NETL data

The other source is the field estimates from OPGEE. The results from 275 fields are shown in the following figure. These values include venting, flaring and fugitive emissions and transportation to California.

Figure 9-3 OPGEE Crude Oil Emission Estimates



Source: (S&T)[2] from OPGEE data

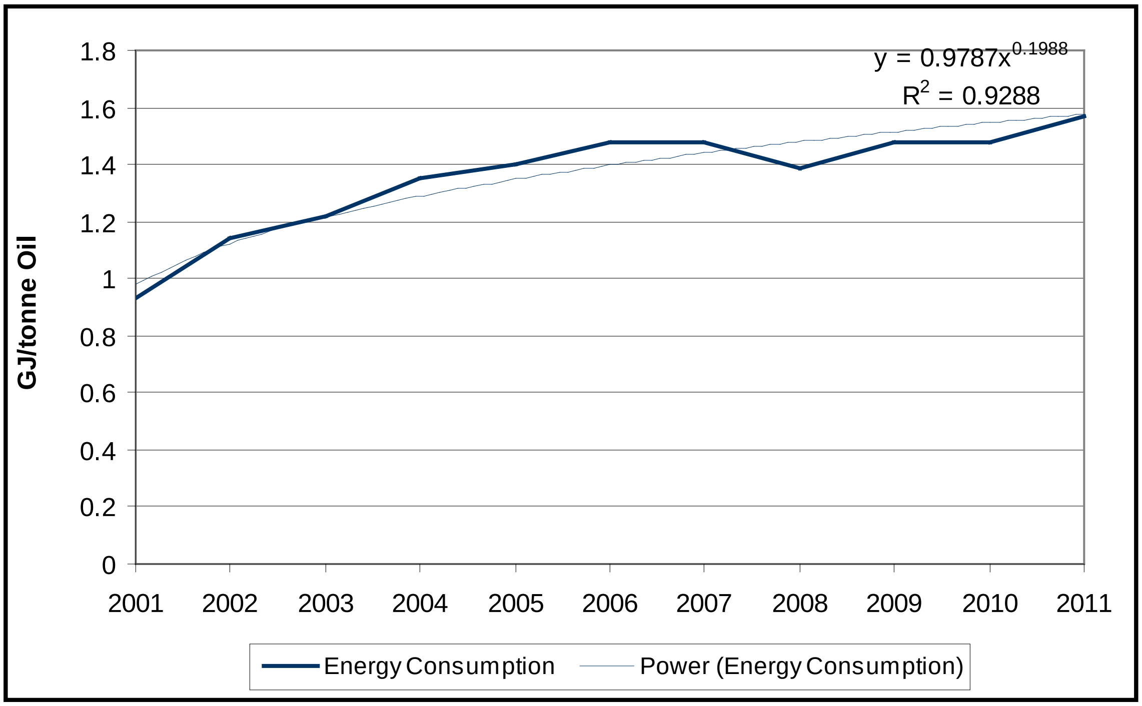
There is obviously significant variability in the GHG emissions between crude oil fields. This could lead to regional differences in emissions when a refinery sources most of its crude oil from low emission fields compared to high emission fields.

Models that include crude oil emission estimates for various regions and include the source of crude oil refined will have greater precision than models that use broad average values for determining the crude oil emissions. The NETL, GHGenius and the OPGEE input into the CA GREET models have this capability.

9.2.2 Temporal

Many different processes exhibit changes over time. There is one data set on crude oil production emissions that can show the impact of time. The International Oil and Gas Producers Association (OGP) have been presenting data on energy and emissions associated with crude oil production since 2001. The data on energy use between 2001 and 2011 (OGP, 2012) is shown in the following figure. The average annual rate of change of energy consumption is 5.6%.

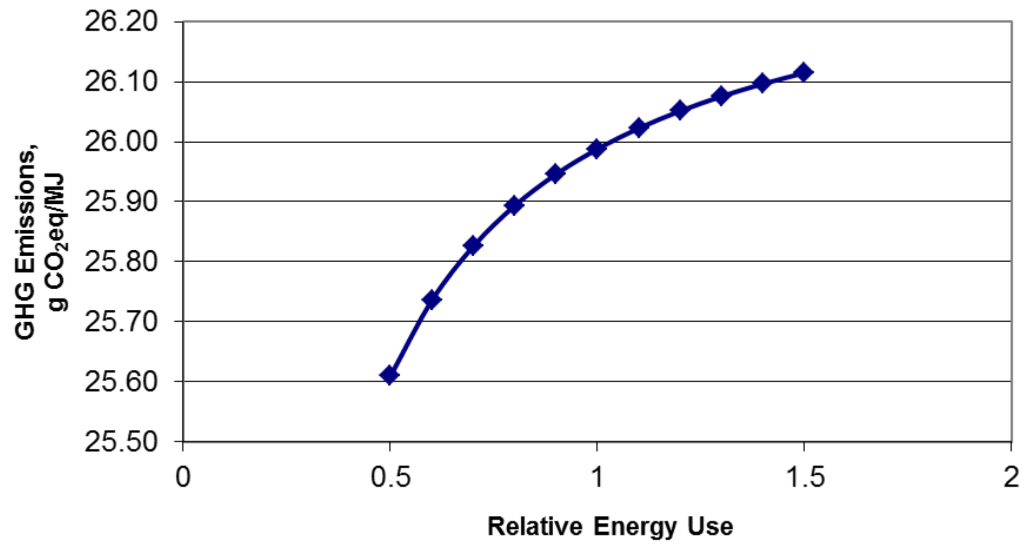
Figure 9-4 Energy Consumption Trend – Crude Oil Production



This association reports data for about one third of the world's crude oil production. Its members are the largest oil companies in the world. This limited sample may result in the reported energy use and emissions being less than fully representative of world production both in terms of the total energy use and the rate of change of energy use. Older, smaller fields would tend to be under represented in this survey. The coverage of the different regions also varies. It has essentially 100% coverage in Europe but less than 10% coverage in Russia and about 10% coverage in North America.

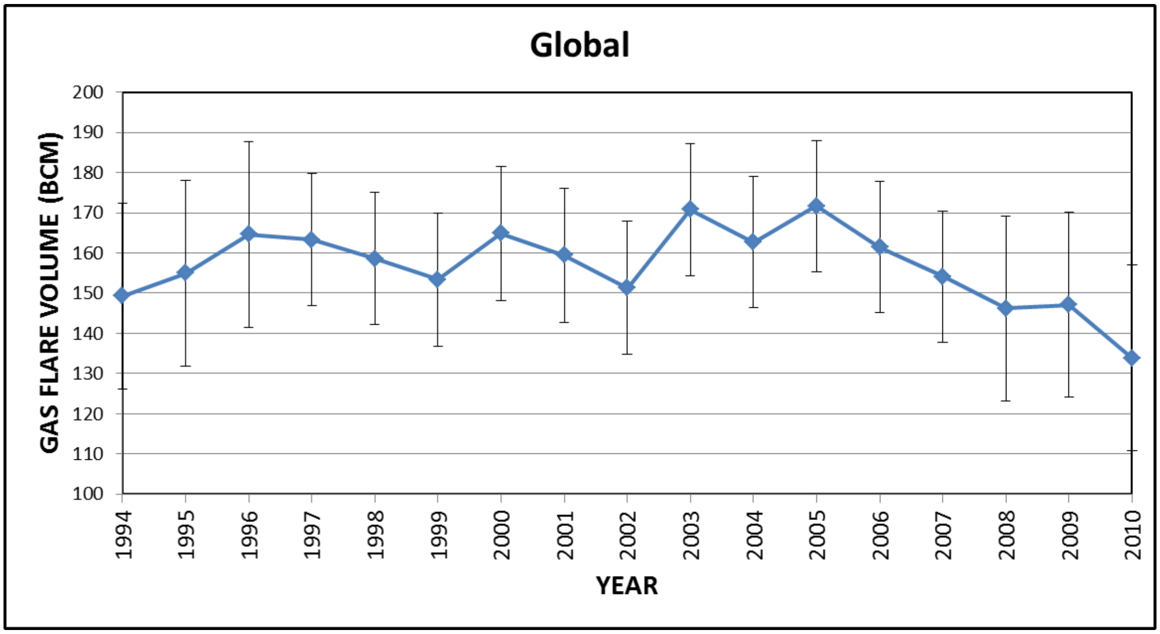
The impact of energy use on gasoline production emissions is shown in the following figure. We have used GHGenius and varied the energy use for all crude oil production between 50% of the baseline and 150% of the baseline value. The impact is relatively small.

Figure 9-5 Gasoline Production GHG Emissions vs. Relative Crude Oil Energy Use



Some crude oil is co-produced with natural gas. Where there is no market for the natural gas, it is either re-injected into the well, as is the case in Alaska and some other regions, or it is flared. There are significant efforts underway to reduce gas flaring and in some regions there have been some success. The National Oceanic and Atmospheric Administration (2012) made estimates of national and global gas flaring volumes based on satellite sensor observations across a series of years - spanning from 1994 through 2010. This project is funded by the World Bank initiative to reduce gas flaring. The global results for this time period are shown below. Most models use this data to estimate flaring emissions and the results will vary depending on which year the data is taken from. There has been a global downward trend over the past several years.

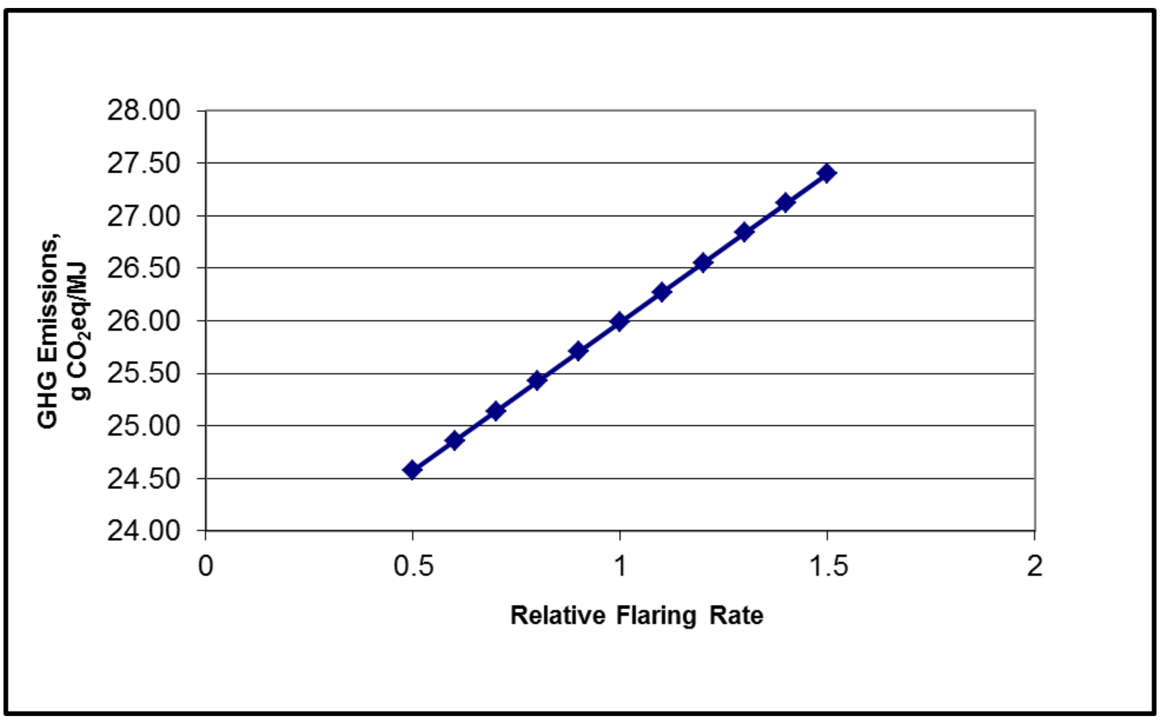
Figure 9-6 NOAA Gas Flaring Results



Source: NOAA

The impact of changing the flaring emissions on the gasoline production emissions is shown in the following figure. The flaring emissions are varied from 50% of the base value to 150% of the base value. The impact is slightly greater than the impact of adjusting the energy consumption.

Figure 9-7 Gasoline GHG Emissions vs. Flaring Emissions



9.2.3 Process/Design

Not all oil fields or refineries employ exactly the same approach in producing or refining oil and this can have an impact on the GHG emissions for the pathway. The issues are discussed below.

9.2.3.1 Crude Oil Production

There are a wide variety of crude oil production systems around the world. Some crude oil is produced using mostly the natural pressure in the reservoir but in other cases, there may be pumping involved to extract the oil, gas or liquids may be injected to boost reservoir pressure, some heavy oils are produced by injecting thermal energy into the reservoir to reduce the oil viscosity, and in some cases (for example oil sands) the oil is mixed with sand and the ore is mined and the oil is extracted from the sand at the surface. Each of the types of oil production will have different GHG emission intensity.

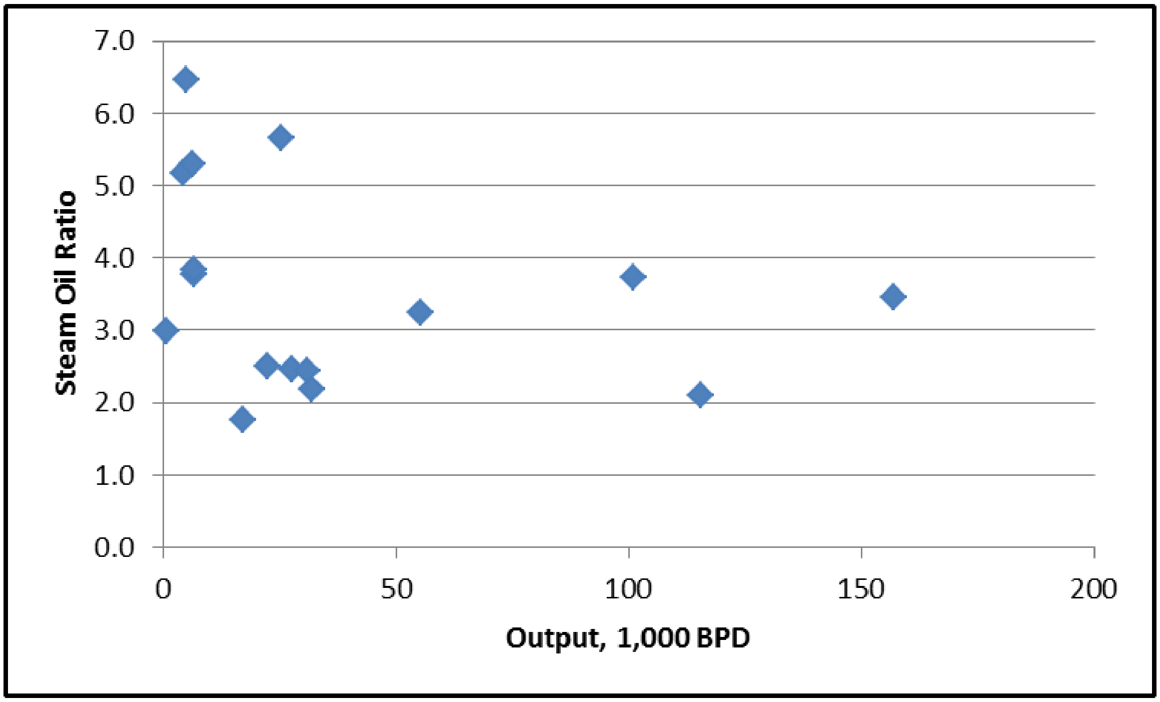
GHGenius has several production methods for the production of bitumen from the Athabasca oil sands. Each has a different emission profile. The GHG emissions for the production of a tonne of bitumen are shown in the following table.

Table 9-2 GHG Emissions – Bitumen Production

	Canadian Bitumen Production		
Process	SAGD	CSS	Mining
	g CO_2eq/tonne of oil		
Fuel dispensing	0	0	0
Fuel distribution and storage	0	0	0
Fuel production	0	0	0
Feedstock transmission	10,835	10,844	10,712
Feedstock recovery	605,923	628,894	243,492
Feedstock Upgrading	0	0	0
Land-use changes, cultivation	10,567	10,567	21,134
Fertilizer manufacture	0	0	0
Gas leaks and flares	58,787	58,787	81,634
CO_2, H_2S removed from NG	0	0	0
Emissions displaced	0	0	0
Total	686,113	709,093	356,972

The characteristics of the deposit can often dictate the best production method. The mining approach is only suitable when the deposit is relatively close to the surface and while it produces the lowest GHG emissions, the approach is only suitable to about 20% of the recoverable resources in the area. Even within a production technology there can be a wide range of performance. The values in the previous table use the industry average steam-oil ratio (SOR) for SAGD of 3.2:1. There are some operations as low as 2.0 and others as high as 5.0, as shown in the following figure. The GHG emission range will be from about 400,000 g CO_2eq/tonne of oil (10 g CO_2eq/MJ) up to over 1,000,000 g CO_2eq/tonne (25 g CO_2eq/MJ) of oil for this range of SOR.

Figure 9-8 SAGD Steam Oil Ratio – Alberta Fields



9.2.3.2 Refining

Refineries have different process configurations processing different crude oil qualities making different product slates. Each of these three factors, crude oil quality, process configuration, and product slates are inter related and each have an impact on the total site emissions and on the emissions to produce each of the products.

Some of these differences can be regional, such as those imposed by the local demand for products. European refineries, where the local demand is dominated by diesel fuel, will be different than North American refineries where gasoline has traditionally been the dominant product.

The following figure shows the Solomon Energy Intensity Index (EII) for participating Canadian refineries (16 refineries participated in 2001) (NRCan, 2002). The Solomon EII value indexes the energy efficiency of a plant using a technology explicit computer model that determines the "standard" energy efficiency of a plant by computing standard energy consumption for each technology present in the plant and the type of crude charged to these technologies. A Solomon EII value of 100 is standard. A Solomon EII plant-specific value below 100 indicates a more efficient plant, while a value above 100 indicates a less efficient plant.

Note that, while the graph displays a Canadian average, this average is an estimate from the weighted averages of all operations undergoing a Solomon analysis. The actual Canadian average as determined by Solomon Associates is considered confidential; the estimate here is to be taken as indicatory rather than actual. There is a wide range in the performance of individual refineries.

Figure 9-9 Variation in Canadian Refinery Solomon EII

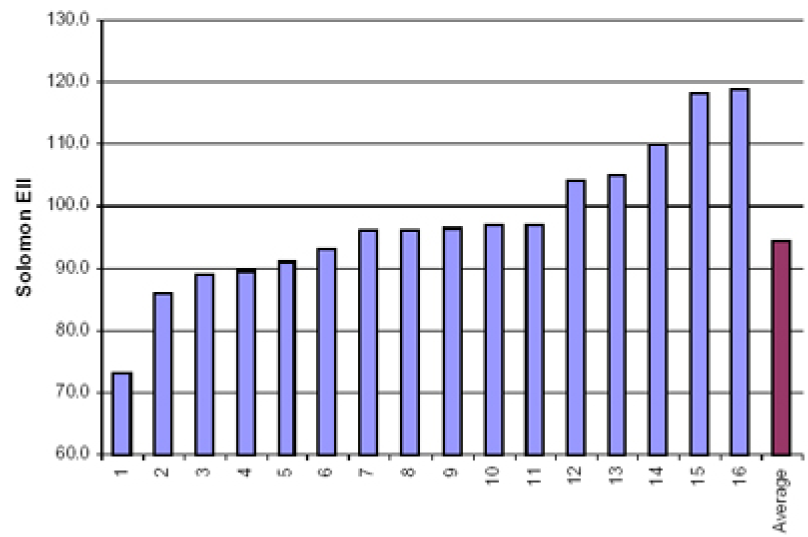
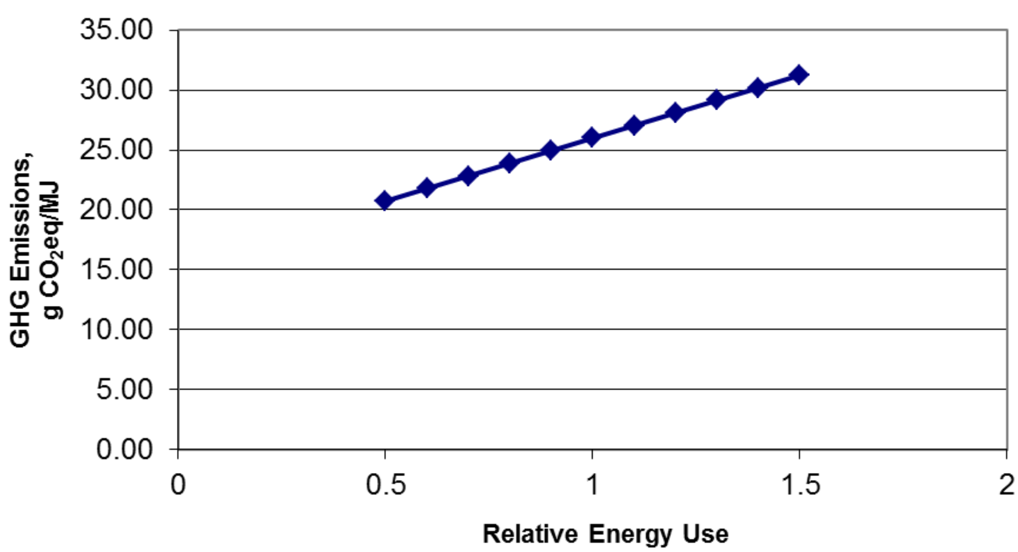


Figure 7. **Solomon Energy Intensity Index of Participating Individual Refineries.** *Source: CIEEDAC, 2002.*

In the following figure the impact of the refinery energy use on the gasoline production emissions is shown. The energy use is varied from 50% of the default energy use to 150% of the energy use. The Impact is larger than the changes made to the crude oil production emissions.

Figure 9-10 Gasoline GHG Emissions vs. Refinery Energy Use



GHGenius has the capacity to analyze the US lifecycle emissions for petroleum products on a regional basis. There are three regions, US east (PADD 1), US Central (PADD 2 and 3) and US West (PADD 4 and 5). Here the data sources are the same, the methodology is the same but there are regional differences. The results for gasoline are shown in the following table.

Table 9-3 GHGenius US Gasoline Regional Results

	US East	US Central	US West	US Average
Crude Oil SG	0.8632	0.8727	0.8873	0.8783
Crude Oil S (wt %)	0.76	1.51	1.29	1.45
	g CO_2eq/MJ (LHV)			
Fuel dispensing	0.321	0.406	0.306	0.376
Fuel distribution and storage	0.856	1.067	0.821	0.994
Fuel production	11.359	11.91	12.645	12.181
Feedstock transmission	1.713	2.076	1.443	2.045
Feedstock recovery	4.591	7.341	10.127	7.637
Feedstock Upgrading	0.05	0.325	0.344	0.303
Land-use changes, cultivation	0.002	0.027	0.019	0.023
Fertilizer manufacture	0	0	0	0
Gas leaks and flares	3.577	2.426	1.931	2.445
CO_2, H_2S removed from NG	0	0	0	0
Emissions displaced	-0.002	-0.014	-0.015	-0.013
Total	22.466	25.565	27.622	25.992

There is a difference of 5 g/MJ between the US East region, which processes the lightest and sweetest crude oil and the US West, which processes the heaviest crude, and a more sour crude than the US East refineries.

The product slates also vary with region. The US East refineries have the highest percentage of residual products even though they process the lightest crude. The refineries just don't have the same conversion capacity as refineries in the rest of the country and they produce fewer GHG emissions as a result.

Forty to fifty percent of the energy consumed in the refinery is process still gas from refining process units. The composition of this gas will vary from refinery to refinery. There is little reporting of the composition of this product. The following table compares some of the results.

Table 9-4 Fuel Gas Composition

	EIA[16]	Kramer[17]	Emerson[18]	CPPI[19]
	Mole fractions			
CH_4	0.281	0.467	0.350	0.276
C_2H_6	0.171	0.089	0.200	0.116
C_3H_8	0.119	0.034	0.070	0.087
C_4H_{10}	0.000	0.015	0.020	0.043
C_5H_{12}+	0.302	0.082	0.050	0.017
CO_2	0.000	0.001	0.010	0.006
CO	0.000	0.008	0.000	0.005
N_2	0.000	0.079	0.050	0.037
H_2	0.127	0.221	0.250	0.411
H_2S	0.000	0.000	0.0001	0.000
H_2O	0.000	0.004	0.000	0.000
HHV, kJ/std. Litre	51.75	44.74	46.83	39.38
Carbon heat content (g-C/GJ)	16,550	14,433	14,447	13,540

There is a significant difference in the GHG emissions between the EIA value and the average Canadian value. There was also a refinery to refinery variation in the data. The CPPI data on a regional basis is shown in the following table.

[16] EIA. 2006. Documentation for Emissions of Greenhouse Gases in the United States 2006. http://www.eia.doe.gov/oiaf/1605/ggrpt/documentation/pdf/0638(2006).pdf

[17] Kramer, K., Patel, N., Sekhri, S., Brown, M. 1996. Flexible Hydrogen Plant Utilizing Multiple Refinery Hydrocarbon Streams. 1996 NPRA Annual Meeting. http://www.h2alliance.com/pdf/AM_96_59.pdf

[18] Emerson. 2004. Measuring Hydrogen Sulfide In Refinery Fuel Gas with a Simple TCD-Based Gas Chromatograph. http://www2.emersonprocess.com/siteadmincenter/PM%20Rosemount%20Analytical%20Documents/GC_ADS%20Measuring%20hydrogen%20sulfide%20in%20refinery%20fuel%20gas%20with%20a%20simple%20TCD-based%20gc.pdf

[19] CPPI data supplied to NRCan for GHGenius update. 2010.

Table 9-5 Fuel Gas Composition in GHGenius

	Canada East	Canada Central	Canada West
	Mole fractions		
CH_4	0.167	0.335	0.262
C_2H_6	0.167	0.089	0.124
C_3H_8	0.093	0.053	0.136
C_4H_{10}	0.051	0.023	0.068
C_5H_{12}+	0.015	0.010	0.028
CO_2	0.000	0.002	0.015
CO	0.003	0.002	0.010
N_2	0.046	0.029	0.044
H_2	0.456	0.453	0.312
H_2S	0.000	0.000	0.000
H_2O	0.000	0.000	0.000
HHV, kJ/std. Litre	40.60	33.50	47.90
Carbon heat content (g-C/GJ)	13,531	12,548	14,660

9.2.4 Petroleum Summary

The differences in the results for the petroleum pathways are driven by a combination of methodological issues, variability in actual emissions and uncertainty about some of the modelling inputs that will be addressed in the next chapter. Nevertheless, there are real variability issues for this pathway. There is a wide range in GHG emissions for different oil fields, this has been established by many studies and analyses. Models that try to account for this variation can be expected to have more precise estimates of GHG emissions than models that don't account for regional variation.

One should also expect some variability in crude oil emissions over time. The energy required for crude oil production appears to be rising over time. As fields become depleted this can be expected. Countering this trend is an effort to reduce the amount of flaring of associated gas undertaken by the industry worldwide and advanced drilling techniques.

Refinery emissions are a function of many factors, crude oil quality (sulphur, density, and other factors), refinery complexity, product slate produced, and efficiency of the refinery. All of these factors are real and produce some variability in the reported emissions. The approach used to allocate a fraction of the total refinery emissions to each product vary between the models. This does cause some variability in the results. None of the models employ the ISO preferred approach of system expansion to eliminate the need for allocation.

9.3 NATURAL GAS

The natural gas emissions reported earlier are summarized in the following table. These are just the emissions for natural gas used in a boiler or similar combustion device.

Table 9-6 Natural Gas Summary

	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA GREET	
GWP	2001	1995	2007	2007	2007
	g CO_2/MJ				
NG Production	3.8	4.9	11.0	3.5	9.6
NG Processing	-	-	3.6	3.7	2.9
NG Transportation	7.5	-	4.4	0.97	7.5
NG Use	56.4	55.6	57.6	57.7	57.0
Lifecycle	67.7	60.5	76.6	62.4	77.0

The only true models for natural gas are the GREET and GHGenius models. BioGrace and the RFS2 modelling frameworks are just for biofuels and they have emission factors for natural gas but not full pathways. GREET1_2012 and GHGenius produce very similar results for natural gas, but much higher than the CA GREET model.

There are no real methodological issues between the models. They use similar system boundaries and allocation approaches to allocate the emissions between the natural gas and the natural gas liquids for the portion of the production that is wet gas.

The CA GREET model uses less energy for natural gas extraction and has much lower methane losses in extraction and in transmission and distribution. The differences are a combination of data updates in GREET and changes made by CARB to localize the model.

9.3.1 Spatial

Unlike crude oil, which is a very portable energy source, most natural gas is moved through fixed transportation systems. The only exception is some LNG is transported from the field to remote end users by ship. LNG imports into North America are declining and this isn't expected to be an important source of natural gas for North American use in the near future.

One should expect some field to field variation in natural gas emissions, just as there is variation in crude oil fields. This does not appear to be a widely investigated issue. One aspect of variability would be the CO_2 content of the fields, since CO_2 above the pipeline specification must be removed in the gas plants and this is generally vented. Some fields can contain more than 10% CO_2 and about 80% of that would be emitted, however these emissions amount to about 3.8 g CO_2/MJ at this extreme level.

There does appear to be quite different results for the natural gas systems between the United States and Canada. In the following table the GHGenius results for natural gas produced and used in Canada are compared to the same emissions for gas produced and used in the United States.

Table 9-7 GHGenius Natural Gas Emissions Canada vs. United States

	Canada	United States
	NG to Industry	
	g CO_2eq/MJ (LHV)	
Fuel dispensing	0	0
Fuel distribution and storage	2.306	4.146
Fuel production	2.765	1.386
Feedstock transmission	0	0
Feedstock recovery	2.98	5.276
Feedstock Upgrading	0	0
Land-use changes, cultivation	0	0
Fertilizer manufacture	0	0
Gas leaks and flares	1.741	8.207
CO_2, H_2S removed from NG	1.005	0.866
Emissions displaced	0	0
Total	10.797	19.882

The US emissions are almost double the emissions in Canada and 65% of the difference is due to methane leaks from the systems. Both countries use similar emission factors for the transportation and distribution methane losses but there are large differences in the equipment inventories in the two countries. In the United States there is still a significant amount of cast iron pipe used in distribution systems whereas this material is no longer used in Canada and all of the previously used cast iron pipe has been replaced.

The quality of the data generated in both countries for energy use in the natural gas extraction, processing and transportation systems appears to be similar and represents real differences. The methane loss rates for Canada and the US as used in GHGenius are summarized in the following table.

Table 9-8 Methane Loss Rates – Canada vs. US

	Canada	US
	Methane % Loss	
Gas Production	0.29	1.25
Gas Processing	0.00	0.21
Gas Transmission	0.11	0.47
Gas Distribution	0.16	0.37
Total	0.56	2.30

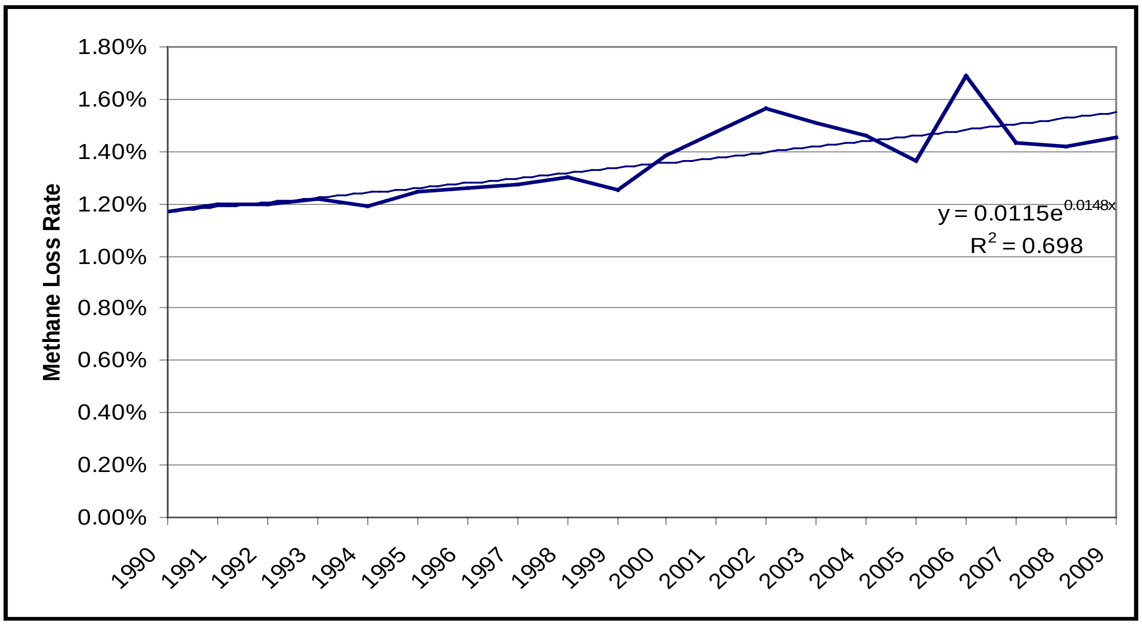
While CARB developed CA GREET to better reflect the local conditions, this only partially accounts for the differences in the emissions between the two models. There were data updates between GREET 1.8b and GREET1_2012 that account for most of the differences between the two models. The one change that CARB made to reflect the local conditions was to reduce the methane leakage rate for the transmission and distribution portion of the lifecycle based on input from the local utilities. This is quite plausible but it is poorly documented.

9.3.2 Temporal

The data sources used for the natural gas pathways are generally time series. The energy use for lease fuel and gas plant fuel was shown in Figure 4-1. Lease fuel has been relatively constant over the past 20 years but there have been some reductions in gas plant energy use.

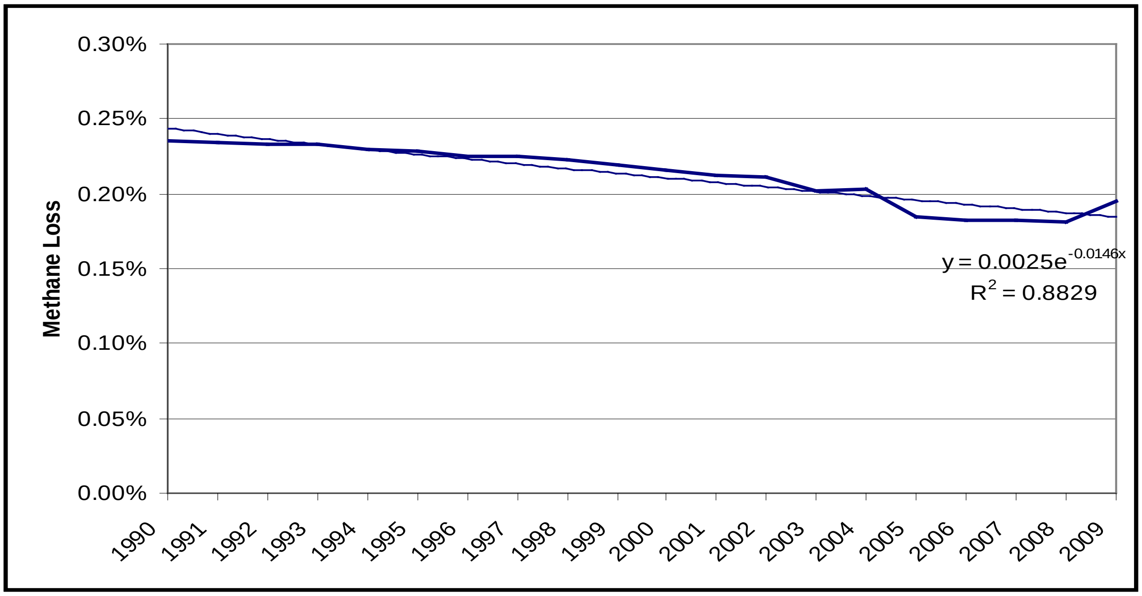
Fugitive emissions of methane for US gas production are included in the US National Inventory report (EPA, 2011). This report is used as a source of data for both GREET and GHGenius. The 2011 US National Inventory Report released in 2013 (US EPA, 2013) has revised much lower methane loss rates for the natural gas sector but these are not reflected in the versions of GREET or GHGenius reviewed here. These emissions can be combined with natural gas production data from the US EIA to develop emission factors for this activity. The developed emission factors that are used in GHGenius are shown in the following figure. Somewhat surprisingly, these emissions appear to be increasing.

Figure 9-11 Methane Loss Rate US Gas Production



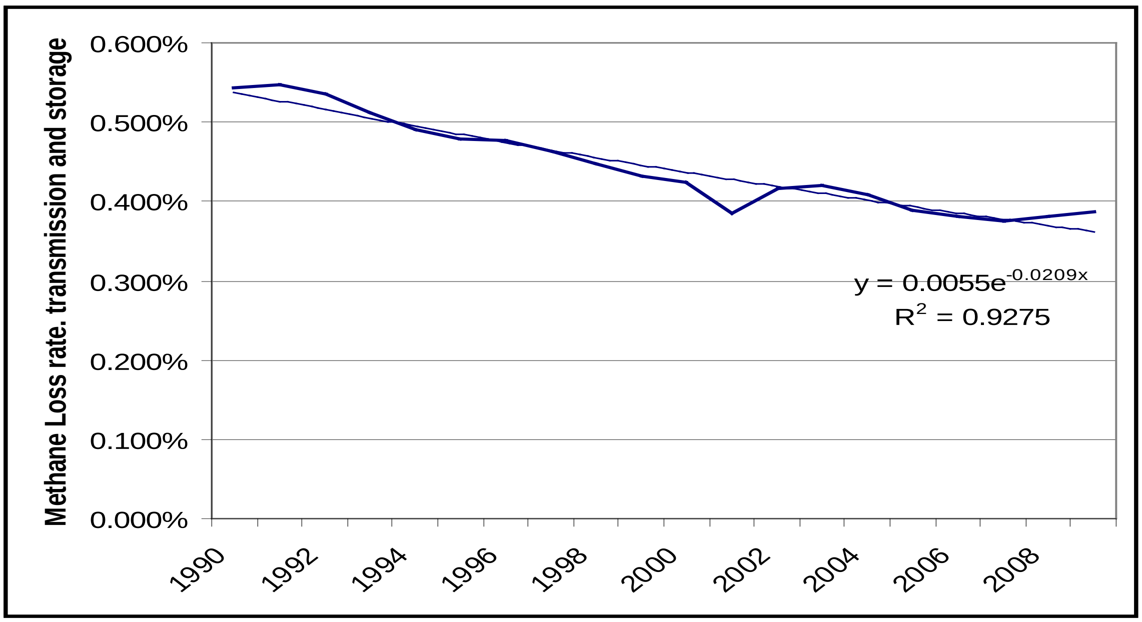
Fugitive emissions of methane for US gas processing from the same sources are shown in the following figure. These emissions appear to be decreasing over time.

Figure 9-12 Methane Loss Rate US Gas Processing



In the gas transmission sector we see similar emission reductions over time.

Figure 9-13 US Methane Loss Rate Transmission and Storage



9.3.3 Process/Design

The largest differences in the natural gas emissions between the models arise when the transportation fuel CNG and LNG are considered. They are discussed separately below.

9.3.3.1 CNG

The CNG compression energy is a function of the inlet and outlet pressures required and on the design of the compressor. The CA GREET model relies on an estimate of compression energy requirements provided to CARB by Clean Energy, the largest provider of natural gas fuel for transportation in North America. There is little documentation for the values provided though. The results are summarized below.

Table 9-9 CNG Summary

	GREET1_2012	CA GREET	GHGenius
	g CO_2eq/MJ		
NG Production	10.97	3.5	9.62
NG Processing	3.65	3.7	2.86
NG Transportation	4.44	0.97	7.49
NG Compression	5.29	2.14	5.41
NG Use	57.56	57.7	59.56
Lifecycle	81.91	68.0	84.94

GREET and GHGenius both calculate the emissions from basic principles. The different assumptions in the two models and the calculated compression related emissions are shown in the following table. Both models assume electric drive as the default case.

Table 9-10 CNG Compression Parameters

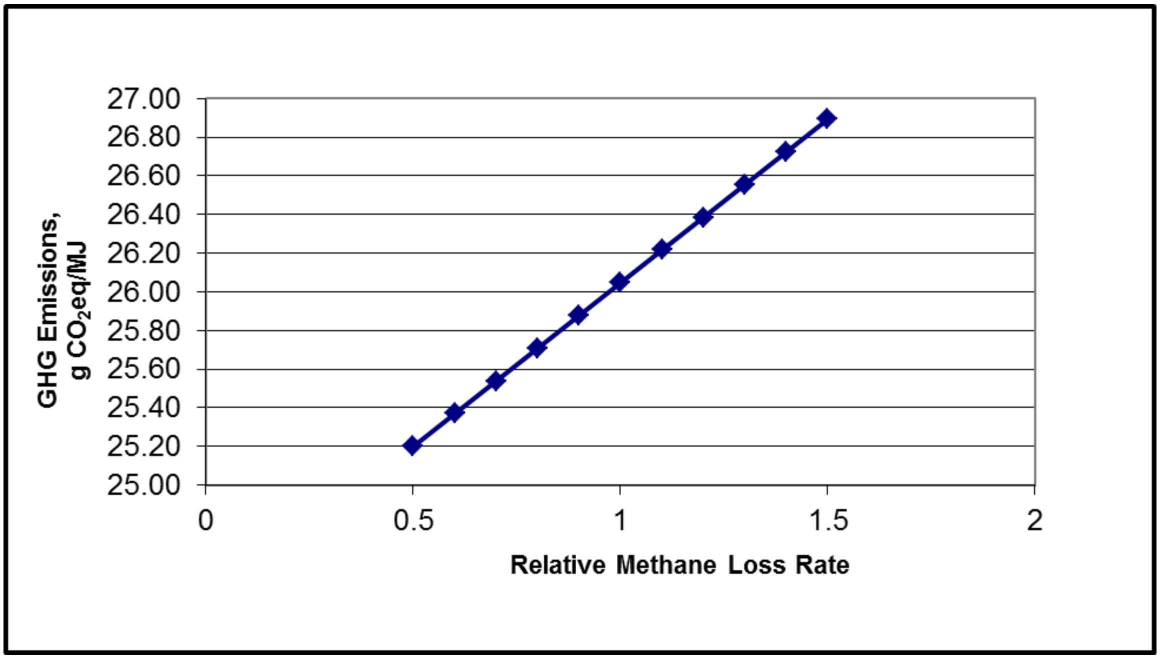
	GREET	GHGenius
Inlet Pressure, psia	50	65
Outlet Pressure, psia	4,800	3,600
Outlet/Inlet ratio	96	55
Power, kWh/kg	0.27	0.22
Methane loss, g CO_2eq/MJ	0.0	1.61
Total GHG Emissions, g CO_2eq/MJ	5.29	5.41

GHGenius includes some methane loss from the compression and dispensing system whereas this is not included in GREET. There is very limited information available on these emissions. While the total emissions for compression are close, the composition of the emissions is different.

There will always be variability between individual compressors as inlet pressure will vary from site to site, but this is an area where the industry should be able to supply average data on energy consumed per kg of fuel delivered.

One of the large differences between GREET1_2012 and CA GREET is the methane loss rates. This is also one of the main differences between gas production in Canada and gas production in the US. In the following figure the impact of changing the methane loss rates throughout the production system on the CNG production emissions is shown.

Figure 9-14 CNG Production Emissions vs. Methane Loss Rates



9.3.3.2 LNG

There are only a few LNG for transportation fuel facilities in North America and thus little public information is available on their performance. The liquefaction of LNG can be driven by electric motors, by natural gas fired systems, or other means. The default cases in the models assume they are natural gas driven. The efficiency of the systems can also vary widely with results from 80 to 95% reported. The model results are presented in the following table.

Table 9-11 LNG Summary

	GREET1_2012	CA GREET	GHGenius
	g CO_2eq/MJ		
NG Production	10.89	3.49	9.62
NG Processing	3.62	3.74	2.86
NG Transportation	0.21	0.97	7.49
NG Liquefaction	7.96	15.79	9.75
LNG Transportation	2.06	0.64	0.98
NG Use	57.79	58.5	59.59
Lifecycle	82.53	83.13	90.29

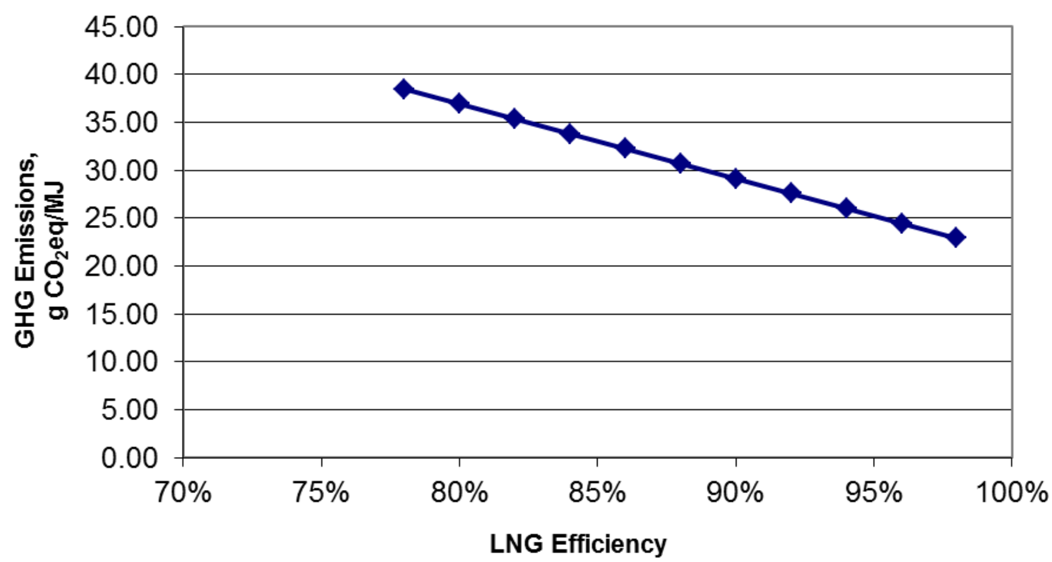
There are two primary areas of difference in the models, there are different location/distribution scenarios used and the efficiency of the LNG process is different.

One of the advantages of LNG is that the energy density of the fuel is increased and that allows the product to be trucked longer distances. Both versions of the GREET model assume that the LNG plant is located close to the gas field, reducing the pipeline emissions for the natural gas, but both have relatively short distances for the transportation of the LNG.

The other difference is the liquefaction efficiency. The CARB version reduced the process efficiency to 80% from the 91% in the GREET1_2012 model.

In the following figure the emissions up to the nozzle from GHGenius are shown as a function of the process efficiency. It can be seen that the process efficiency has a significant impact on the emissions.

Figure 9-15 LNG Emissions vs. Process Efficiency



9.3.4 Natural Gas Summary

There has not been as much attention paid to the variability of natural gas production as there has been to the variability of crude oil production. This is probably due to the different nature of the distribution infrastructure. Crude oil can be physically traced from the well to the refinery, natural gas goes into a common transmission and distribution system and there is no means to physically tie removals from the system to specific gas production.

The models use similar boundary conditions and methodology. The variances are caused primarily by different assumptions about methane loss rates at all stages of the lifecycle.

The emissions associated with compression and liquefaction are tied to the specific process conditions. The compression ratio for CNG systems has a large impact on the energy requirements but compressor design also plays a role. LNG systems can have varying efficiencies and use natural gas or electricity as the source of energy to drive the process. Both factors can lead to variability between facilities.

9.4 CORN ETHANOL

The corn ethanol results summary from section 5 is shown in the following table.

Table 9-12 Corn Ethanol Summary

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement			
	g CO_2eq/MJ (LHV)				
Feedstock Production	36.78	15.63	33.50	35.85	37.22
Feedstock Transport	0.51	2.83	2.21	2.22	1.62
Ethanol Production	86.01	30.7	33.74	38.30	38.26
Co-product (power)	-46.73	-	-	0.00	0.00
Co-Product (DDG)	-34.75	-	-14.52	-11.51	-18.87
Ethanol Distribution	1.54	1.18	1.52	2.70	1.61
Fuel Use	-	0.83	-	-	2.22
Total	43.4	51.21	56.44	67.56	62.06

A number of variability issues were identified earlier with respect to corn production and ethanol production from the corn. These are discussed further in the following sections.

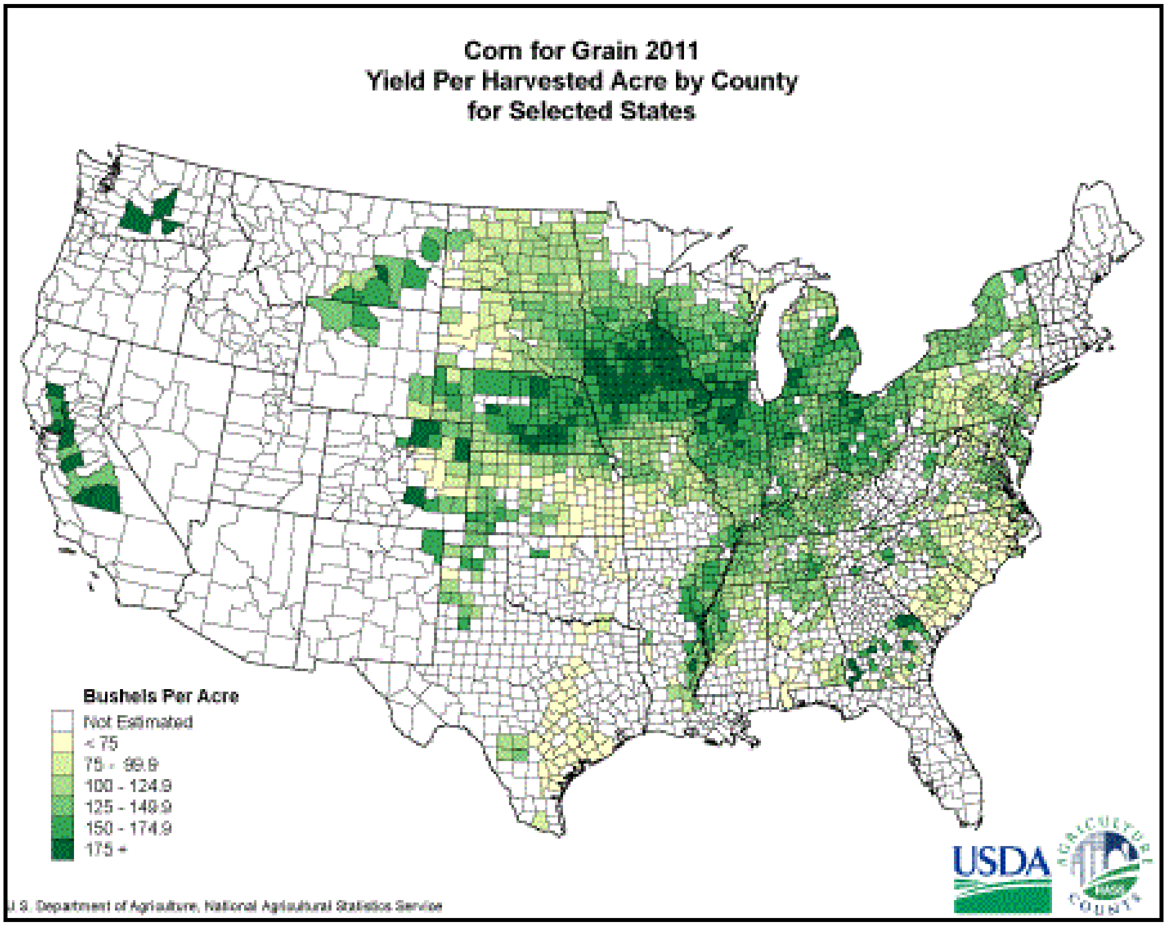
9.4.1 Spatial

There was a significant difference in the modelling inputs used for European corn and for US corn production, indicating the potential for some spatial variation in the results. Several aspects are investigated below.

9.4.1.1 Yield

The corn yield varies nationally and internationally. The 2011 US corn yield by county is shown below. County yields range from less than 75 bu/acre to over 175 bu/acre. Some of the high yielding areas are due to irrigation and it is expected that additional energy will be required for the irrigation. Yield will have a relatively small impact on the model results since most of the inputs in the models are scaled to the expected yield. Inputs that are typically area related are field fuel use, and some pesticide application rates. Irrigation energy and drying energy should both be mostly scaled to yield.

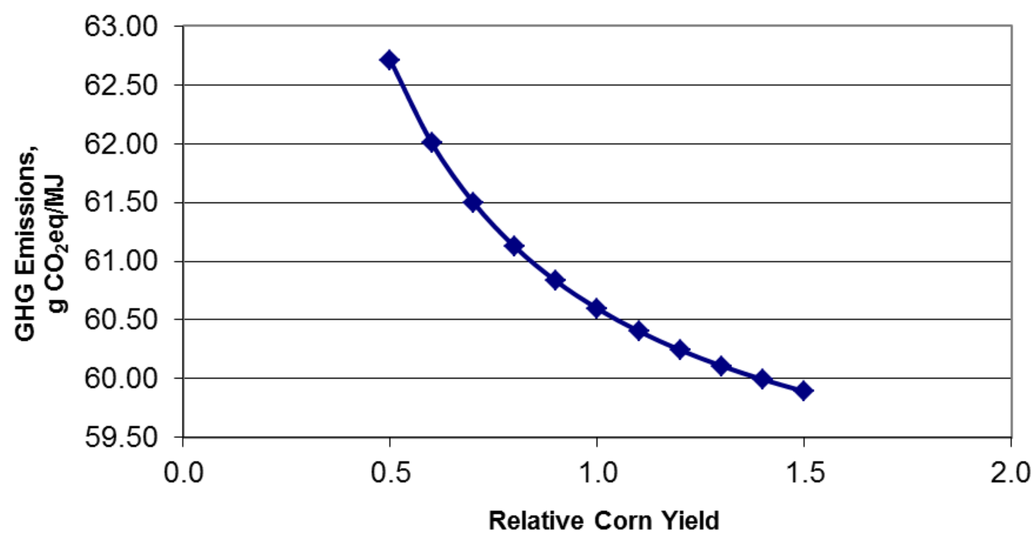
Figure 9-16 Regional Corn Yield



Fertilizer inputs should be scaled to the expected yield, at least in the mid to long term. Failing to scale the inputs will lead to nutrient depletion in the soil and eventually lower yields.

The following figure shows the impact of yield on the ethanol lifecycle emissions. This is generated using GHGenius. The overall impact is small.

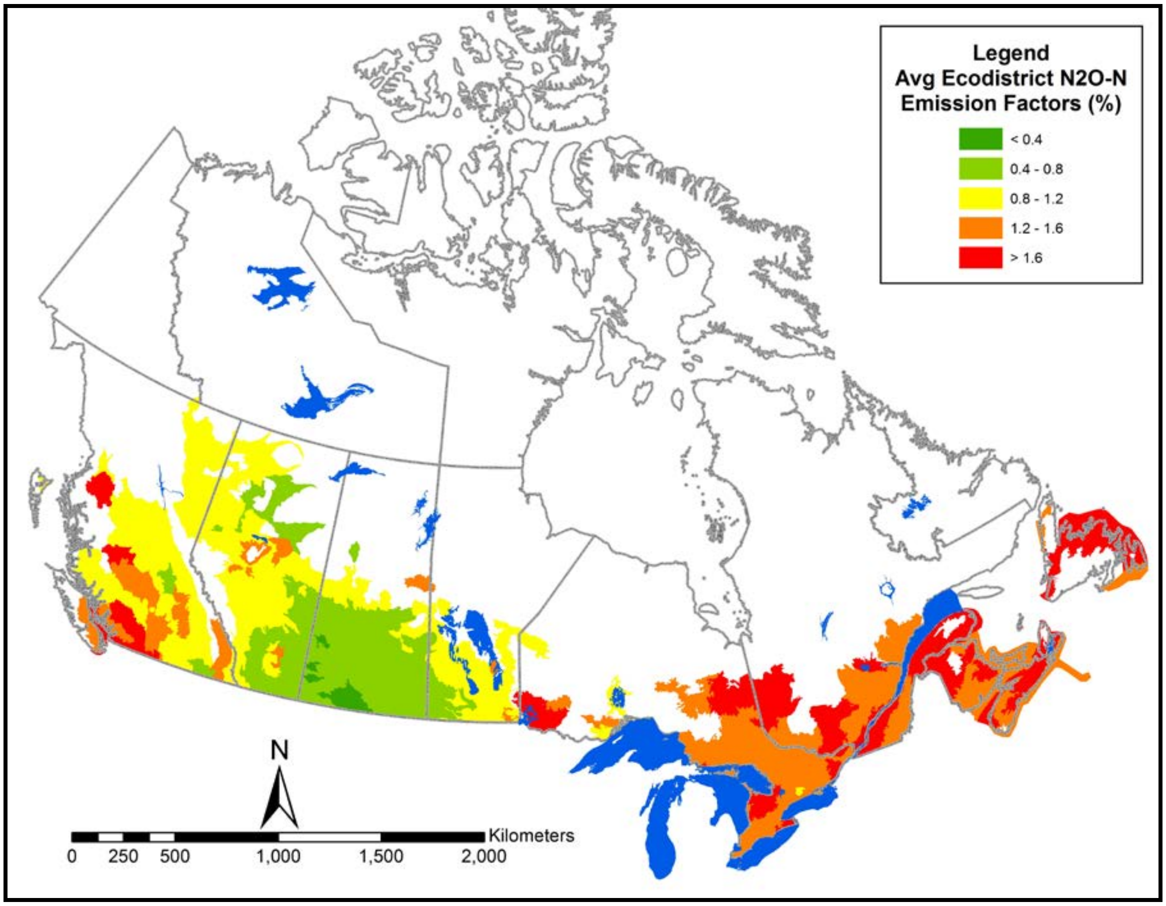
Figure 9-17 Corn Ethanol GHG Emissions vs. Corn Yield



9.4.1.2 N_2O Emissions

In addition to the uncertainty of the N_2O emission factors there is some variability of N_2O emission rates. A number of factors influence the emission factors including soil types, precipitation and other factors. Agriculture and AgriFood Canada have developed a Tier 2 N_2O emission model for Canada. This model can be used to generate the following figure, showing the spatial variation of the EF_1 direct emission factor for N_2O.

Figure 9-18 Spatial Variation in N_2O Emission Factors

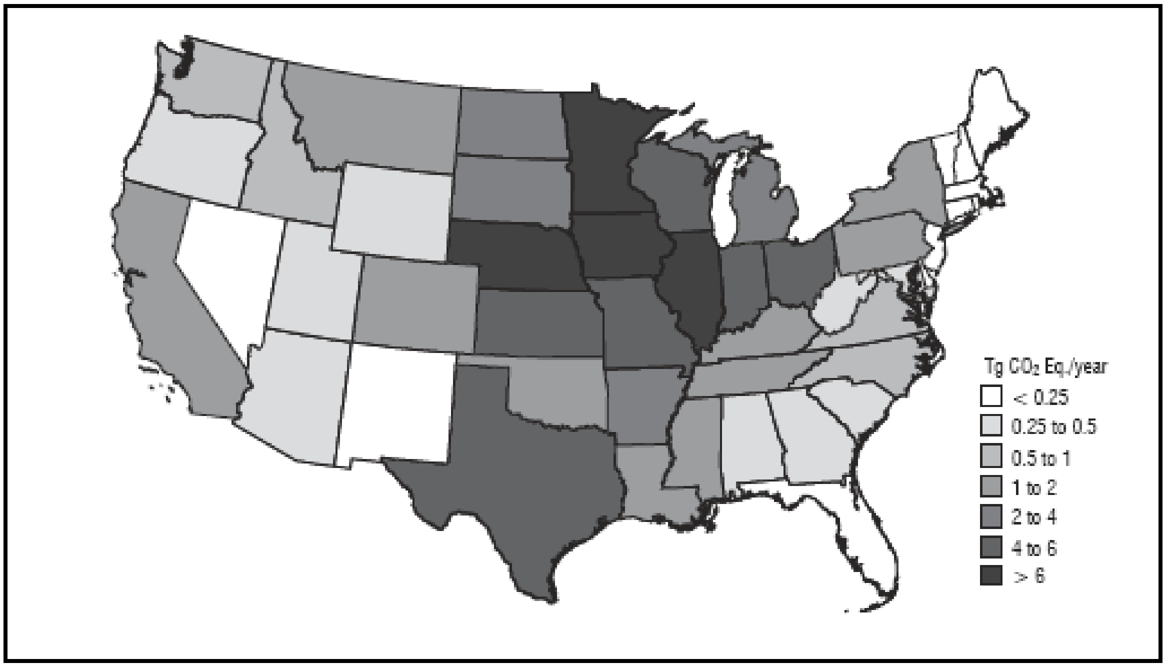


Source: Agriculture and AgriFood Canada

Across Canada the EF_1 factor varies from less than 0.4 to more than 1.6%. The level of variation for any specific crop will be less than this as not all crops are suited to all regions, but if one looks at Ontario and Quebec, where most Canadian corn is produced, the factor can vary from 0.8 to over 1.6%.

The US EPA (2012) has similar regional data on N_2O emissions but they present it differently, showing the direct N_2O emissions per hectare. The following figure thus has three variables, the N_2O emission factor, the nitrogen application rate, and the nitrogen in the biomass residuals returned to the soil. Nevertheless, it demonstrates the potential for spatial variability.

Figure 9-19 Direct N_2O Emissions



Source: USDA

9.4.1.3 Nitrogen Fertilizer Type

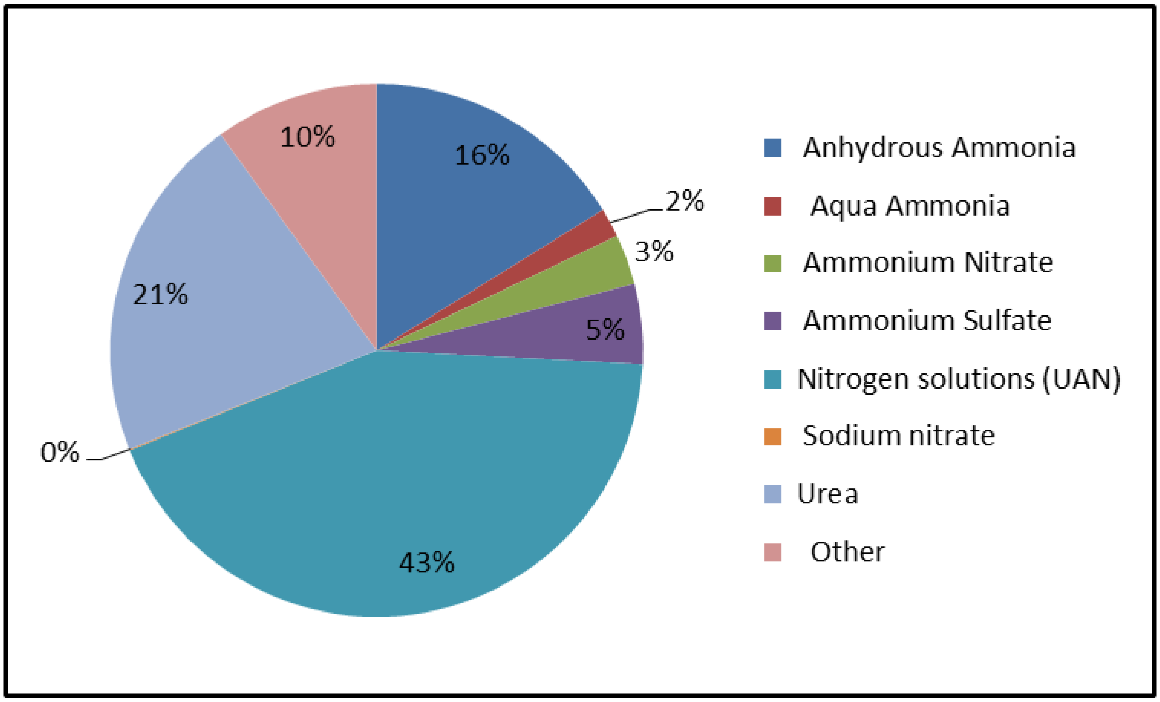
The carbon intensities of the fertilizer production systems in the various models are different. Some of this is real and relates to different types of fertilizer and some may reflect different production methods in different countries. The following table shows the carbon footprints from various nitrogen fertilizers (Eco Invent 2.2).

Table 9-13 Carbon Footprints for Nitrogen fertilizers

Product	Carbon Footprint
	kg CO_2eq/kg N
Ammonia	2.096
Ammonium nitrate	8.551
Ammonium nitrate phosphate	5.265
Ammonium sulphate	2.691
Calcium ammonium nitrate	8.654
Calcium nitrate	3.848
Diammonium phosphate	2.799
Monoammonium phosphate	2.823
Potassium nitrate	15.970
Urea	3.304
Urea ammonium nitrate	5.838

Europe uses higher amounts of ammonium nitrate fertilizer than North America. The types of nitrogen fertilizer use reported by the USDA (Fertilizer Use, 2011) are shown in the following figure.

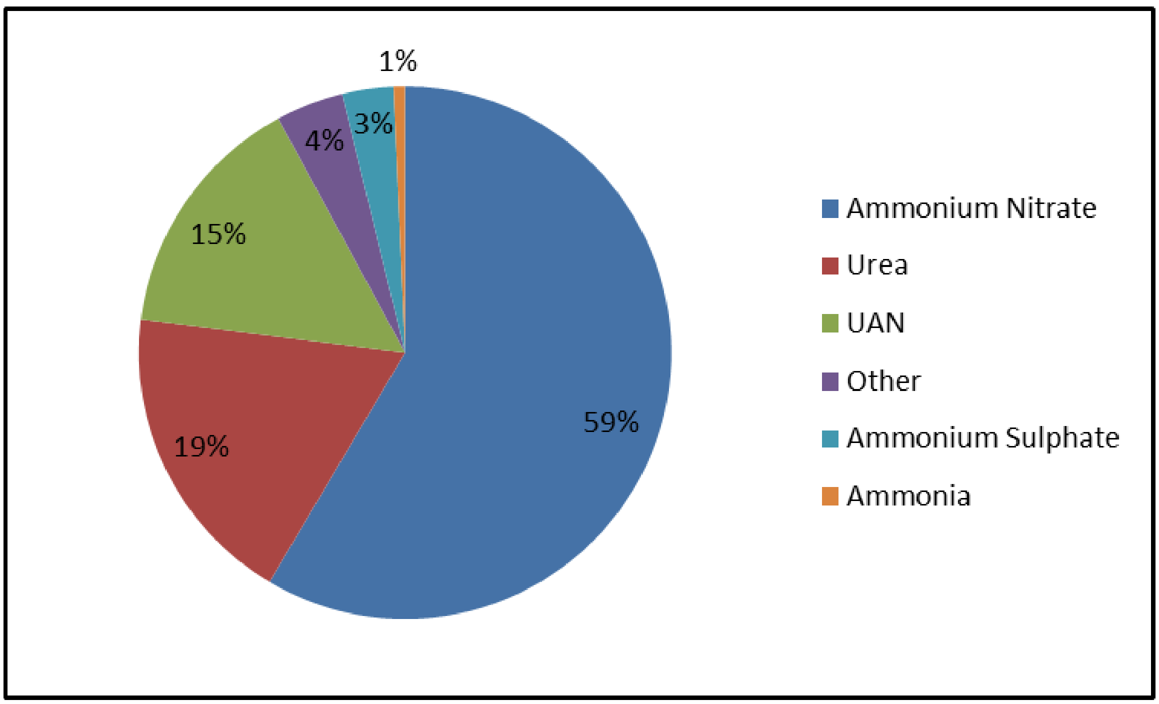
Figure 9-20 Nitrogen Fertilizer by Type – US



Source: USDA

The EU nitrogen fertilizer use by type for the year 1999 is shown in the following figure (Isherwood).

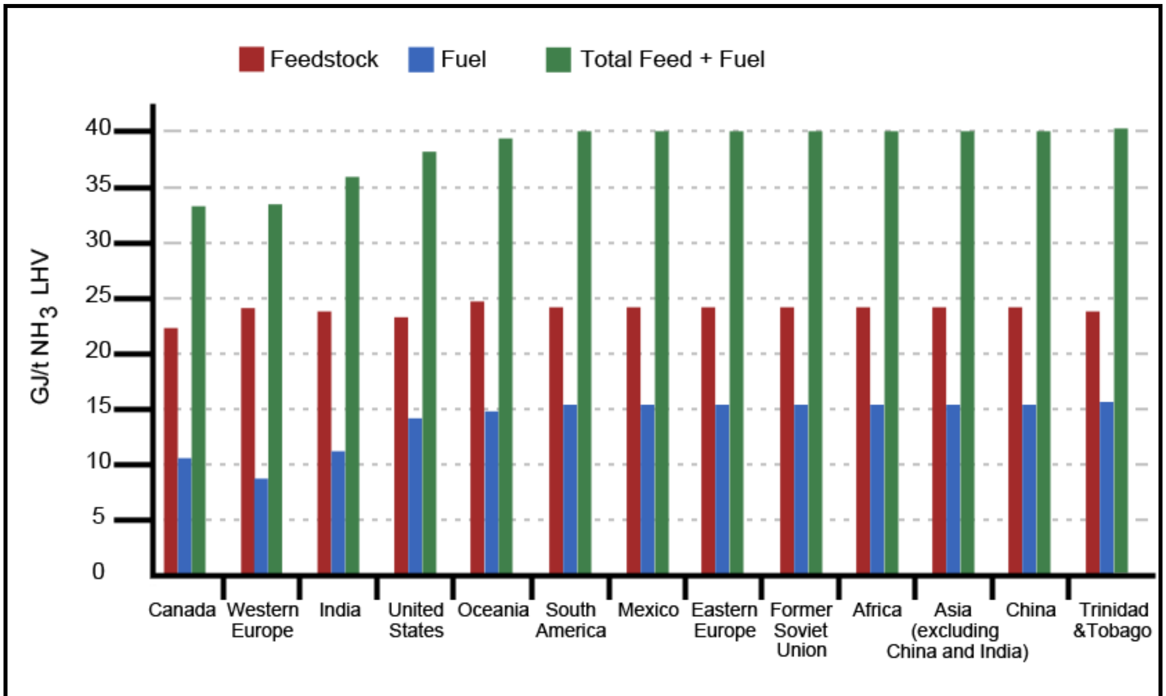
Figure 9-21 Nitrogen Fertilizer by Type – Europe



Source: Isherwood

Most of the nitrogen fertilizers start with the production of ammonia and there is some evidence (NRCan, 2004) that the efficiency of ammonia production varies by region, as shown in the following figure.

Figure 9-22 Regional Ammonia Production Efficiency



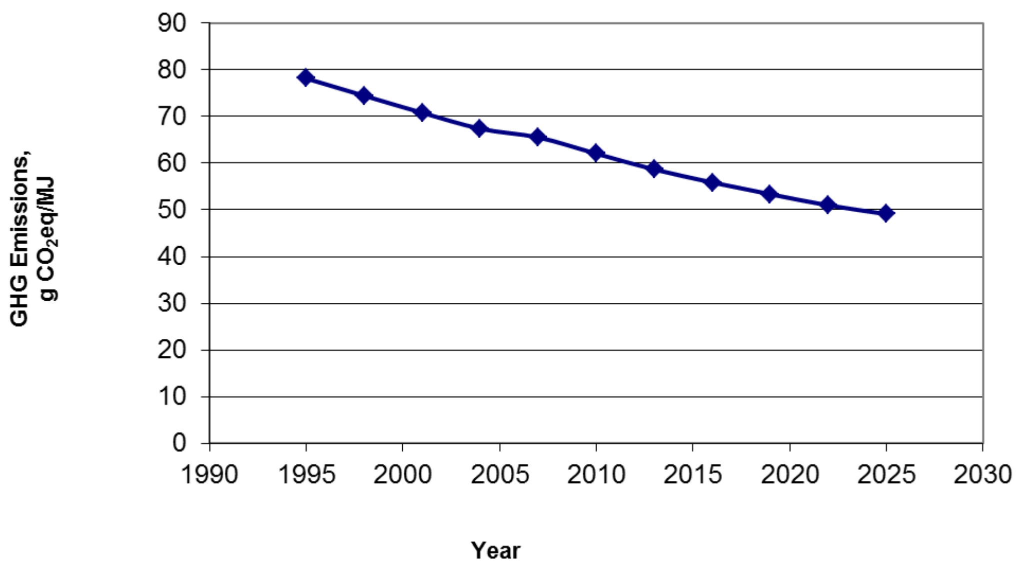
Source: (S&T)[2] from NRCan data

The combination of the different carbon intensities for the different nitrogen fertilizers, the regional efficiencies, and the different regional use patterns adds significant spatial variability to the emissions associated with corn production.

9.4.2 Temporal

Many temporal issues can impact the biofuel pathways. These can impact the data that is chosen for use in models as well as the overall emissions. GHGenius has time series of data included for many of the aspects of fossil and biofuel production. GREET also has some time series data for some pathways, including corn ethanol. The corn ethanol GHG emissions from GHGenius as a function of time are shown in the following figure from the period 1995 to 2025. This figure only address some of the possible changes over time, it includes yield, fertilizer use (but not fertilizer types), ethanol plant energy use, and changes in the fossil energy and electric power sectors. It doesn't include changes in management practices that might sequester soil carbon.

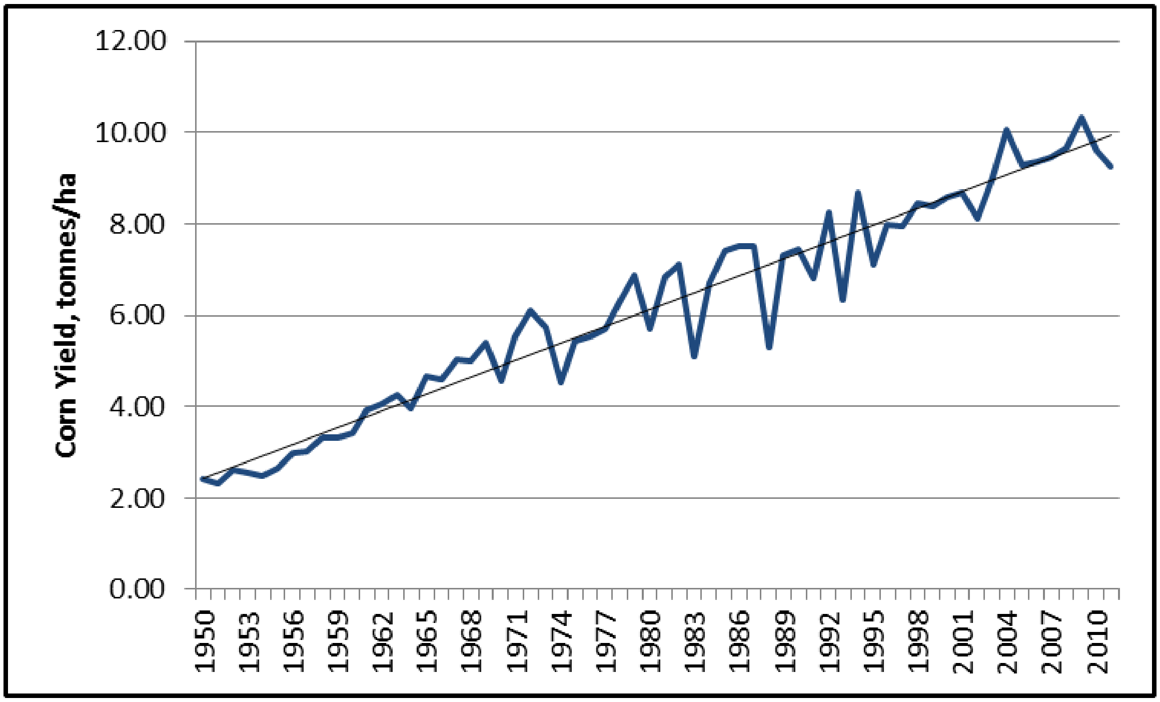
Figure 9-23 Corn Ethanol GHG Emissions vs. Time



9.4.2.1 Yield

The yield of corn has changed significantly over the years, but this has a relatively small impact on the GHG emissions as was shown earlier. It does impact factors such as land requirements and the potential for indirect land use emissions. The US Corn yield trend is shown in the following figure.

Figure 9-24   Corn Yield Trend

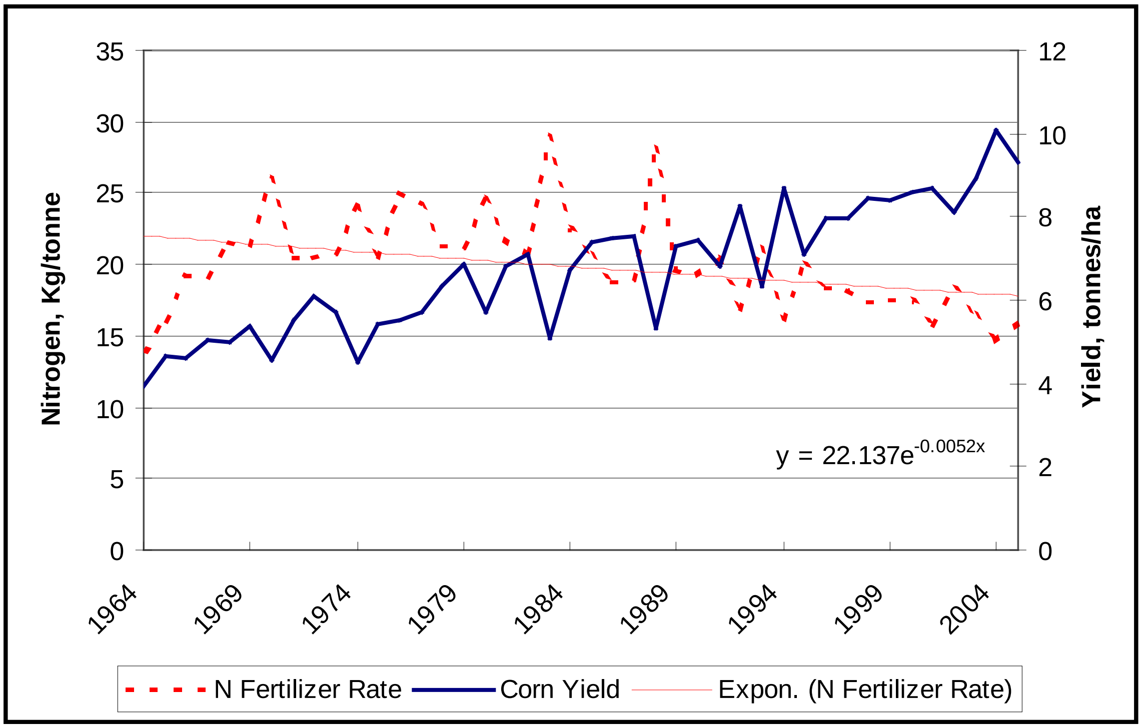


Source: USDA

9.4.2.2 Fertilizer Use

At the same time that corn yields have been increasing the fertilizer application rates, per tonne of production, have been decreasing. This is shown in the following figure for nitrogen application rates, but the same trend is apparent for the other fertilizers. This is due to changes in corn varieties, introduction of precision farming practices, and other factors. This figure also demonstrates the challenge of using data from a single year. There is a very apparent inverse relationship between yield and fertilizer use per tonne for a number of years. The fertilizer is generally applied in anticipation of a certain yield and if the weather subsequent to the fertilizer application is unfavourable and negatively impacts the yield, this will lock in high fertilizer rates per unit of production for that year. In some years the opposite trend (higher than expected yield and thus lower fertilizer per tonne of production) is also apparent.

Figure 9-25 Corn Nitrogen Fertilizer Rates

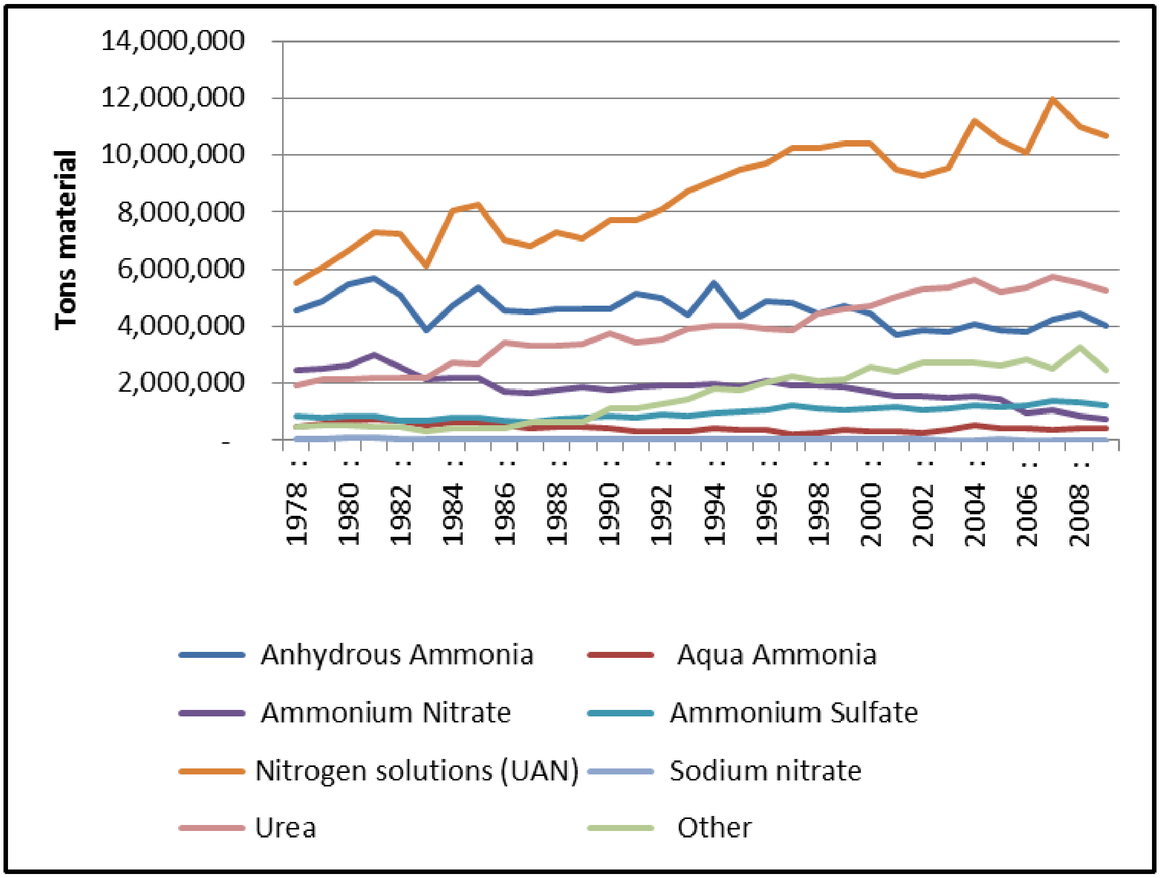


Source: USDA

9.4.2.3 Fertilizer Type

One trend that is not included in most models is that the type of nitrogen fertilizer that is applied is changing. USDA data on this is shown in the following figure. Ammonium nitrate and anhydrous ammonia have decreased and UAN (a urea and ammonium nitrate solution) has increased in the past four decades.

Figure 9-26 Fertilizer Types vs. Time

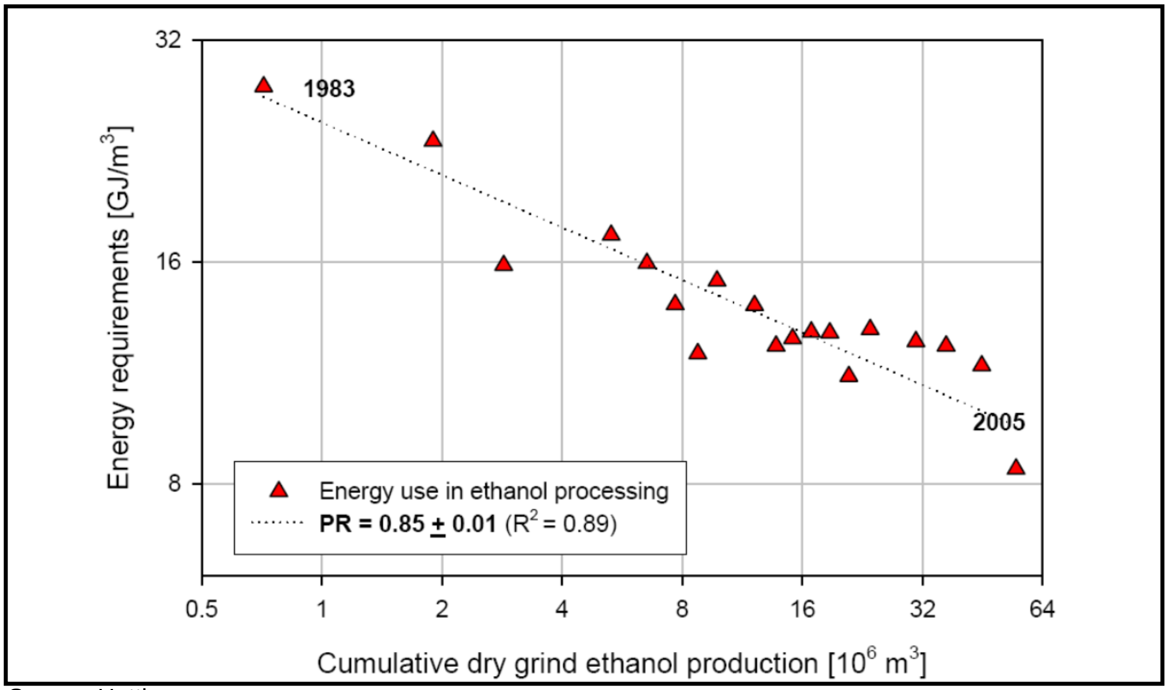


Source: USDA

9.4.2.4 Process Energy

Ethanol plant process energy has also decreased significantly over time. This is shown in the following figure (Hettinga, 2007). The energy use in ethanol dry mills has declined by 65% over the past three decades. It is very important, therefore, that current data is used in ethanol LCA analyses.

Figure 9-27 US Corn Ethanol Energy Use



Source: Hettinga

9.4.3 Process/Design

Not all ethanol plants have identical designs. There have been a number of different companies involved in the plant design and often the designs are customized to meet specific local conditions.

9.4.3.1 Plant to Plant Variation

A number of US corn ethanol plants have shared operating data with $(S\&T)^2$ in the past several years and the distribution of natural gas, electric power, and yield for these plants is shown in the following three figures. Each of these three major input variables show significant plant to plant variation and this results in some plant to plant variation in the carbon intensity of the ethanol production.

Figure 9-28 Natural Gas Variation

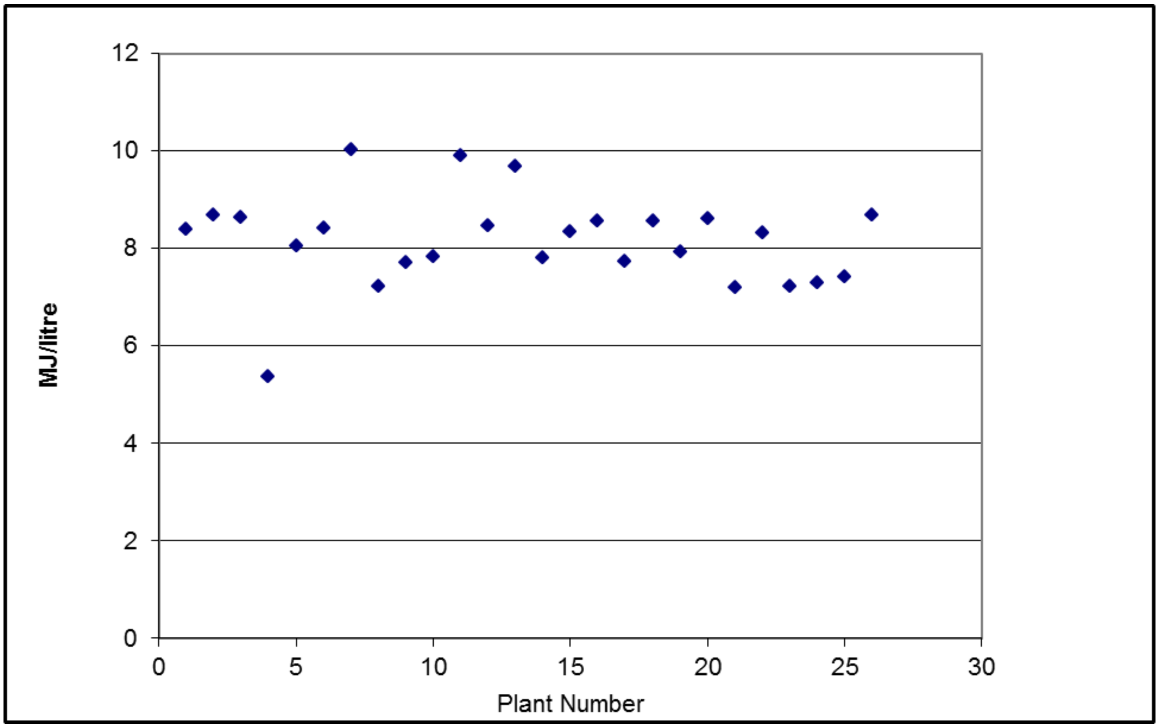


Figure 9-29 Electric Power Variation

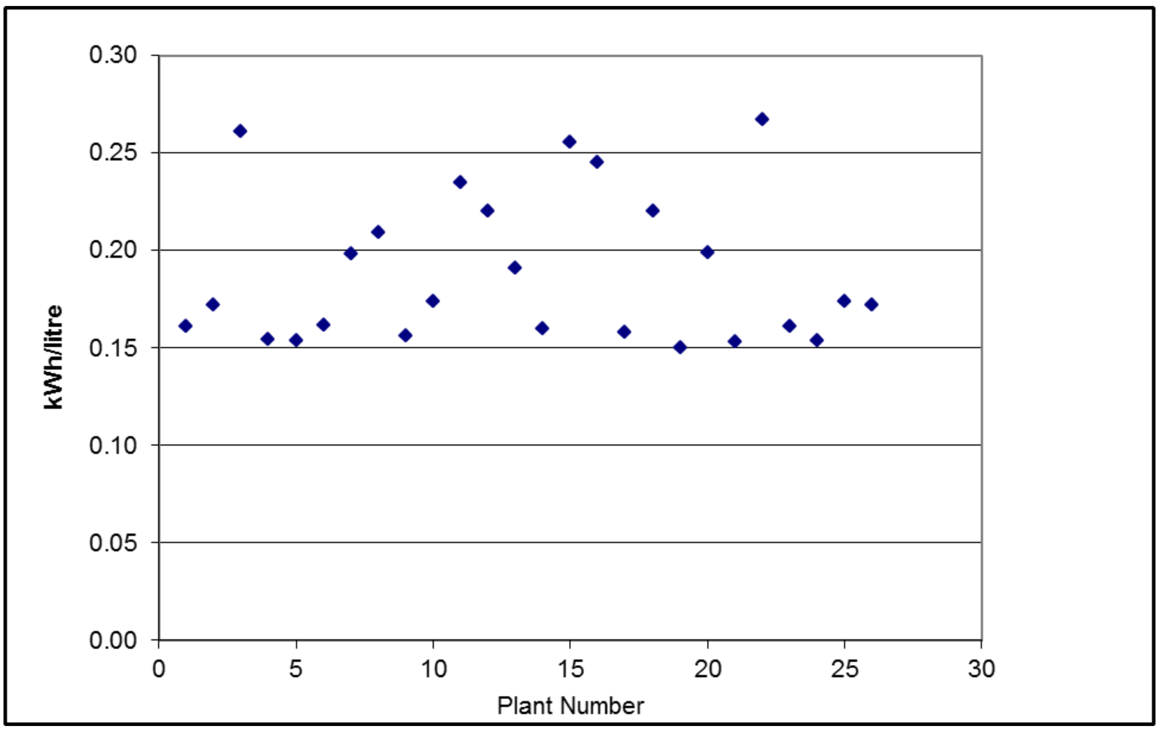
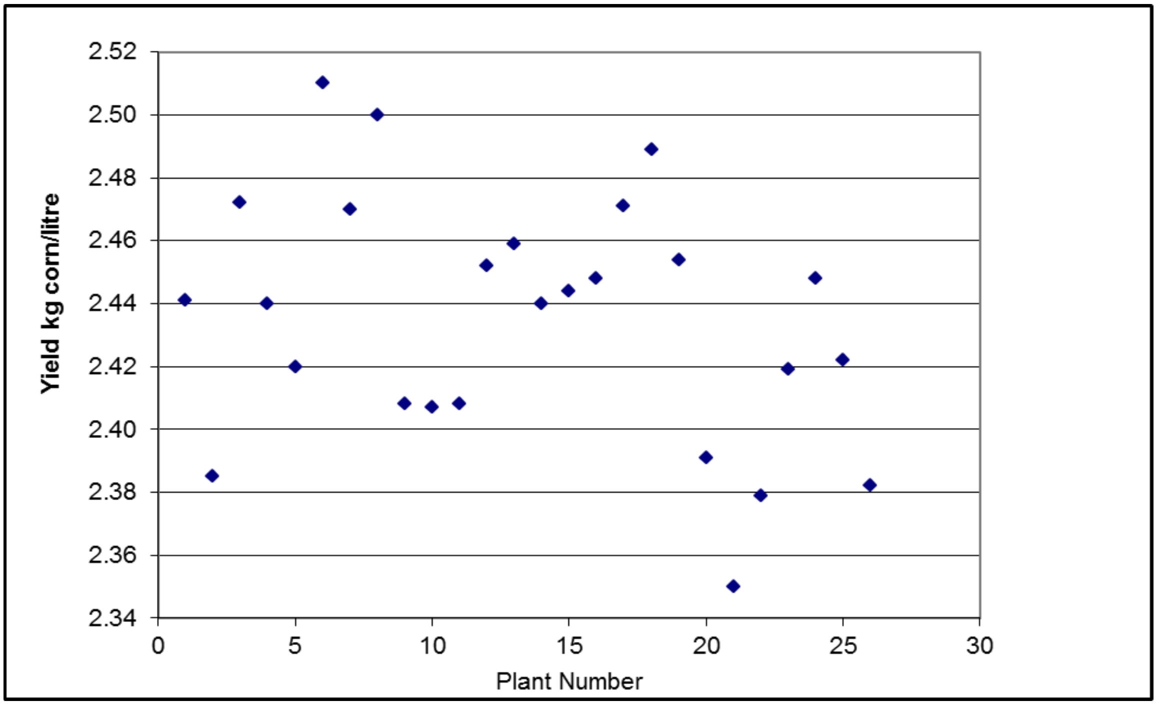
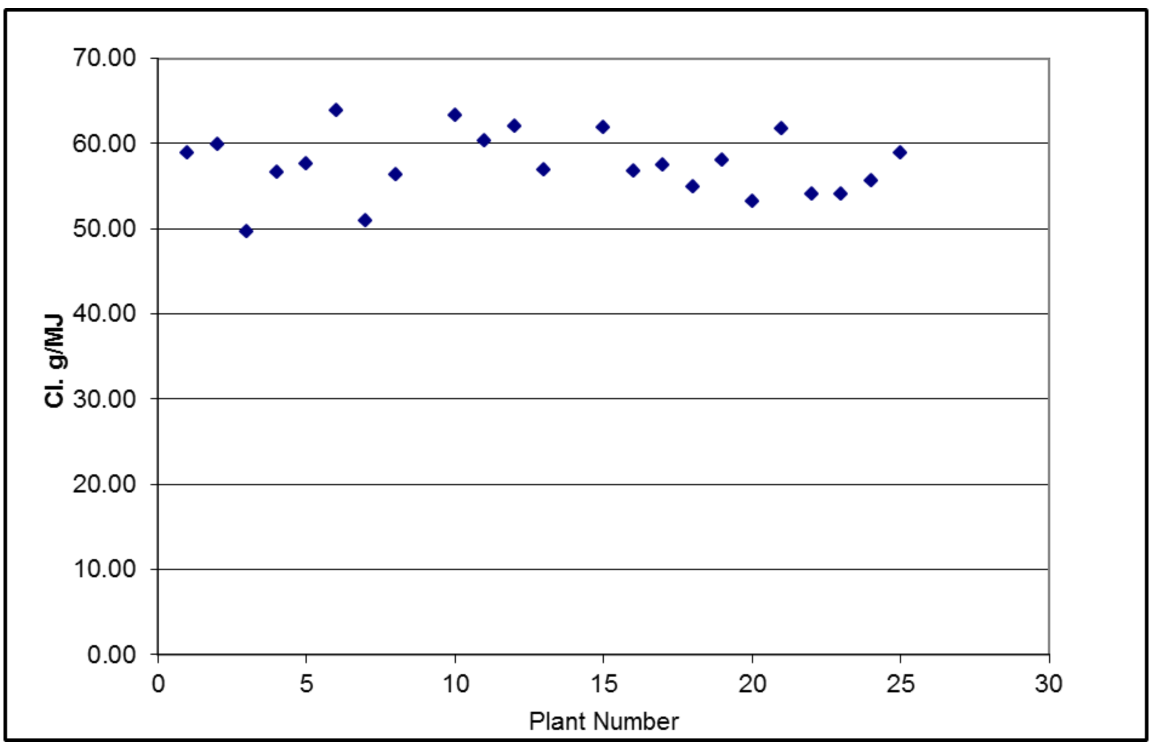


Figure 9-30 Yield Variation



All of this variation in the major plant inputs sets the variation in individual plant carbon intensity. Three plants with some special conditions have been removed from the data set.

Figure 9-31 Carbon Intensity Variation



9.4.4 Other

There are two other modelling issues that can lead to some variation between the models, the system boundaries and the method of dealing with co-products.

9.4.4.1 System Boundaries

For this pathway there are small differences in the system boundaries between the models.

- The GREET models (Including the EPA RFS2) do not include the dispensing energy at the retail stations. This is included in BioGrace and in GHGenius.
- The issue of the energy required to build tractors and trucks used in the process is included in GHGenius and it can be included in GREET, although the default setting is to exclude this energy and emissions.
- The models consider different levels of process chemicals. BioGrace, CA GREET, and the EPA RSF2 models do not consider any process chemicals, GREET1_2012 considers enzymes and yeast, and GHGenius considers enzymes, yeast, caustic soda, and ammonia.

9.4.4.2 Co-product Allocation

There are differences in the treatment of co-products in the different models. BioGrace uses an energy allocation approach, GHGenius and GREET use a displacement approach but have different assumptions about what is displaced, and the RFS2 modelling has a very comprehensive assessment about sector wide displacement impacts. GHGenius and GREET1_2012 take a first step to sector wide impacts by providing a credit for methane reduction in the livestock sector resulting from the change in the diet. The co-product credits were shown earlier but are repeated in the following table.

Table 9-14 Ethanol Co-Product Credit Comparison

	BioGrace	GREET 1_2012	CA GREET	GHGenius
	g CO_2eq/MJ			
Method	Energy	Displacement	Displacement	Displacement
Power	46.73			
DDG	34.75	14.52	11.5	18.87
Total Co-products	81.48	14.52	11.5	18.87

The BioGrace credit for the DDG is inflated by the CHP configuration. The energy allocation approach applies the ratio of the energy in the DDG to the energy in the DDG and the ethanol to the total energy expended to that point to allocate a portion of the energy to the DDG. In this case a portion of that energy was used to produce electricity for the grid which receives a displacement credit for natural gas combined cycle power. As well, it effectively receives a second credit through the energy allocation approach used for the DDG. This is why the credit is double the other systems.

GREET and GHGenius both provide options for alternative allocation approaches. The results from these alternative approaches are shown in the following table.

Table 9-15 Alternative Allocation Approaches

	GREET1_2012		GHGenius	
	g CO_2eq/MJ (LHV)			
	Total	DDG Credit	Total	DDG Credit
Base (Displacement)	56.44	14.52	59.84	18.87
Energy	41.41	29.55	51.14	27.55
Market Value	51.91	19.05		
Mass basis			41.32	37.36

The allocation approach used does make a significant difference to the results. The default approach of using the displacement method results in the lowest credit and the highest lifecycle emissions in both models. However, it is the most consistent with ISO guidelines.

9.4.5 Corn Ethanol Summary

As with the two fossil energy systems analyzed, the difference in the corn ethanol results between the models is driven by a combination of methodological issues, variability in actual emissions, and uncertainty about some of the modelling inputs. There are also real variability differences for this pathway. N_2O emission rates vary due to climate and soil conditions, fertilizer manufacturing efficiencies and fertilizer types vary regionally. There are also real temporal issues with many of the important parameters in this pathway.

There are also significant methodological issues with the corn ethanol modelling. There are some plant configuration issues, particularly between BioGrace and the North America models, system boundary issues (although these are relatively small), and allocation differences between the models.

9.5 Sugarcane Ethanol

The results for sugarcane ethanol from the five models are shown in the following table. The results range from 24 to 44 g CO_2eq/MJ. There is a large variation in the results for almost all of the stages of the lifecycle.

Table 9-16 Sugarcane Ethanol Summary excluding ILUC

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation		Displacement			
	g CO_2eq/MJ (LHV)				
Feedstock Production	14.11	37.26	22.30	19.0	28.93
Feedstock Transport	0.84	1.69	2.31	2.0	2.31
Ethanol Production	0.85	2.27	2.76	2.1	5.81
Co-product (power)	0.0	-13.29	-1.63	0.0	-4.26
Ethanol Distribution	8.16	2.71	9.09	3.5	11.04
Total	23.97	32.03	34.83	26.6	43.83

The drivers for the variability are discussed in the following sections.

9.5.1 Spatial

All of the models consider sugarcane production in Brazil and thus limit the spatial variability in the modelling efforts. Other countries do produce sugarcane and some of them are developing an ethanol industry. Peru, for example has a new plantation and ethanol plant that is now exporting fuel ethanol to North America and Europe. This project utilizes irrigated sugarcane production and operates year round and thus should be expected to have a different emission profile than the Brazilian mills.

Within Brazil there are several distinct sugarcane production regions but there has only been limited analysis of the emissions from the various regions.

9.5.2 Temporal

There is limited time series type data available for sugarcane production in Brazil, so temporal impacts on the GHG emissions are difficult to document. There are three factors that will lead to significantly different emission profiles over time.

1. The burning of sugarcane fields prior to harvest is being phased out through out countries. There are methane and N_2O emissions that result from the burning. These can be reduced but the alternative of leaving the trash in the field will lead to N_2O emissions as the trash decomposes and there can be methane generated if the trash decomposes anaerobically.
2. In conjunction with the phase out of burning, there is an increase in mechanical harvesting. This has increased fuel consumption compared to manual harvesting.
3. Historically, Brazilian sugar mills were not allowed to sell excess power back to the grid. The sugarcane bagasse still had to be disposed of, and as a result there was little incentive for the mills to be energy efficient. The restrictions on power sales are no longer in place and mills that are grid connected can now sell power back to the grid. New mills could have significant quantities of power available, perhaps as much as 1 kWh/litre of ethanol.

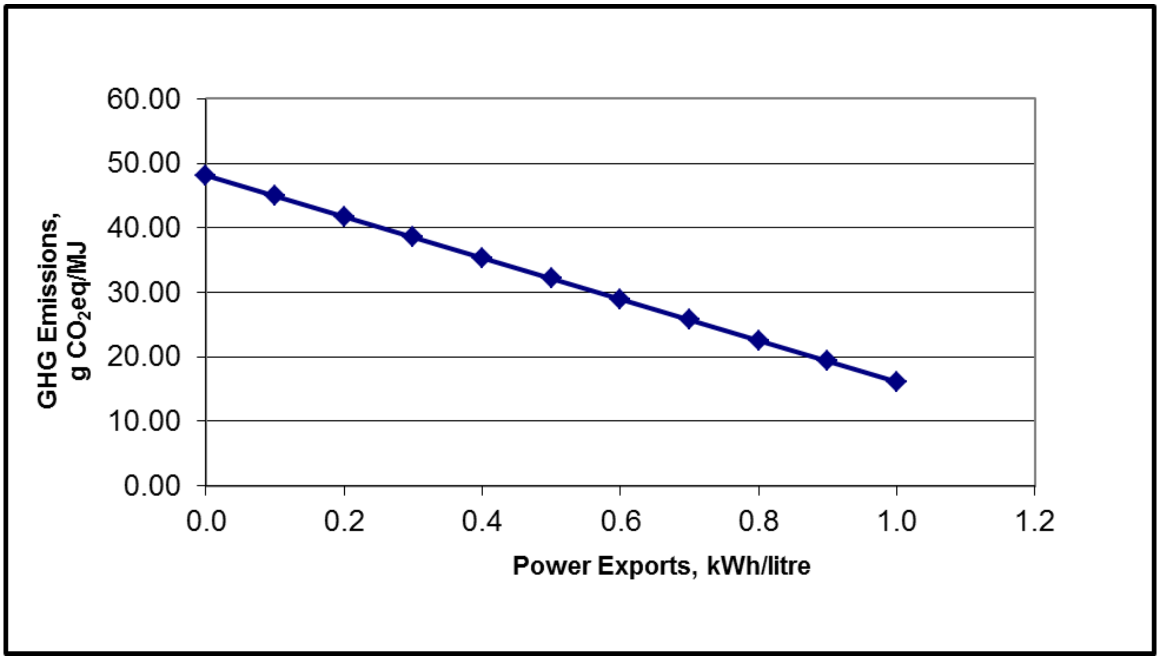
GHGenius has some information for both manual harvesting with burning and mechanical harvesting without burning. The results of the two scenarios are shown in the following table.

Table 9-17 Sugarcane Harvesting Scenarios

	Burned Fields, Manual Harvest	Unburned Fields, Mechanical Harvest
	g CO_2eq/MJ (LHV)	
Fuel dispensing	0.61	0.61
Fuel distribution and storage	10.42	10.42
Fuel production	5.81	5.81
Feedstock transmission	2.31	2.31
Feedstock recovery	4.49	7.58
Feedstock Upgrading	0.00	0.00
Land-use changes, cultivation	20.72	18.03
Fertilizer manufacture	4.90	4.98
Gas leaks and flares	0.00	0.00
CO_2, H_2S removed from NG	0.00	0.00
Emissions displaced	-4.26	-4.26
Total	45.01	45.48

The impact of power exports on the GHG emissions is shown in the following figure. This has a temporal aspect to it as new mills are built they will be more efficient and more mills are likely to be connected to the grid in the future. The high end of the range, at 1 kWh/litre represents the state of the art. This assumes that the marginal power displaced is a combined cycle natural gas facility.

Figure 9-32 Impact of Power Exports



9.5.3 Process/Design

The ethanol production process does not have significant GHG emissions, due to biomass being used for process heat, and the only aspect of the plant design that has variability is the amount of electric power that is exported. With a range of zero to 1 kWh/litre this can have a significant impact on the emissions of a single plant. The models all use different assumptions about power exports, either the quantity or the type of power displaced. This is summarized in the following table.

Table 9-18 Sugarcane Ethanol Power Summary

	BioGrace/ JEC	RFS2	GREET	GHGenius
			2012_rev2	
	g CO_2eq/MJ (LHV)			
Power exported, kWh/litre	0	0.45	0.55	0.13
Power Displaced CI	0	166	16.3	186
Co-product (power)	0.0	-13.29	-1.63	-4.26

9.5.4 Other

There is significant variability in the models with respect to system boundaries. For example, the process chemicals used in the ethanol production process are excluded in most models.

For sugarcane production, the largest variation is in the N_2O emissions and the methane emissions from burning. Some models do not appear to include the N_2O emissions associated with burning the trash. These emissions are compared in the following table.

Table 9-19 Sugarcane N_2O and Methane Emissions

	BioGrace	EPA	GREET	GHGenius
	g CO_2eq/MJ (LHV)			
N_2O	5.49	29.43	5.63	11.3
Methane	3.37	0.47	1.84	2.8
Oxidation of CO and VOC	-	0	4.49	-
Total	8.9	29.9	12.0	14.1

The fuel transportation emissions vary significantly between models as shown in the following table. The two low values are both derived from versions of GREET 1.8. The transportation assumptions in Brazil were a combination of pipeline and rail, whereas the other models all assume truck transportation, the actual model of transportation.

Table 9-20 Sugarcane Ethanol Summary

	BioGrace/ JEC	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
	g CO_2eq/MJ (LHV)				
Ethanol Distribution	8.16	2.71	9.09	3.5	11.04

9.5.5 Summary Sugarcane Ethanol

There are some large differences in the sugarcane ethanol results from the different models. Some are from different assumptions, such as the transportation scenarios and the carbon intensity of displaced power. There are also methodological issues with respect to the process chemicals used in the ethanol plant and perhaps the straw burning emissions.

Spatial and temporal variability are less clear due to a lack of data for the system.

9.6 CELLULOSIC ETHANOL

There is a very wide range in the emissions for this pathway. That is perhaps not too surprising given that there are no commercial operations and thus the data quality for this pathway is quite low. Nevertheless there are also some fundamental differences to what is included (or not included) in the models. The results are compared in the following table. CARB has only published a wood to ethanol pathway, whereas the other three models consider corn stover as the feedstock.

Table 9-21 Cellulosic Ethanol Summary

	RFS2	GREET		GHGenius
		2012_rev2	CA-GREET	
IPCC GWP	1995	2007	2007	2007
Feedstock	Stover	Stover	Wood	Stover
	g CO_2eq/MJ (LHV)			
Feedstock Production	0.34	10.32	4.44	10.52
Feedstock Transport	1.11	1.05	2.10	2.48
Ethanol Production	2.66	8.19	2.56	33.14
Co-Product Credit (Power)	-33.60	-17.11	-10.2	-15.84
Ethanol Distribution and storage	1.18	1.52	2.70	2.25
Total	-28.31	3.97	1.60	32.55

The three stages with significant variability are feedstock production, ethanol production, and the co-product credit. Unlike the more developed pathways there is little information available to establish any spatial or temporal variations with the systems and the modelling data. The variation is due to either assumptions about the process design or the system boundaries for the model.

9.6.1 Process/Design

The basic design for the corn stover ethanol process that is modelled in the three systems is basically the same process and all models rely on data from NREL. The largest difference between the designs is in the quantity of power produced and the carbon intensity of the power that is displaced by the exported power. This data is summarized in the following table.

Table 9-22 Cellulosic Ethanol Power Summary

	RFS2	GREET1_2012_rev2	GHGenius
	g CO_2eq/MJ (LHV)		
Power exported, kWh/litre	0.95	0.66	0.50
Power Displaced CI	208	150	183
Co-product (power)	33.6	17.1	15.8

9.6.2 Other

System boundary issues include a large increase in soil carbon sequestration in the RFS2 modelling framework. This does not occur in the GREET and GHGenius models and this one item accounts for essentially all of the differences in feedstock production emissions between the three corn stover models.

There are also large differences in the number of process chemicals that are used in the production process between the three models. The EPA RFS2 model includes no emissions from the chemicals that are required, even though the NREL analysis that the EPA work was based on included these chemicals. The GREET model includes emissions for enzymes and yeast only, and GHGenius includes enzymes, yeast and the major chemicals used in the process (caustic soda, ammonia, lime, sulphuric acid, glucose).

9.6.3 Cellulosic Ethanol Summary

There are no commercial operating plants for this pathway and thus all of the model parameters could be classed as uncertain. There are some significant variations in the methodology applied for this pathway as the system boundaries vary in the three models. As the system boundaries are expanded to include enzymes, yeast and other process chemicals, the GHG emissions for the pathway increase.

9.7 Soybean Biodiesel/Renewable Diesel

The soybean biodiesel results are summarized in the following table. There is a very wide range in the results. The BioGrace results are impacted by the transportation scenario selected. Soybeans are not a significant crop in Europe so the pathway was built using soybeans imported from Brazil and this adds significant emissions that are only partially offset by the soybean meal credit. All of the model results are impacted by the choice of co-product accounting use.

Table 9-23 Soybean Biodiesel Summary excluding ILUC

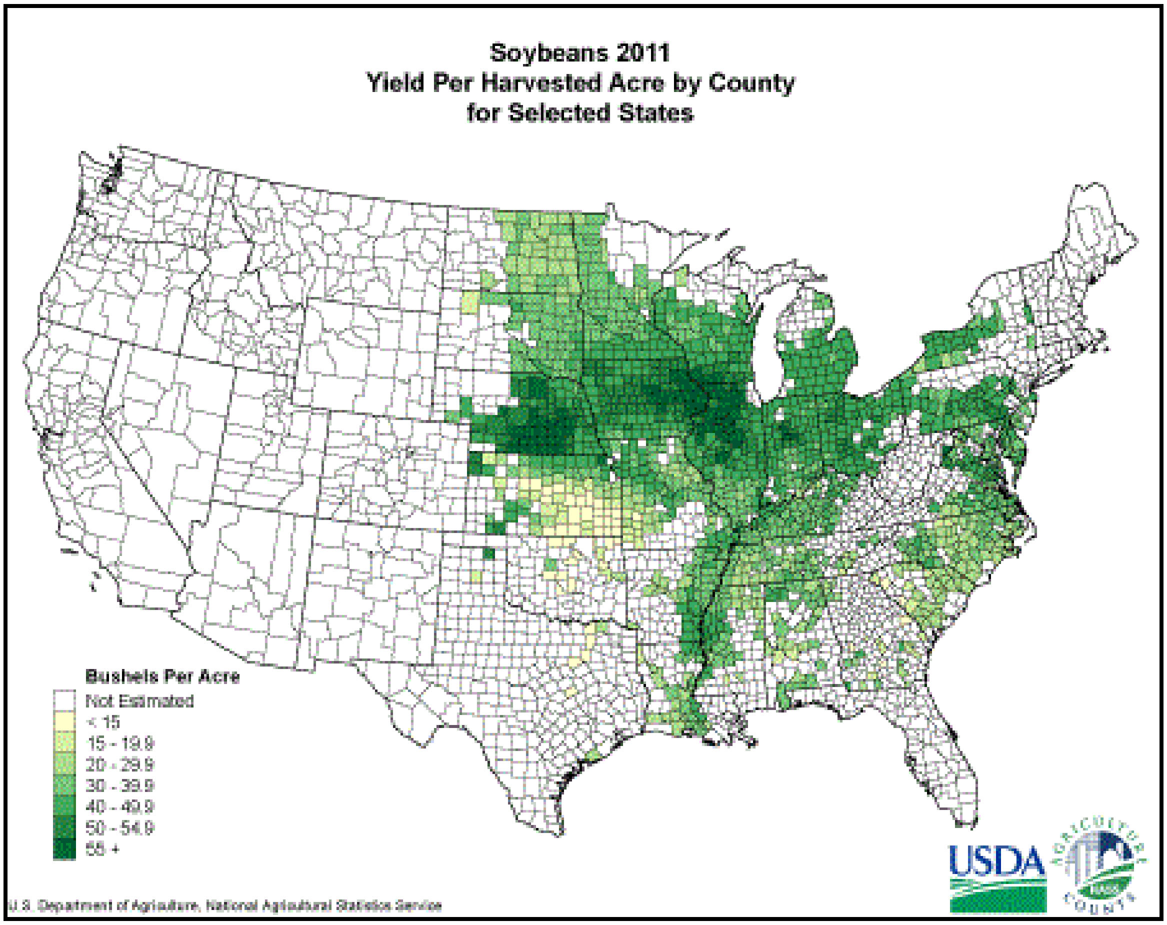
	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement	Energy	Mass/energy	Displacement
	g CO_2eq/MJ (LHV)				
Feedstock Production	56.21	-16.78	8.39	5.42	61.65
Feedstock Transport	35.95	2.52	1.19	0.50	2.20
Oilseed Crushing	17.24	-	22.74	20.53	19.21
Biodiesel Production	12.50	17.83	7.48	5.47	14.80
Co-products meal	-72.89	-	-13.55	-15.33	-46.53
Co-products glycerine	-0.58	-5.35	-4.45	-0.27	-17.69
Biodiesel Distribution	1.26	0.76	0.71	0.75	1.15
Total	49.69	-1.03	22.50	17.06	34.80

The soybean biodiesel system is subject to many of the same issues that were identified for corn ethanol and many of the same types of data sets that are available for corn and corn ethanol are available for soybeans and soybean biodiesel.

9.7.1 Spatial

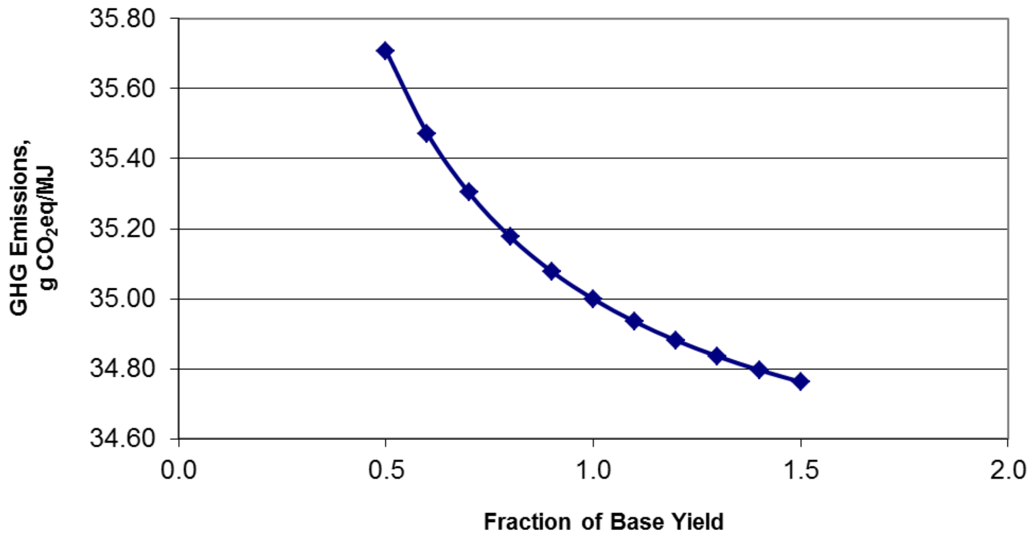
Soybean yields vary nationally and internationally. The 2011 US soybean yield by county is shown in the following figure. County yields of less than 20 bu/acre to over 55 bu/acre can be found. The national average yield was 41.9 bu/acre (2.8 tonnes/ha). Soybeans have relatively low inputs per unit of production since they fix their own nitrogen. The other fertilizer inputs will be scaled to the expected yield but like corn, the fuel and pesticide application rates will be mostly a function of area and thus will show some variation with yield.

Figure 9-33 Regional Soybean Yields



The following figure shows the impact of yield on the soybean biodiesel emissions. This is prepared using GHGenius and like the corn ethanol system, the impact is small.

Figure 9-34 Soybean Biodiesel GHG Emissions vs. Soybean Yield



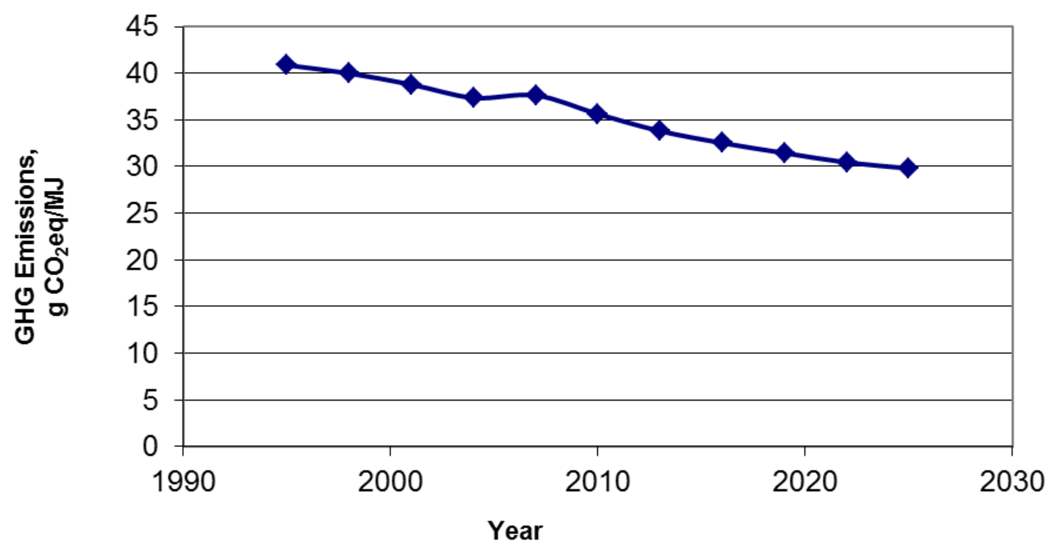
The same spatial issues with respect to N_2O emissions that were discussed in the corn ethanol pathway are applicable to the soybean biodiesel pathway.

With the low inputs of nitrogen fertilizer used to produce soybeans, the type of nitrogen fertilizer used is not a significant factor in the soybean lifecycle.

9.7.2 Temporal

As with corn ethanol, there are many issues that impact the performance of the soybean biodiesel pathway over time. The GHGenius results for this system for the time period 1995 to 2025 are shown in the following figure.

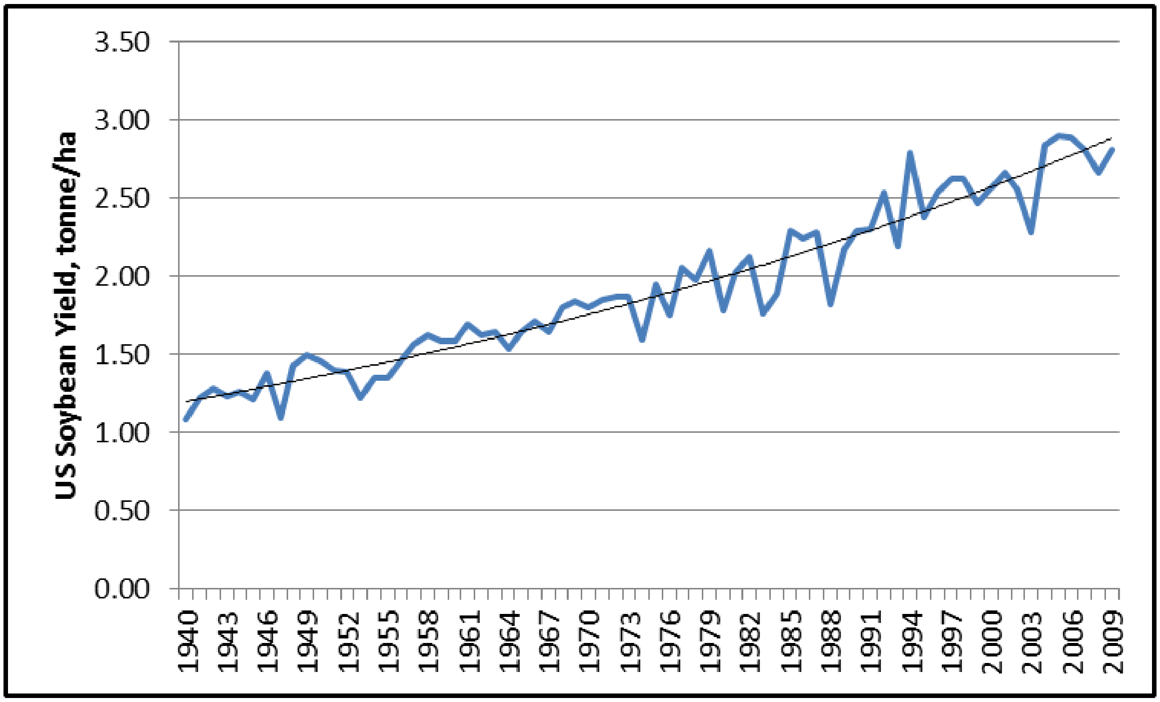
Figure 9-35 Soybean Biodiesel GHG Emissions vs. Time



9.7.2.1 Yield

The yield of soybeans produced in the United States has increased significantly over the years. This is shown in the following figure. It was shown earlier that this has only a small impact on the GHG emissions as many of the production inputs are scaled to the expected yield.

Figure 9-36 US Soybean Yield vs. Time

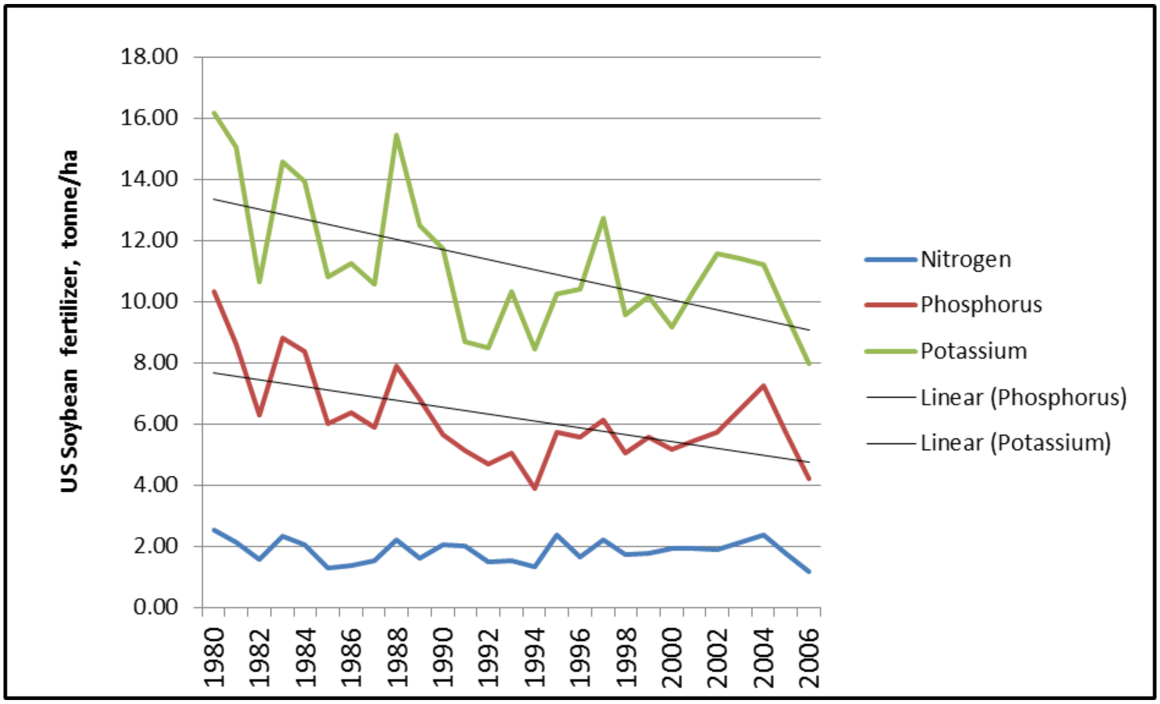


Source: USDA

9.7.2.2 Fertilizer Use

While soybeans fix their own nitrogen they still need the addition of phosphorus and potassium fertilizers for optimum production. The efficiency of fertilizer use has improved over time, particularly in the past 30 years, as shown in the following figure. A small amount of nitrogen is used to start the crop and this has stayed relatively constant over time but the P and K fertilizer rates per tonne of production have decreased over time.

Figure 9-37 Soybean Fertilizer Rates vs. Time



Source: USDA

9.7.3 Process/Design

No time series of information on the soybean crushing energy or the energy use for biodiesel production has been identified, so it is not possible to identify the impact of time on these two aspects of the production cycle.

9.7.3.1 Plant to Plant Variation

There is a significant amount of variation in the biodiesel technologies that are employed in North America. A number of vegetable oil biodiesel plants have shared operating information with $(S\&T)^2$ in the past several years. The variation in natural gas use, power requirements, and biodiesel yield are shown in the following figures. The variation in Carbon Intensity is not shown since the plants used different vegetable oils as feedstocks.

Figure 9-38 Variation in Natural Gas Use

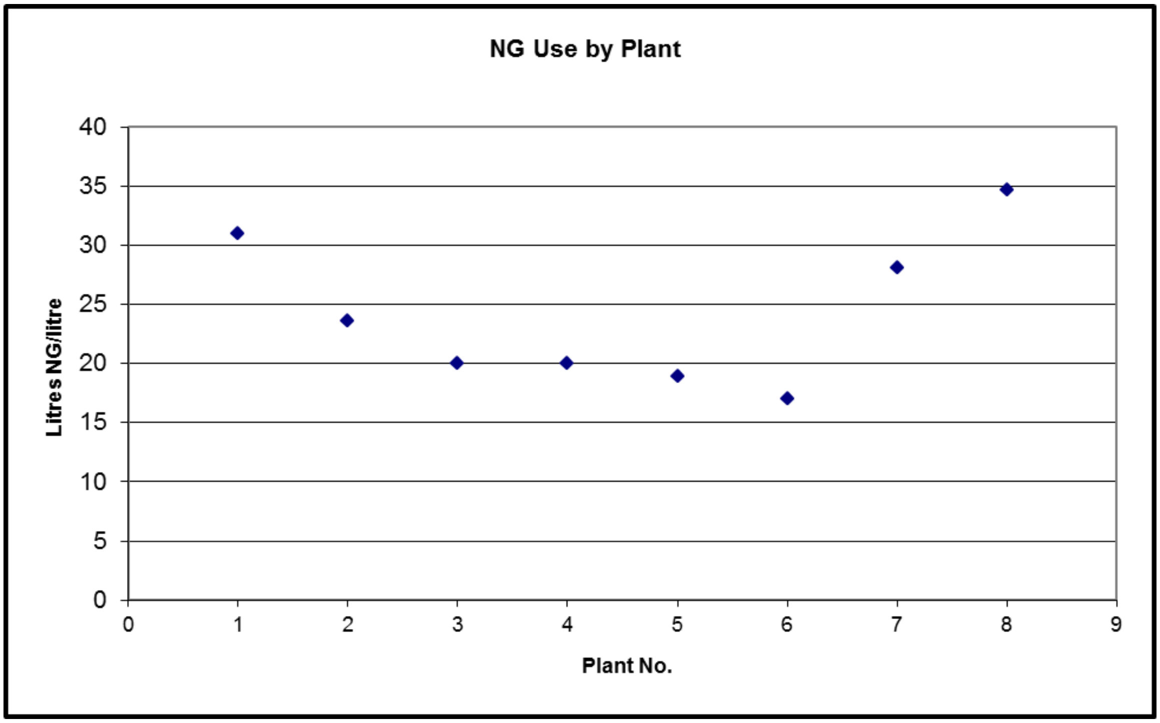


Figure 9-39 Variation in Power Use

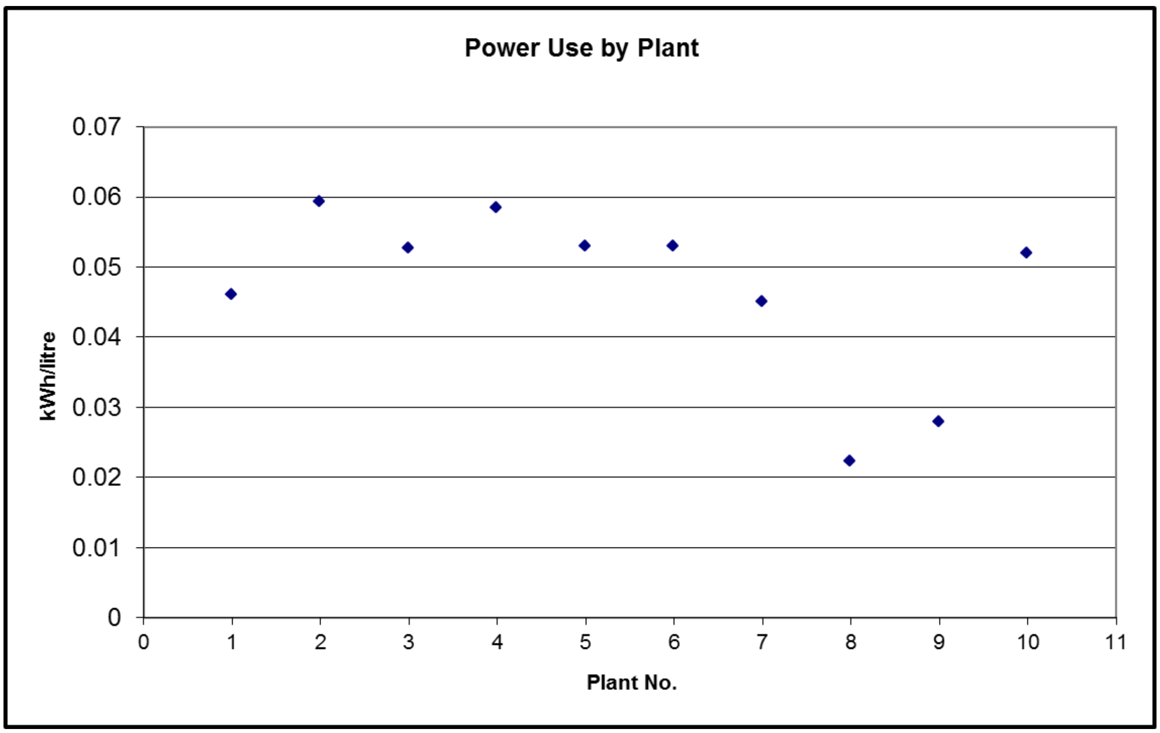
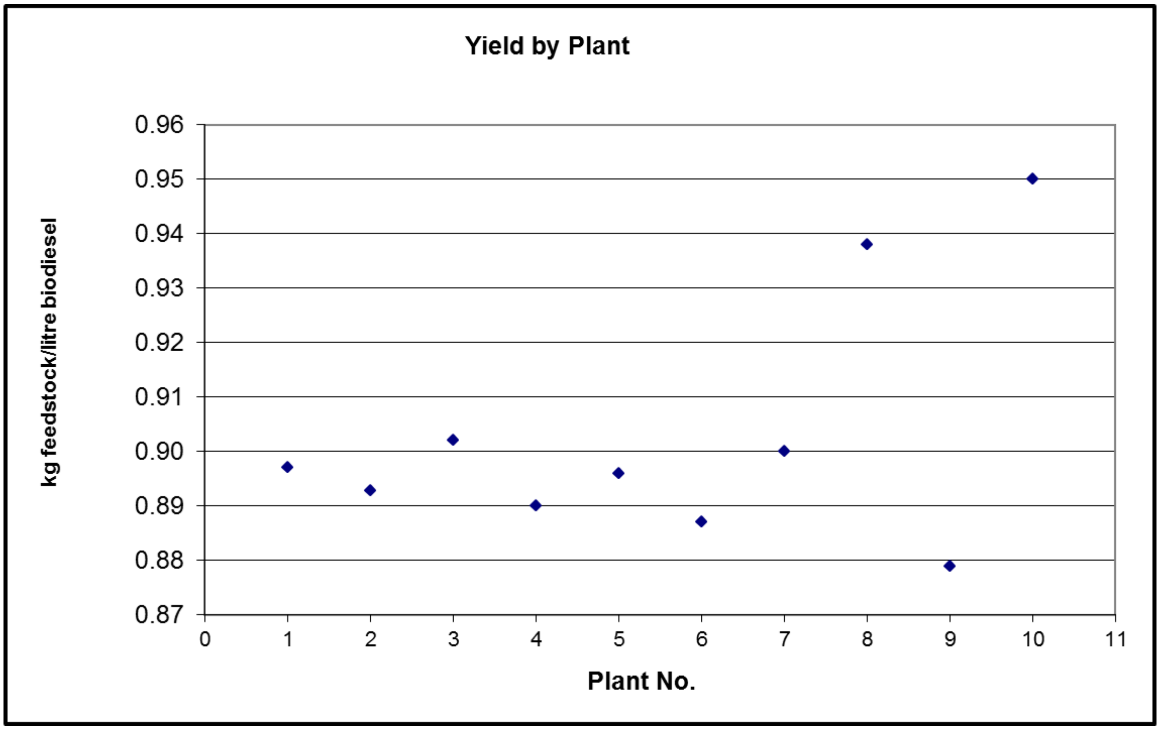


Figure 9-40 Variation in Feedstock Requirements



9.7.4 Other

There are two other modelling issues, system boundaries and co-products, that are common to most biofuel pathways but have even more importance in the biodiesel pathways. They are discussed below.

9.7.4.1 System Boundaries

A unique aspect of the biodiesel systems is that the product is produced by a reaction between a biogenic carbon source (fats or oils) and usually a fossil carbon source (methanol). The final product is mostly biogenic carbon but it has some fossil carbon in it. The co-product, glycerine, is built with biogenic carbon and it can replace products that are produced from either biogenic or fossil carbon. The difference in the system emissions can therefore be significant depending on whether the end of life of the co-product is included in the system boundaries or is excluded. Lifecycle basic principles would suggest that co-product end of life should be included in the analysis, but when one utilizes allocation by energy or mass, or some other allocation method, it is rare to see the end of life of the co-product then included in the analysis. Allocation, therefore, has a tendency to truncate the system boundaries.

The modelling systems that have been studied have treated the issue of the biogenic/ fossil carbon in the biodiesel system differently.

1. BioGrace. BioGrace includes the methanol end of life emissions in the biodiesel production process emissions. The glycerine receives a credit based on its energy content if technical grade glycerine is produced. End of life emissions of the bio

based glycerine vs. alternative fossil based glycerine is not considered in the modelling.

2. EPA RFS2. The glycerine credit in the EPA modelling is based on the displacement of heating oil. It assumes that the glycerine is biogenic but it also assumes that the biodiesel is 100% biogenic, thus the emissions from the oxidation of the fossil carbon in the methanol is not included in the analysis. However, the credit for the displacement of the heating oil is a very conservative estimate of the emissions displaced by all applications of glycerine.
3. GREET1_2012. The issue of the fossil carbon is not dealt with in GREET. The quantity of glycerine produced is also too high at 0.215 kg glycerine/kg of biodiesel, double the theoretical rate.
4. CA GREET. The fossil carbon emissions are modelled as part of the exhaust emissions of biodiesel as it is assumed that there is about 5% fossil carbon in the biodiesel. An energy allocation credit is provided for the glycerine and no end of life emissions or emissions credit is considered. The glycerine production rate is 0.105 kg/kg of biodiesel.
5. GHGenius. GHGenius assumes that the glycerine contains fossil carbon and the biodiesel contains the biogenic carbon. In the model the product can displace synthetic glycerine (containing fossil carbon), or feed or fuel. In all cases the end of life is considered and the appropriate credit is provided.

9.7.4.2 Co-product Allocation

The soybean biodiesel system has two allocation challenges, the oilseed crushing process produces oil and meal and thus all of the emissions up to that point must be accounted for in the environmental burden carried forward to the biodiesel step. At the biodiesel stage there is the glycerine co-product that must be addressed.

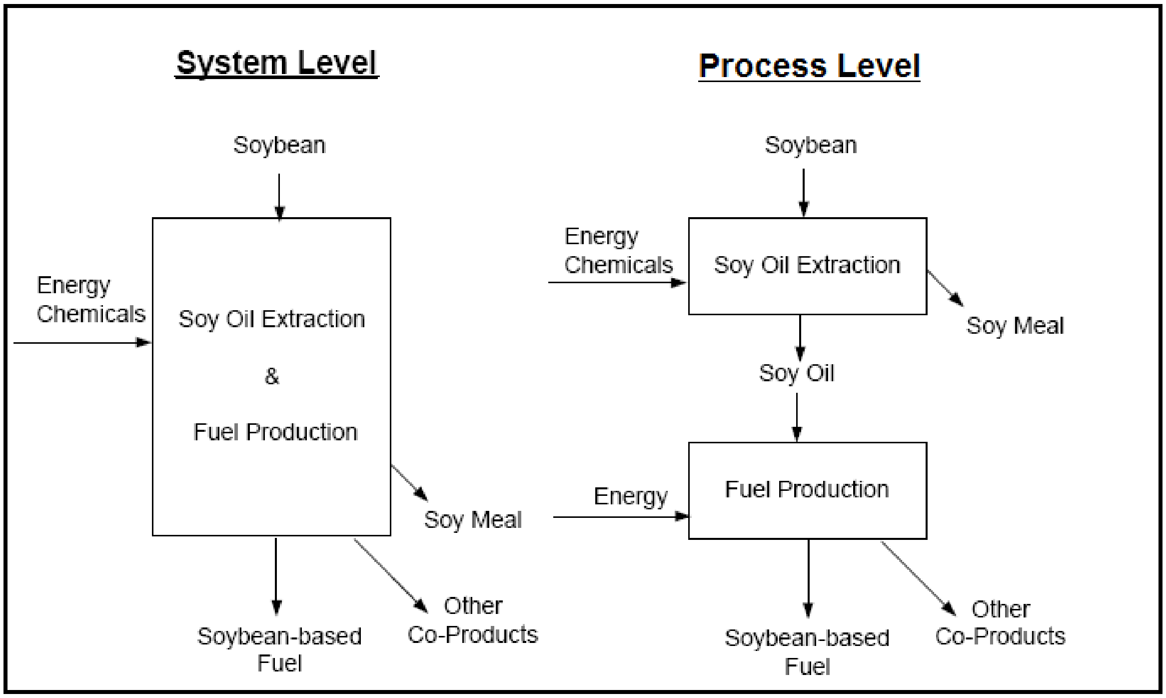
The models take different allocation approaches and report very different allocation results for the two co-products as shown in the following table.

Table 9-24 Soybean Biodiesel Co-Product Credit Allocation Summary

	BioGrace	RFS2	GREET		GHGenius
			2012_rev2	CA-GREET	
IPCC GWP	2001	1995	2007	2007	2007
Allocation	Energy	Displacement	Energy	Mass/energy	Displacement
	g CO_2eq/MJ (LHV)				
Co-products meal	-72.89	-	-13.55	-15.33	-46.53
Co-products glycerine	-0.58	-5.35	-4.45	-0.27	-17.69
Total	-73.47	-5.35	-18.00	-15.60	-64.22

GREET and GHGenius have the ability to use alternative methods of dealing with the co-products. In GREET there are also sub-options depending how the process is modelled and one example is shown in the following figure.

Figure 9-41 GREET Options for Allocation



Source: GREET

In the following table some of the GREET options are compared. In the first table, both process level and system level allocation schemes are shown.

Table 9-25 Alternative GREET Co-Product Approaches

Overall	Process Level Allocation/ Displacement	System Level Energy-Based Allocation	System Level Market Value-Based Allocation	System Level Mass-Based Allocation
Meal	Displacement	-	-	-
Glycerine	Energy	-	-	-
	g CO_2eq/MJ (LHV)			
Feedstock Production	18.78	8.39	10.20	4.10
Feedstock Transport	2.67	1.19	1.45	0.58
Oilseed Crushing	22.74	22.74	22.74	22.74
Biodiesel Production	7.48	7.48	7.48	7.48
Co-Product meal	-22.44	-13.55	-11.57	-18.25
Co-Product glycerine	-0.71	-4.45	-3.80	-6.00
Biodiesel Distribution and storage	0.71	0.71	0.71	0.71
Total	29.23	22.50	27.20	11.37

In the following table, just the process level approach schemes are shown, the impact of changing the approach for each of the co-products is shown.

Table 9-26 Alternative GREET Co-Product Approaches

Overall	Process Level Allocation/ Displacement			
Meal	Displacement	Energy	Market	Mass
Glycerine	Displacement	Energy	Energy	Energy
	g CO_2eq/MJ (LHV)			
Feedstock Production	20.76	8.07	8.79	4.00
Feedstock Transport	2.96	1.15	1.25	0.57
Oilseed Crushing	22.74	22.74	22.74	22.74
Biodiesel Production	7.48	7.48	7.48	7.48
Co-Product meal	-22.41	-13.49	-12.73	-17.79
Co-Product glycerine	-34.75	-0.71	-0.71	-0.71
Biodiesel Distribution and storage	0.71	0.71	0.71	0.71
Total	-2.51	25.93	27.52	16.98

The use of the displacement approach for glycerine has a very large impact on the results. The glycerine production method that is displaced is the Farben approach. This was the dominant glycerine production method until the large expansion in the biodiesel market in the past decade. The method involves the chlorination of propylene and is both energy and emission intensive.

GHGenius can apply the displacement approach, or mass or energy allocation to both of the co-products from the system. The results are shown in the following table. The glycerine has a large impact on the results.

Table 9-27 GHGenius Allocation Approaches

	Soybean Biodiesel			
Meal	Displacement	Energy	Mass	Mass
Glycerine	Displacement	Energy	Mass	Energy
	g CO_2eq/MJ (LHV)			
Feedstock Production	61.65	61.65	61.65	61.65
Feedstock Transport	2.20	2.20	2.20	2.20
Biodiesel Production	34.01	34.01	34.01	34.01
Co-product meal	-46.53	-60.34	-66.98	-66.98
Co-product glycerine	-17.69	-4.32	-9.03	-4.32
Biodiesel Distribution	1.15	1.15	1.15	1.15
Total	34.80	38.68	32.04	27.74

9.7.5 Summary Soybean Biodiesel

There is significant variability in the soybean biodiesel results from the models. While spatial and temporal issues exist for this pathway, the largest variation results from methodological issues. GREET has very low emissions for soybean production, the primary driver being very low N_2O emissions compared to BioGrace and GHGenius. This is a result of low residue nitrogen content assumptions.

The emission credit for glycerine varies widely as well. The energy allocation provides a small credit, as does the displacement of energy. Glycerine production by the Farben process is very energy and emission intensive, so if the biodiesel glycerine displaces Farben produced product there is a much larger co-product credit.

There is also a variation between the models on how the fossil carbon in the methanol is treated. The biodiesel production process sees methanol being added to the oil and biodiesel and glycerine being produced. The fossil carbon in the methanol ends up in the biodiesel and an equivalent amount of biogenic carbon from the oil ends up in the glycerine. In BioGrace the oxidation of the fossil carbon from methanol is included in the biodiesel production emissions, in CA GREET, the oxidation of the carbon is added to the vehicle emissions. In GHGenius it is assumed that the glycerine from the process displaced fossil glycerine and only the difference in the emissions is needed to be included.

9.8 Summary

The analysis of the variability of the six pathways has demonstrated how complex some of the systems are and how there can be real differences in the same system in different locations and how some aspects of the systems change over time.

All of the systems demonstrate spatial variability, particularly in the feedstock production stage of the lifecycle. In some cases this is due to factors out of the control of operators (climate, soil conditions, etc.) but in other cases there are opportunities to reduce the emissions from some regions, flaring of associated gas for example.

Many of the systems have temporal variability. In some cases this leads to increasing emissions, increasing energy use in crude oil production, and in other cases the emissions tend to decrease with time, better fertilizer utilization for example.

No two production facilities are identical and design differences that accommodate local conditions will lead to variability between two similar production facilities.

The different models also contribute to the variability in the results as they use data from different time periods, from different regions, and they have some different methodological approaches to co-products, and system boundaries.

10. ASSESSMENT OF UNCERTAINTY

Uncertainty is different from variability. Uncertainty results from a lack of knowledge about the parameters that characterize the physical system that is being modeled, and can arise from inaccurate measurements, and/or a lack of appropriate data. Sometimes the uncertainty can be reduced through access to better information but in other cases it may not be feasible to collect the quality of data that is required. Uncertainty can also result from natural randomness, for example the N_2O emissions from a field can vary from one year to the next due to different precipitation patterns.

While some have suggested that models introduce uncertainty as a result of different system boundaries or approaches to allocation, we have treated these issues as model variability issues and will focus on the data issues with respect to uncertainty.

Note that some parameters can be both variable and uncertain. Flaring rates for associated gas production and N_2O emission rates would be examples of parameters that are both spatially variable and uncertain.

ISO LCA standards define uncertainty as:

> **Uncertainty:** parameter associated with the result of quantification, which characterizes the dispersion of the values that could be reasonably attributed to the quantified amount
>
> - Uncertainty information typically specifies quantitative estimates of the likely dispersion of values and a qualitative description of the likely causes of the dispersion.

An uncertainty analysis takes a set of randomly chosen input values (which can include parameter values), passes them through a model to obtain the distributions (or statistical measures of the distributions) of the resulting outputs. The output distributions can be used to;

- describe the range of potential outputs of the system at some probability level
- estimate the probability that the output will exceed a specific threshold or performance measure target value.

Uncertainty analyses are often used to make general inferences, such as the following:

- estimating the mean and standard deviation of the outputs
- estimating the probability that the performance measure will exceed a specific threshold
- assigning a reliability level to a function of the outputs, for example, the range of function values that is likely to occur with some probability
- describing the likelihood of different potential outputs of the system
- estimating the relative impacts of input variable uncertainties.

Implicit in any uncertainty analysis are the assumptions that statistical distributions for the input values are correct and that the model is a sufficiently realistic description of the processes taking place in the system. Neither of these assumptions is likely to be entirely correct.

Thus an assessment of uncertainty should provide a quantitative estimate of the dispersion of values (the shape of the curve) and qualitative description of the uncertain parameters. This assessment is done by using Monte Carlo analyses. This requires analysts to identify the uncertain parameters, assess the uncertainty with respect to the mean value and its statistical distribution for each uncertain parameter, and then run the model thousands of times to get the statistical distribution of the model results. We have developed a special version of GHGenius that has the capability of considering up to seven input parameters and seven distributions (normal, lognormal, uniform, triangular, beta, exponential and Weibull) for each of the parameters. This process still relies on judgement with respect to the choice of uncertain parameters, the type of distribution to be applied, and the choice of the defining variables for the distribution.

The results from a Monte Carlo analysis provide information on the potential range of emissions from a system and the distribution of the results within the range. The main strength of using a Monte Carlo simulation is the ability to address the uncertainty of input parameters and to determine the impact of this uncertainty on the output or results. Monte Carlo simulation is well suited to computer solutions where multiple random numbers are generated (within user defined boundaries) that are used as input values and their impact on the results is determined.

Users can usually choose from a variety of distributions of input parameters such as uniform, normal or lognormal. The difference between the types of input distributions used and the distribution of the output results can provide significant information about the system. For example, if multiple inputs are modelled as uniform distributions but the results indicate a normal or lognormal distribution then the user should have added confidence in the mean value of the output data. Similarly, when modelling a single input one would expect that the output distribution will take a similar form to the input distribution, if it is a related value. Results that do not change would suggest that the input varied has no effect on the output results. Should the output look different than the distribution of the input variable, further study of the issue may be warranted.

The weakness of Monte Carlo simulations is mostly with how the results are interpreted by users. It must be remembered that inputs are generated with a random number generator (within the distribution selected), these inputs are used to calculate results, and thus the calculated results might only approximate the results of the real world. The results produced by Monte Carlo simulation are not exact. In many systems it will be found that modelling a series of inputs with different distributions will produce results with no apparent trend in the distribution. In these cases care must be taken to not place too much reliance on the results.

10.1 Primary vs. Secondary Data

Uncertainty is reduced when the quality of the data is high. The proposed ISO 14067 specification on developing and reporting on the carbon footprint of products or services requires the use of primary data where the data should be readily available (from the entity undertaking the carbon footprint study) and the use of secondary data for other aspects of the lifecycle where the party doing the study would not normally have access to the data.

In an ideal world, primary data would be available for all of the lifecycle but this is not currently the case. To fill the void of primary data, modellers use data from databases and published literature (secondary data) to undertake lifecycle assessments.

None of the six pathways studied here can be analyzed with just primary data and thus all of them rely on some secondary data, which probably is of lower quality and thus introduces uncertainty into the analysis.

10.2 Choice of Input Parameters

In most of the pathways there are a large number of input parameters in the models, but not all input parameters have a significant impact on the lifecycle emissions. For this work the focus has been on those input parameters that were identified in the pathway reviews that do have a large degree of uncertainty and have a significant impact on the emissions. Transportation distances, modes of transport, transport efficiencies, etc. are excluded as they are generally minor contributors to the total emissions.

In many cases there is insufficient data to formally assess the probability distribution function that is applicable to the parameter. Expert judgement has been used in those cases to choose the appropriate distribution function. The choice of the parameter and the distribution function is discussed for each pathway.

In some cases we are able to set the actual model value as the mean value for the Monte Carlo analysis but in other cases we modify the model so that a multiplier is used in the model. This new multiplier cell (the value is always 1.0) is added to the model equation and it is adjusted by the random number generator. This approach is used when multiple cells must be modified at the same time to achieve the desired result. For example when farm energy is varied, there may be diesel fuel, natural gas, LPG, and electricity that make up the farm energy use. All of these parameters are adjusted at the same time by the single multiplier.

In some cases we defined the standard deviation in terms of an actual value and in other times, particularly when multiplier cells are used, we define the standard deviation as a function of the mean.

10.3 PETROLEUM FUELS

The emissions from the production of petroleum fuels contribute 15 to 25% of the lifecycle emissions, with the remainder being from the combustion of the fuel. The combustion emissions are not nearly as variable as the production emissions since there are specifications that the fuels must meet and those specifications limit the variability of the composition of the fuels. There can be some regional differences due to different specifications and some differences due to the vehicle technology employed but these are generally small. The combustion emissions can vary with time as new regulations are imposed. The changes over time are related to the methane and nitrous oxide emissions, as the carbon dioxide emissions are generally determined by the fuel composition and not the engine performance, at least when the functional unit is a unit of energy.

Four areas where there has been some potential for significant uncertainty have been identified and are discussed below.

10.3.1 Crude Oil Production Energy Use

The extraction of crude oil requires some energy use, usually natural gas and electricity, but sometimes liquid petroleum fuels. The OGP reports both spatial and temporal variation in energy use, and these factors combined with the constantly changing trading patterns for crude oil contribute to uncertainty about how much energy is used to extract crude oil. At the field level, the OPGEE model also shows significant variation in energy use between fields.

We have assumed that the mean value is the value that is in GHGenius and that the uncertainty is best described by using a log normal distribution. A longer tail above the mode than below the mode characterizes this distribution. The standard deviation chosen is 50% of the mean.

10.3.2 Fugitive Emissions

Emissions from gas leaks and flares are a significant component of the GHG emissions in some regions. The estimates of the volume of gas flared are provided by satellite imagery but this can only estimate emissions that are combusted. Methane that is vented or not combusted cannot be identified by the satellites. There is also uncertainty with respect to the combustion efficiency.

For the volume of gas produced with the oil, a lognormal distribution is chosen, since it is more likely that the emissions are understated than overstated. The mean is set to the values in GHGenius and the standard deviation chosen is 5% of the mean.

For the flare combustion efficiency, a beta distribution is used. This distribution can be similar to a lognormal distribution, except that the long tail is to the left, instead of the right. The alpha value is set to the GHGenius default values. The beta is set to 2% of the alpha value.

10.3.3 Refining Energy

There is some refinery to refinery variation in energy use. This is driven by crude oil properties, refinery configuration and the product slate produced. We have used a normal distribution for this energy use. The mean value is the GHGenius default value. The standard deviation is set to 5% of the mean value. This will result in a fairly tight distribution of this parameter.

10.3.4 Still Gas Composition

The still gas can supply up to 50% of the energy used in the refinery. The composition of the gas and the emissions per unit of energy produced will vary from refinery to refinery. The mean value for the Monte Carlo analysis is the GHGenius default value and the standard deviation is 5% of the mean based on the information in Tables 9-4 and 9-5. A normal distribution is used.

10.3.5 Results

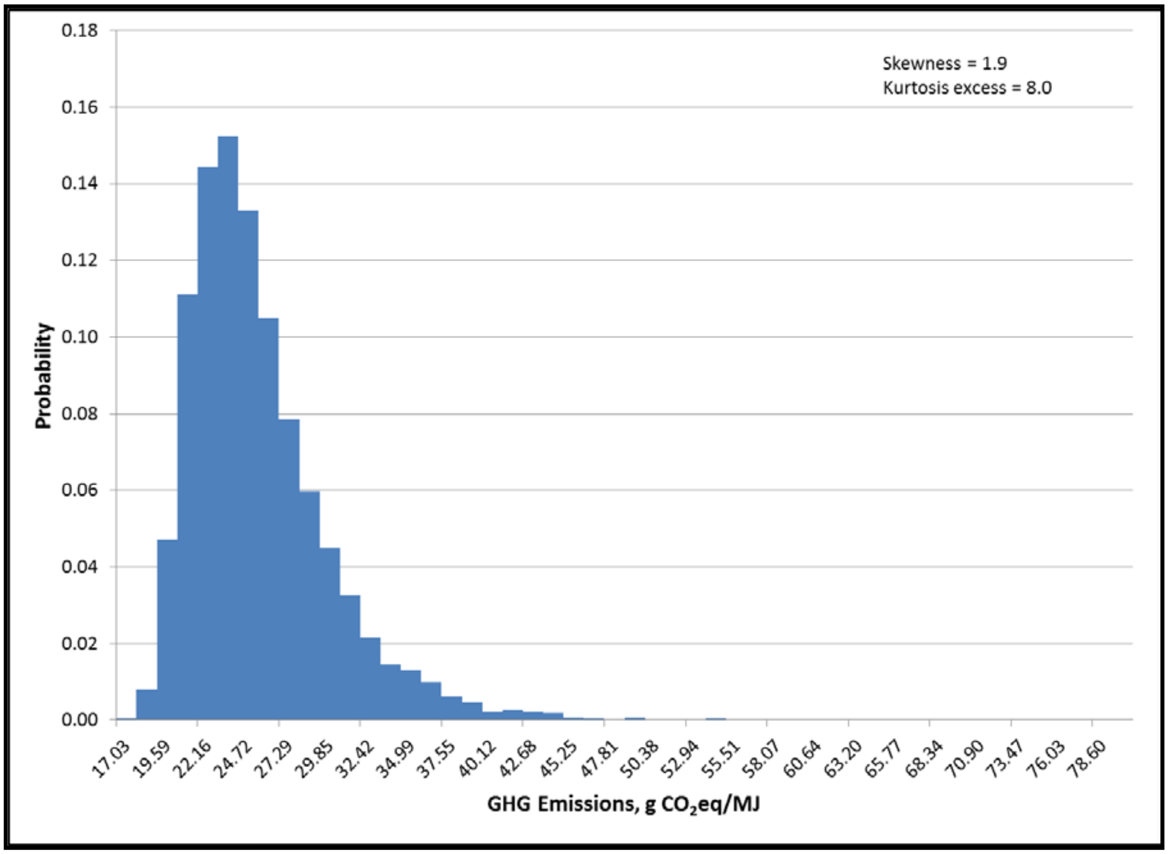
The Monte Carlo tool in GHGenius is set for 10,000 iterations in order to provide a reasonable distribution of the overall emissions.

Skewness and kurtosis are terms that describe the shape and symmetry of a distribution of scores. Skewness refers to whether the distribution is symmetrical with respect to its dispersion from the mean. If one side of the mean has extreme scores but the other does not, the distribution is said to be skewed. If the dispersion of scores on either side of the mean are roughly symmetrical (i.e. one is a mirror reflection of the other), the distribution is said to be not skewed.

Kurtosis or kurtosis excess refers to the weight of the tails of a distribution. Distributions where a large proportion of the scores are towards the extremes (low peak and large range) are said to be platykurtic. These are characterized by negative kurtosis. If, on the other hand, the scores are bunched up near the mean, the distribution is said to be leptokurtic (positive kurtosis). A normally distributed distribution of scores is said to be mesokurtic (zero kurtosis).

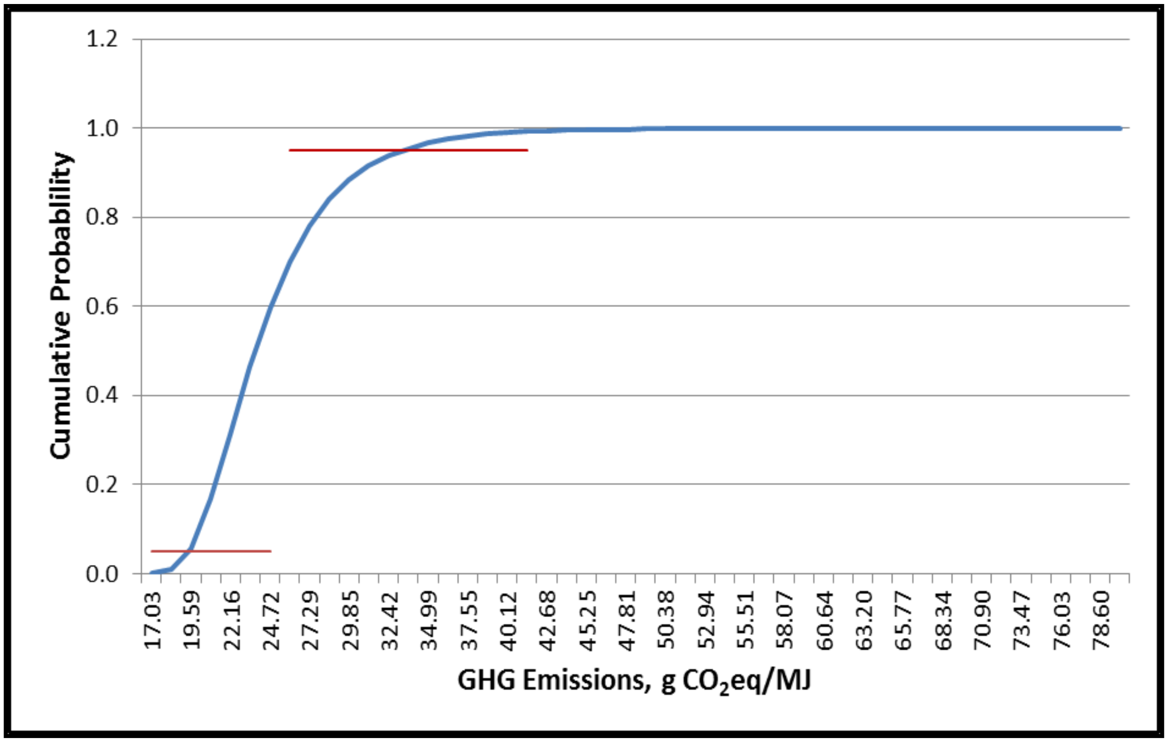
The results for the well to tank emissions (up to the nozzle) are shown in the following figure. The mean value is 26.0 g CO_2eq/MJ, the same as reported earlier for the GHGenius gasoline well to tank emissions. The high skewness and the positive kurtosis excess values indicate that it is not a normal distribution and that there is a long tail.

Figure 10-1 Gasoline Monte Carlo Results – Well to Tank



The data plotted in a cumulative distribution format is shown in the following figure. The 90% probability range (horizontal red lines) is from 19 to 33.7 g CO_2eq/MJ.

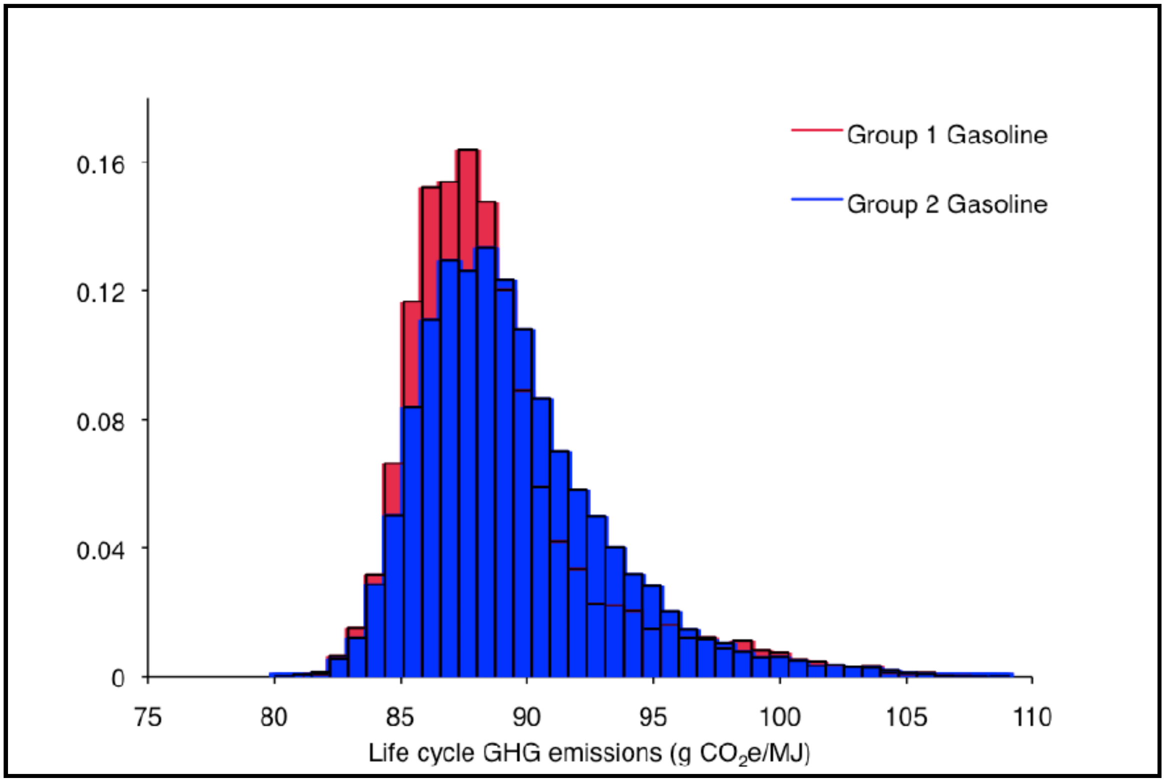
Figure 10-2 Cumulative GHG Emissions – Gasoline



Venkatesh et al (2011) reported on an uncertainty analysis of the GHG emissions of petroleum based fuels. They included the combustion emissions and used the IPCC mean, min and max emission factors for the combustion emissions and applied a triangular distribution to these. They note that there is a much smaller range for the combustion emissions than the other stages. They reported a mean of 18.3 g CO_2eq/MJ and the 90% probability range of 13.0 to 27.2 g CO_2eq/MJ. Their mean value is lower than GHGenius. They reported using data from a variety of sources including NETL, GaBi, and Ecoinvent. Their overall emissions were very close to the NETL results reported earlier.

Their distribution of gasoline emissions is shown in the following figure. The shape of the curve is very similar to the one generated here although it is slightly less skewed. The 90% probability range is the same as determined by this work; it is just shifted by the difference in the means.

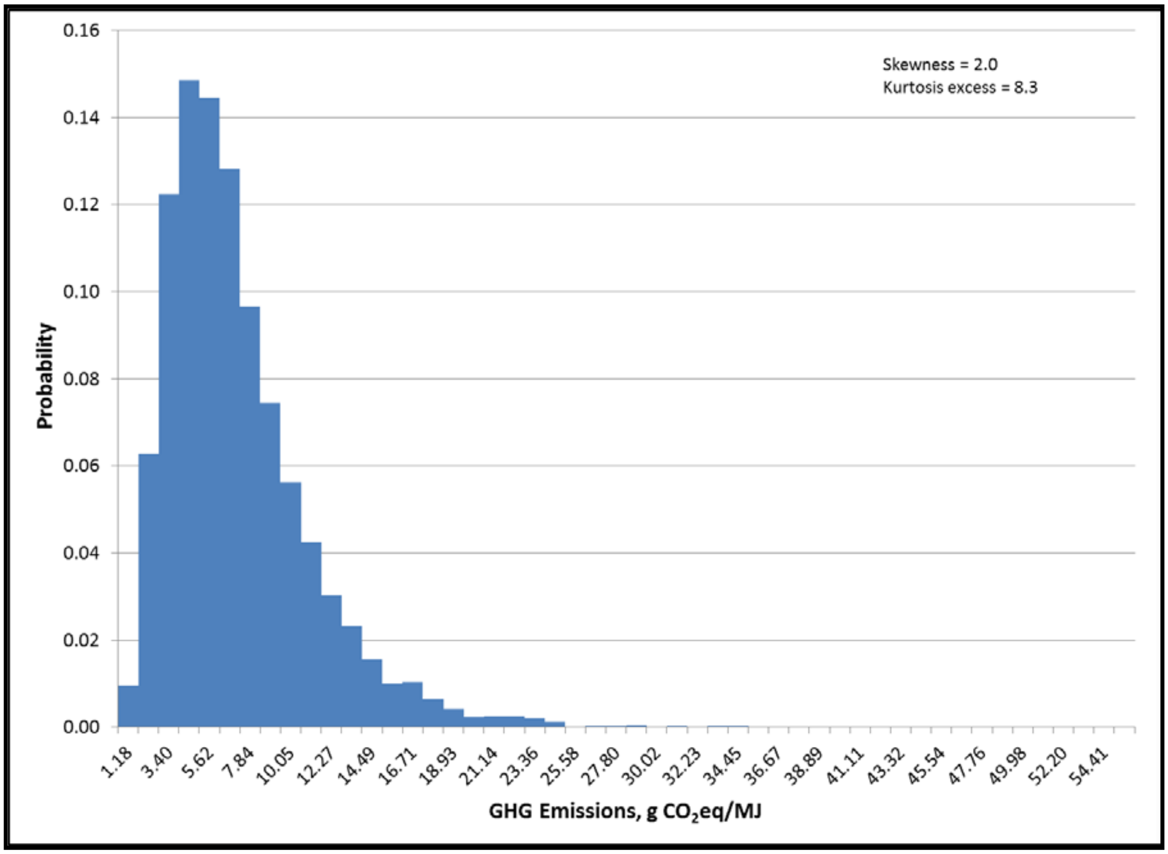
Figure 10-3 Venkatesh et al MC Results



10.3.5.1 Feedstock Production

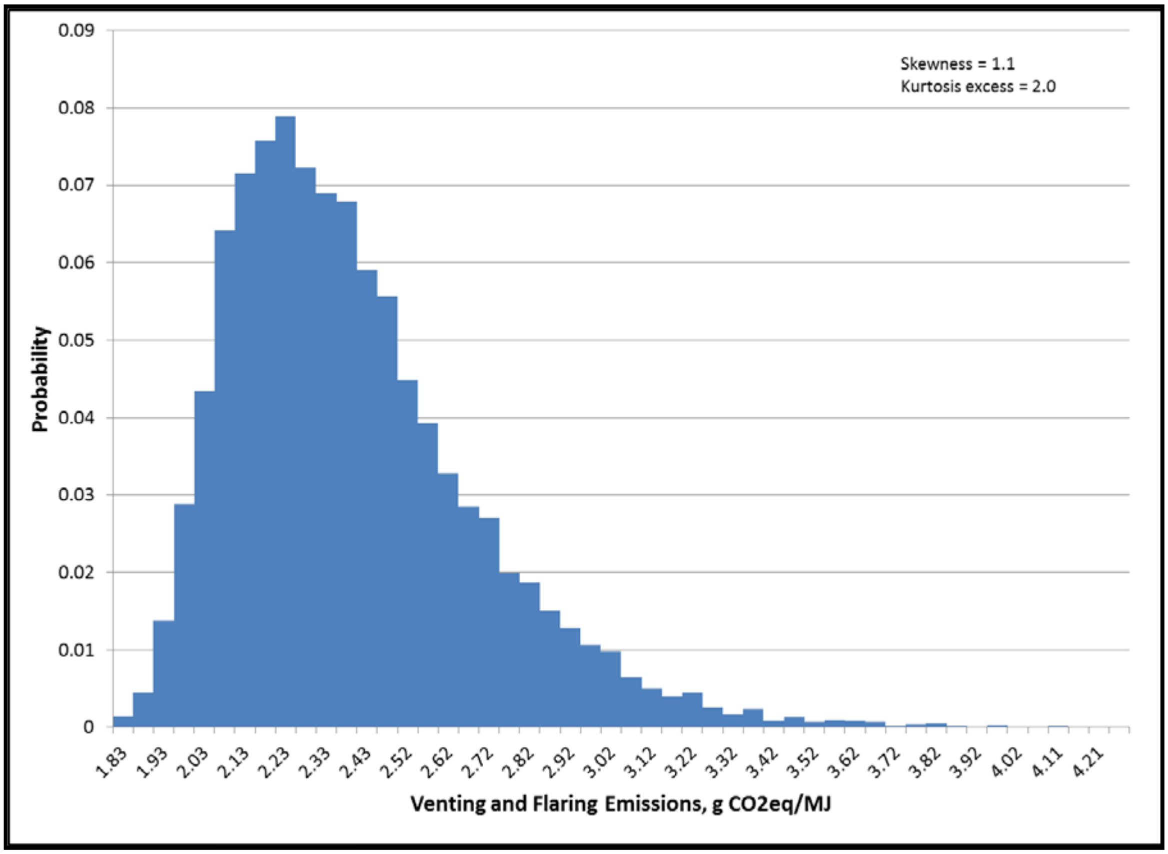
The uncertainties that are modelled deal with both the feedstock production and the refining. In the feedstock production stage the energy related emissions are reported separately from the venting and flaring emissions, so these two aspects can be looked at independently. The following figure shows the MC results for the energy used in crude oil extraction. The mean value for this stage is 7.7 g CO_2eq/MJ. These results are skewed with a long tail (high positive kurtosis).

Figure 10-4 Crude Production Energy MC Results



The Monte Carlo results for the venting and flaring emissions are shown in the following figure. These results are the result of two variables changing, one with a log normal distribution (gas volume) and one with a beta distribution (methane destruction rate). The different distributions partially offset each other and the results have less skewness and kurtosis than the energy results shown in the previous figure.

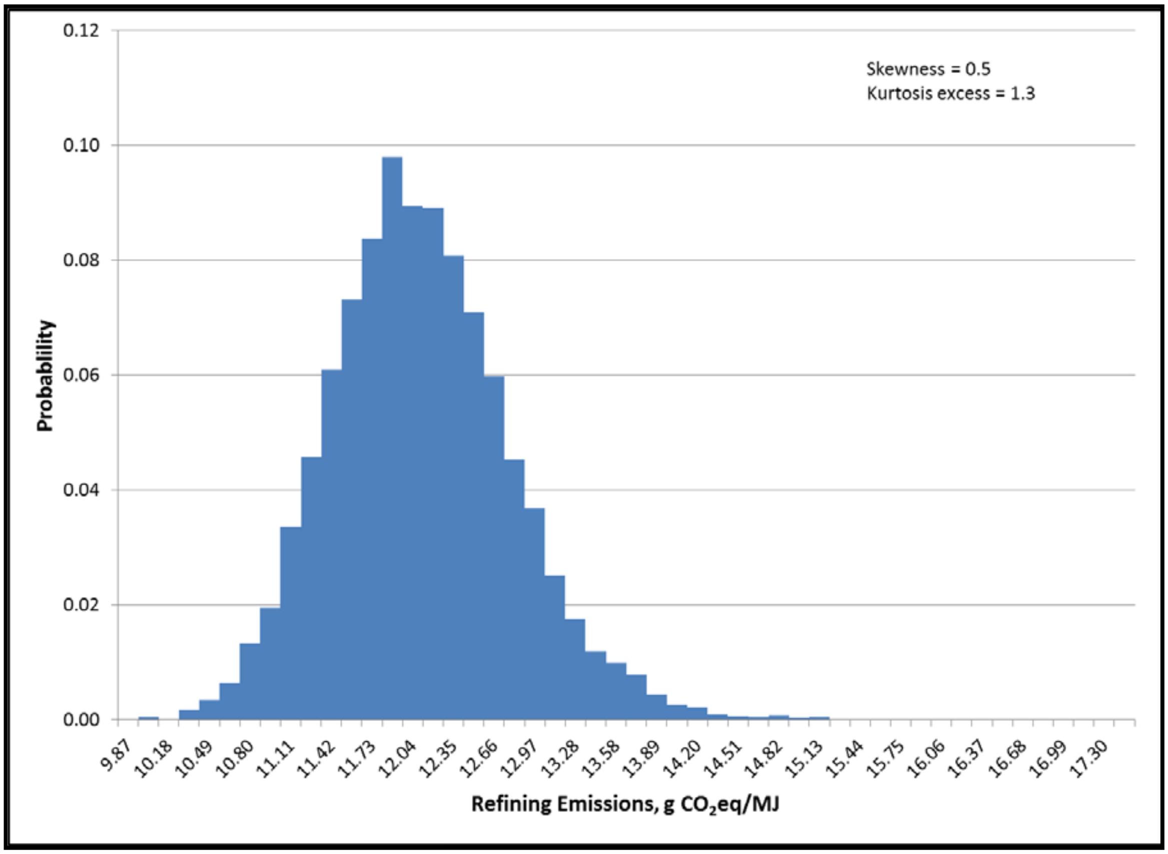
Figure 10-5 Venting and Flaring MC Results



10.3.5.2 Fuel Production

There are two variables that have been subject to the Monte Carlo analysis in the refining stage, the refinery energy use and the carbon intensity of the still gas that supplies a large portion of the refinery energy. A normal distribution was used for both variables with a relatively small standard variation of 5% of the mean. The results are shown in the following figure. The mean value is 12.2 g CO_2eq/MJ. There is less skewness due to the assumption of a normal distribution for both of the variable parameters.

Figure 10-6 MC Results Refinery Emissions



10.4 Natural Gas

There were only GREET and GHGenius with true natural gas pathways. The BioGrace and RFS2 models have GHG emission factors for natural gas but not full pathways. The primary difference in the emission factors and the model results is the methane emissions from the system. The early models (GREET 1.8 (CARB and EPA) and BioGrace) use a relatively low factor for methane emissions, whereas GREET1_2012 and GHGenius rely on methane emission rates from the 1990-2010 EPA National GHG Inventory for the United States[20].

Other differences between GHGenius and GREET include the energy used for compression of the gas in CNG systems. GHGenius also has a heavy-duty vehicle NG pathway, which isn't in GREET. There can be differences in the relative engine efficiencies between natural gas and diesel fuel for different engine manufacturers.

The Monte Carlo analysis is run just for these three parameters. The modelling parameters are discussed below.

[20] The methane emission rates in the 1990-2011 National GHG Inventory Report have been significantly reduced.

10.4.1 Fugitive Emissions

The factor with the largest impact on the results and the greatest uncertainty is the methane emissions in the form of venting, flaring, and fugitive emissions. This has been modelled with a lognormal distribution and a standard deviation of 30% of the mean value. These are applied to the base value in GHGenius.

10.4.2 CNG Compression Energy

The energy required to compress the natural gas depends on the inlet and outlet pressures, and the compressor design. GREET and GHGenius have different assumptions for both pressures and different compressor efficiencies.

There is no data available on the energy requirements for compressors. It is likely that there are a number of efficient stations and a fewer number of less efficient stations. We have therefore selected a lognormal distribution for this factor. Using a standard deviation of 30% of the mean produces a minimum value of 30% of the mean and a maximum value of 2.9 times the mean.

10.4.3 Engine Efficiency

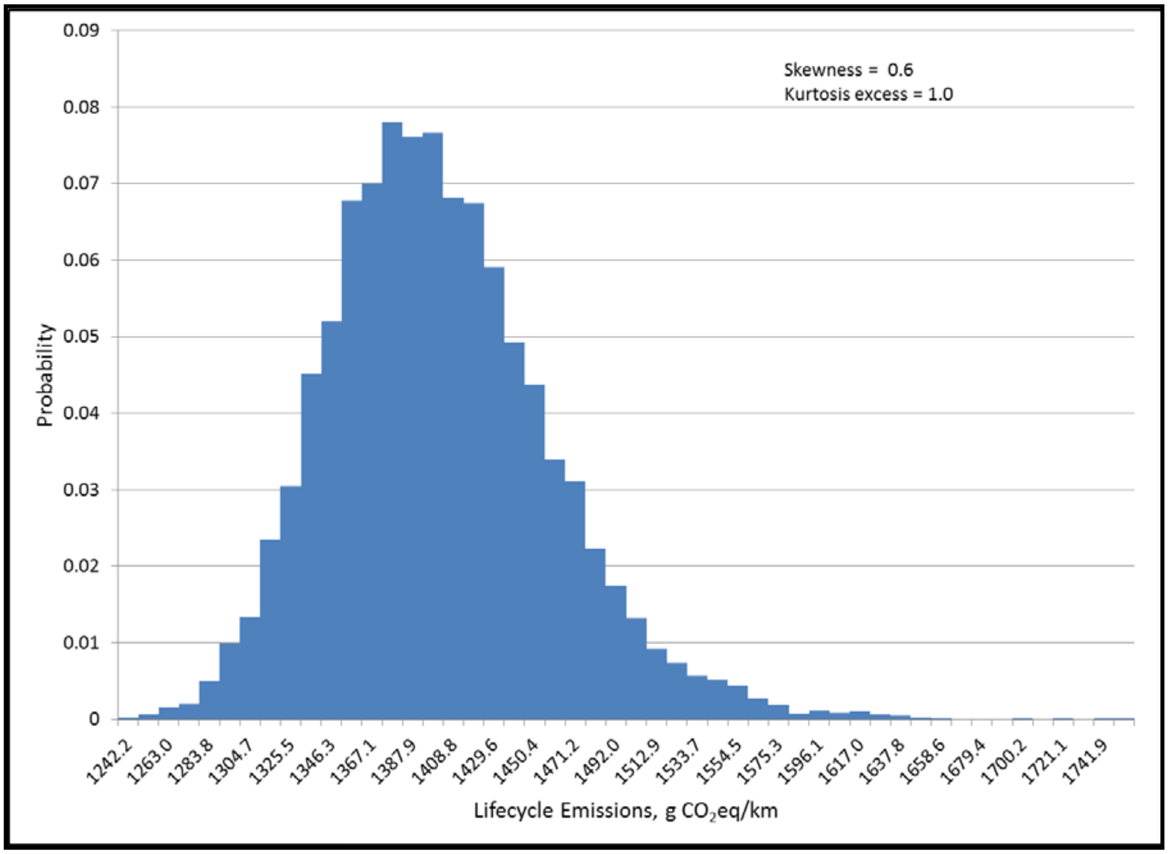
The engine efficiency for heavy-duty natural gas engines in GHGenius is based on the recent Cummins Westport engines certification tests. The actual relative efficiency for engines from other manufacturers could be different and real world load profiles could result in different values.

Very little data is available on the parameter, a lognormal distribution is used again. The mean value is a relative efficiency of 86%. The standard deviation that has been chosen is 2% of the mean. This produces a minimum value of 80% relative efficiency and a maximum value of 92% relative efficiency, which seems reasonable.

10.4.4 Results

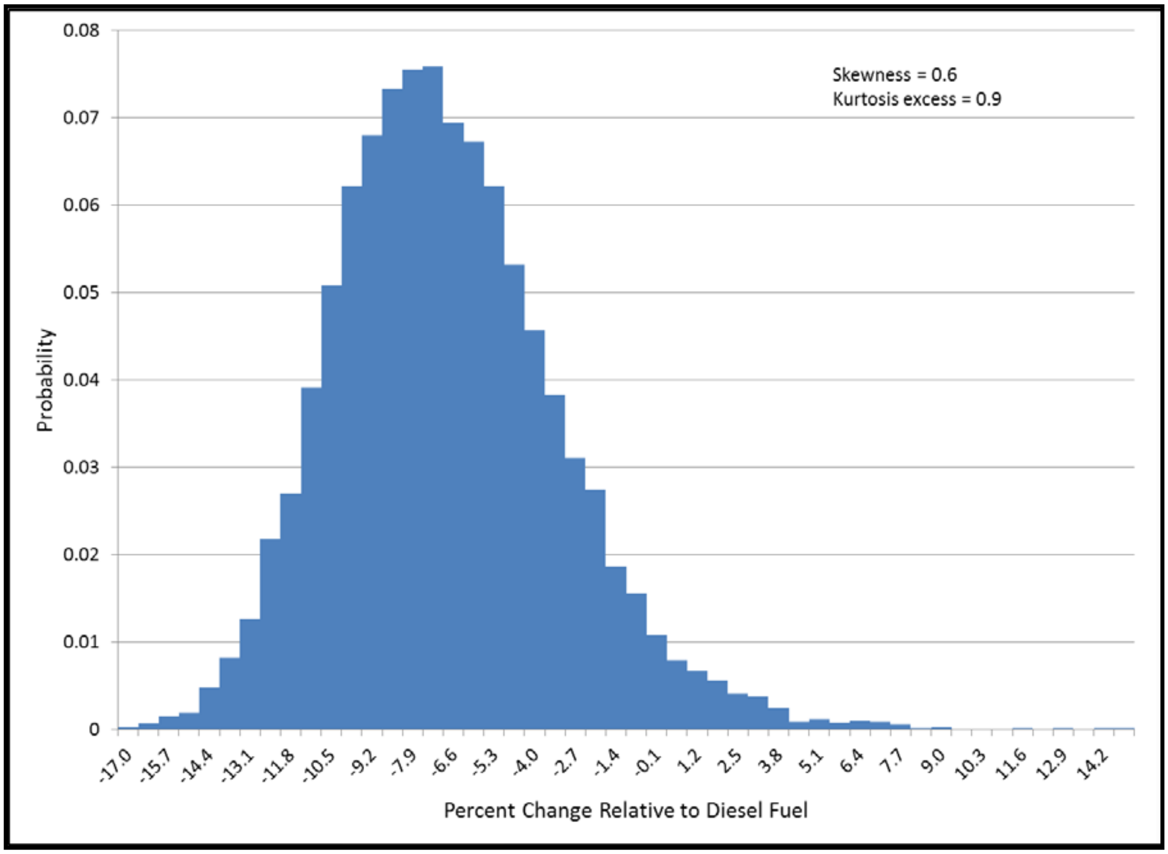
The lifecycle results from a 10,000 iteration Monte Carlo simulation are shown in the following figure. The function unit is a kilometre of travel since the vehicle is included in this system. The results are only slightly skewed.

Figure 10-7 NG Monte Carlo Results



The mean represents a 6.5% reduction in GHG emissions relative to diesel fuel. In the following figure the distribution of the emissions relative to the mean diesel engine are shown. 96.3% of the results show a reduction in GHG emissions compared to the diesel fuel mean.

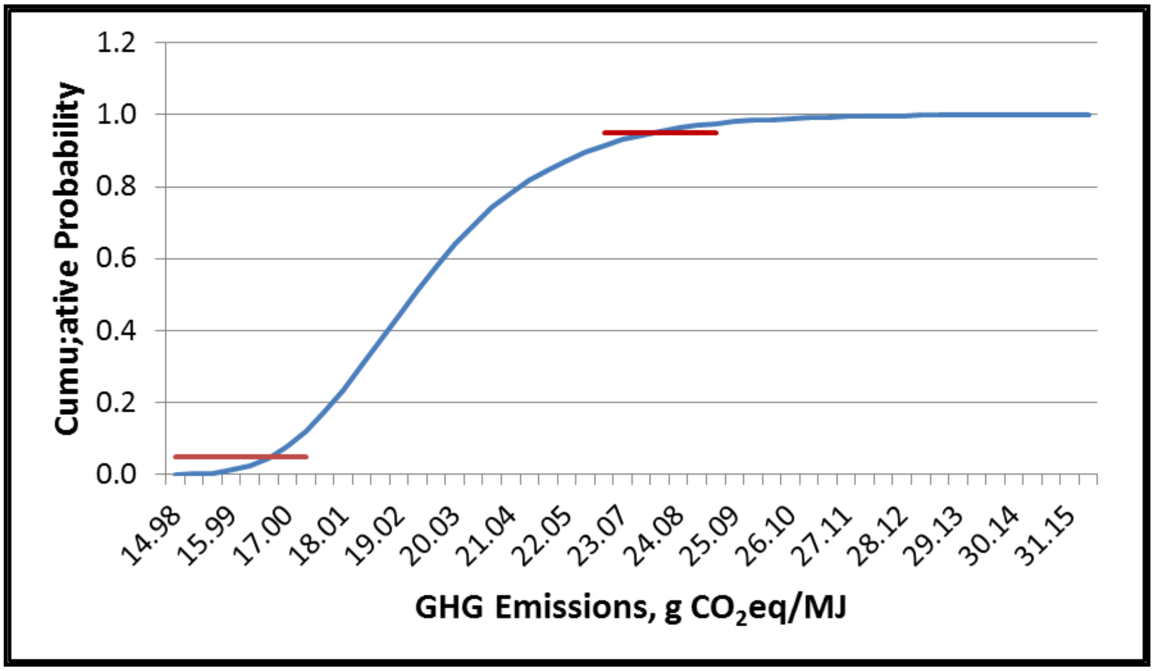
Figure 10-8 Emission Reduction MC Results



10.4.4.1 Natural Gas Production and Transmission

There was only one variable that impacted the emissions up to the point of compression and a lognormal distribution was used for that parameter. The distribution of the results is shown in the following figure. There is a 90% probability that the results are between 16.7 and 23.6 g CO_2eq/MJ. There is a range of 6.9 CO_2eq/MJ between the 5% and the 95% probability.

Figure 10-9   Distribution of Well to Tank Emission Results



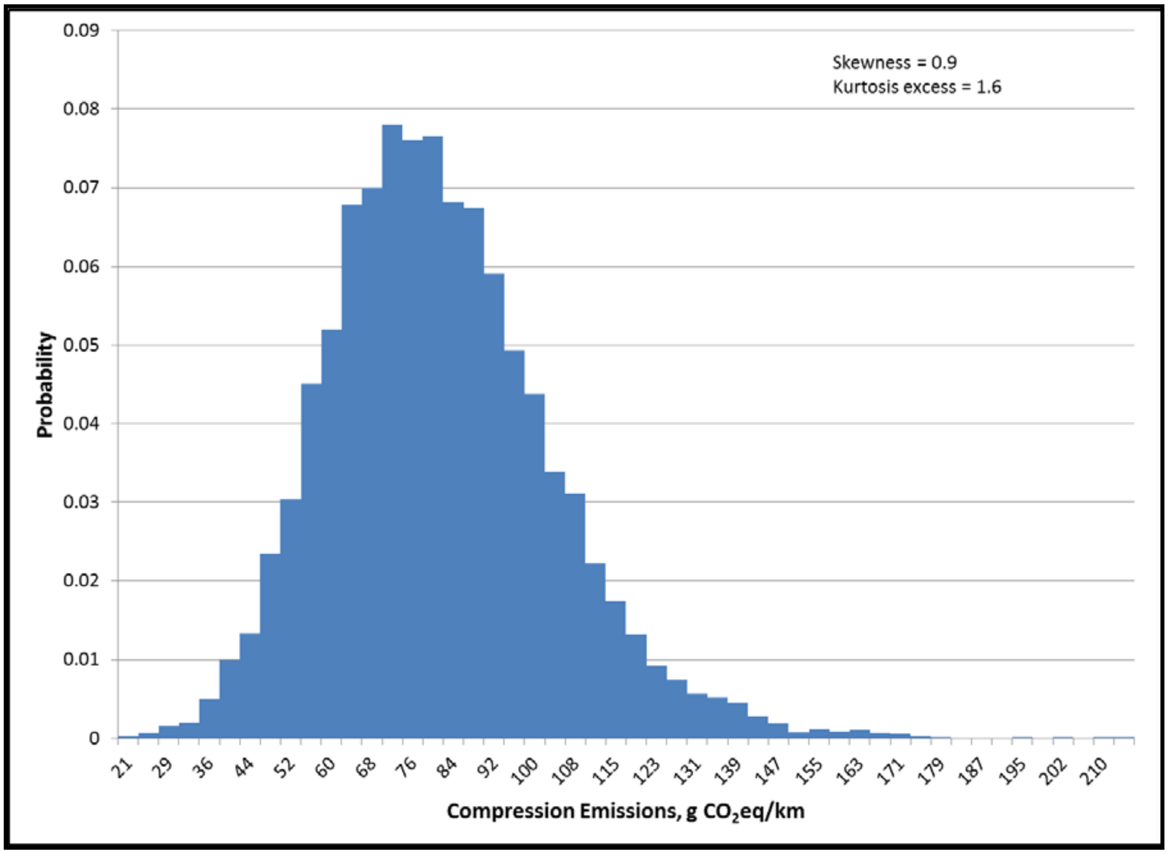
Venkatesh et al (2011b) also studied the uncertainty in natural gas systems. While they reported a mean upstream value of 16 g CO_2eq/MJ, they found that the 90% probability range was also 7 g CO_2eq/MJ. The transmission and distribution emissions were lower in their work and the difference accounts for most of the difference in the results.

They applied probability distributions to 17 parameters in the well to tank fuel cycle. They used triangular, exponential, uniform, discrete, normal, and lognormal distributions to the 17 parameters and yet their results, in terms of the distribution of the results, are essentially the same as derived here with the single important variable.

10.4.4.2 Compression Energy

The Monte Carlo results for the compression emissions at the CNG service station are shown in the following figure. The results reflect the lognormal distribution applied to this parameter. These emissions represent from 1.5 to 4.5% of the lifecycle emissions for the production and use of CNG in a heavy-duty vehicle.

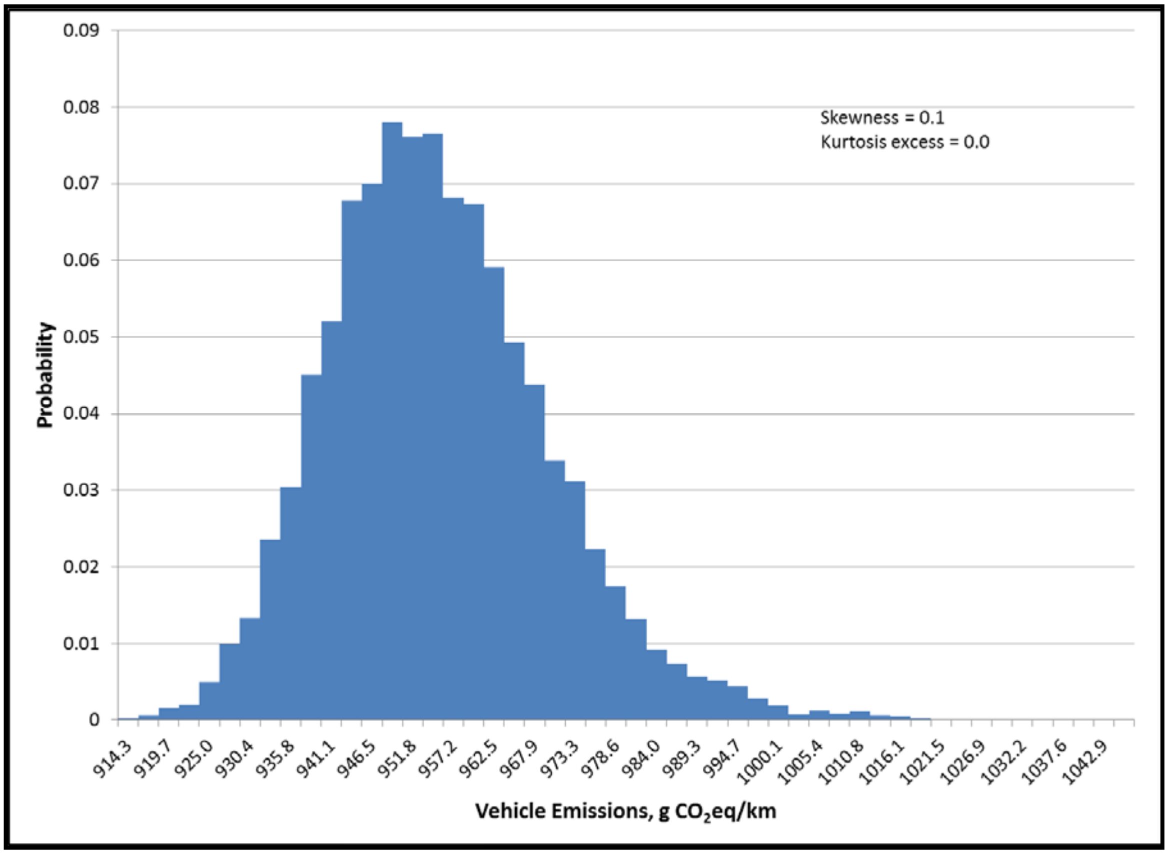
Figure 10-10   MC Results Compression Energy



10.4.4.3 Vehicle Emissions

An uncertainty distribution was applied to the relative efficiency of the natural gas engine to the diesel engine. The mean value was 0.86 and a lognormal distribution was applied. This results in emissions of 977 g CO_2eq/km of travel. The model results for the engine emissions are shown in the following figure.

Figure 10-11 Vehicle Emissions MC Results



10.5 CORN ETHANOL

There is a considerable amount of information available on some aspects of the ethanol production lifecycle but other aspects have significant amounts of uncertainty. This is due in part to spatial variation in some of the important parameters such as N_2O emission rates. Six parameters have been chosen for the uncertainty analysis. Most of them have a significant contribution to the lifecycle emissions. The parameters and the distributions assigned to each of them are discussed below.

10.5.1 N_2O Emissions

N_2O emissions are a significant part of the lifecycle of most biomass production systems. As was shown earlier there is significant spatial variability due to soil and climate conditions. The IPCC default value for the emission factor for direct emissions from fertilizer and crop residues is 0.01, but they identify a low end of the range of 0.003 and a high end of 0.03. This distribution is skewed so we have applied a lognormal distribution to the parameter. The mean value is the 0.015 default value in GHGenius and the standard deviation that has been chosen is 15% of the mean value.

This emission factor will have an impact not only on the emissions for producing corn, but also on the magnitude of the co-product credit as DDG is assumed to replace corn and soybeans in livestock rations.

10.5.2 Nitrogen Fertilizer Rates

Just as the N_2O emission factor is important, the rate of nitrogen applied to the fields is also an important driver in the overall emissions. The nitrogen rate will influence the N_2O emissions and is directly proportional to the emissions for producing fertilizer.

We have chosen a lognormal distribution for the Monte Carlo analysis. The mean value is set to the nitrogen default value in GHGenius and the standard deviation is set to 20% of the mean value.

10.5.3 Nitrogen Production GHG Emissions

It was shown earlier that different types of nitrogen fertilizer have different emissions per tonne of nitrogen. There also appears to be some regional variation in the efficiency of nitrogen production facilities and there will be some plant to plant variation. We have applied a lognormal distribution to this parameter with the mean value set to the GHGenius default and the standard deviation set to 15% of the mean value.

10.5.4 Field Energy Use

The direct energy use for corn production is derived from USDA surveys that are undertaken every five years or so. There will be a large range of production practices that are included in the survey and there will be a range of energy consumption. We have used a normal distribution for this parameter. The mean is the default values in GHGenius and the standard deviation is 15% of the mean. All types of energy are adjusted at the same time with the same relative value.

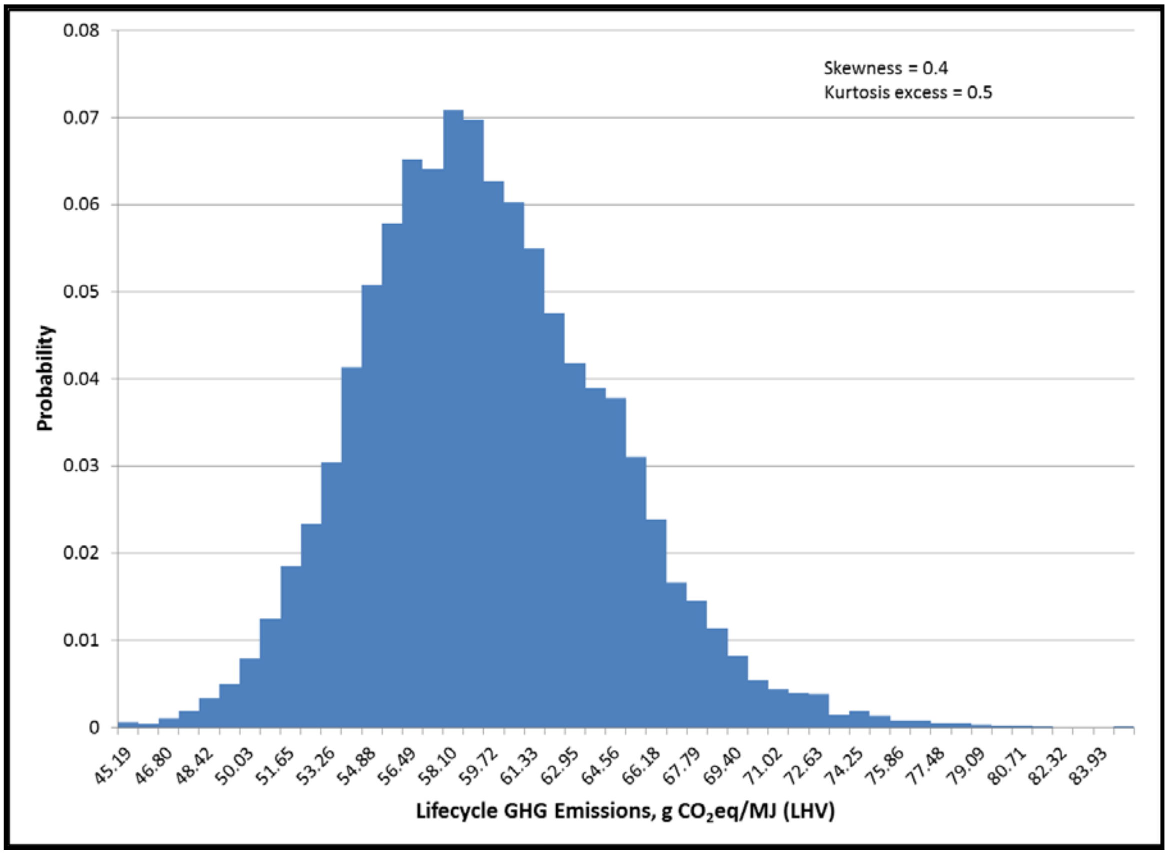
10.5.5 Ethanol Plant Energy Use

Ethanol plants use natural gas and electricity for the energy. For both of these parameters we have selected a lognormal distribution with the mean set to the default value in GHGenius. The standard deviation for the gas is set to 10% of the mean and for the electricity it is 15% of the mean.

10.5.6 Results

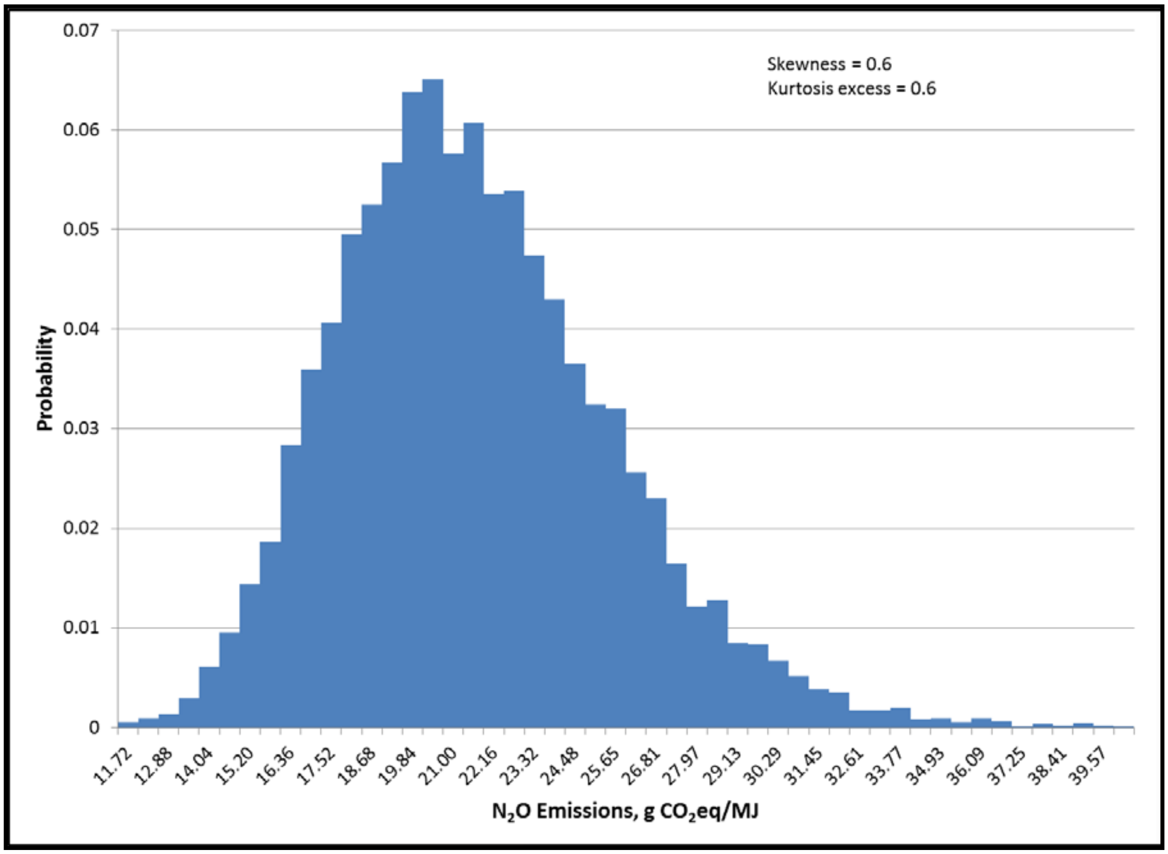
The Monte Carlo results for the complete lifecycle are shown in the following figure. The results are only slightly skewed and the 90% confidence range is 51.6 to 67.8 g CO_2eq/MJ. The mean value is 59.8 g CO_2eq/MJ.

Figure 10-12 Ethanol Lifecycle Emissions – MC Results



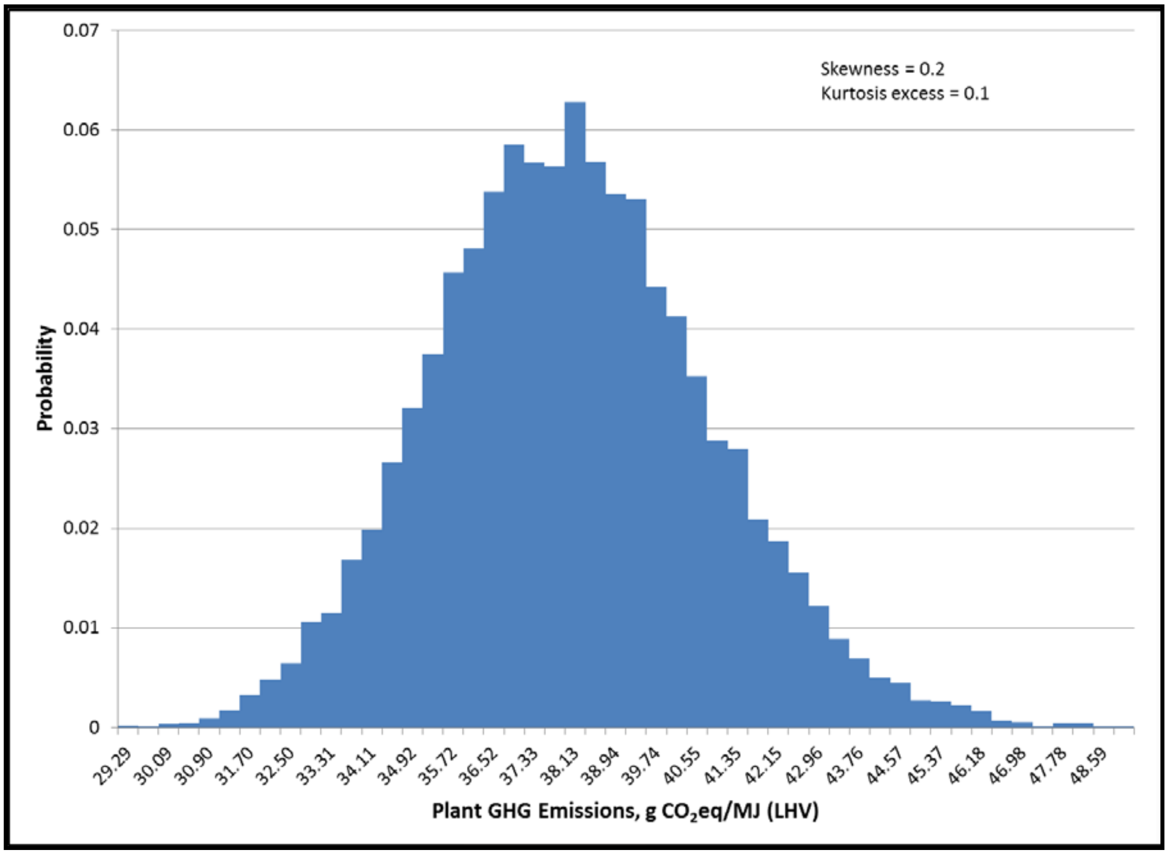
The N_2O emissions account for more than one quarter of the lifecycle emissions, but they are partially offset (~50%) by the co-product credit emissions. The distribution of the N_2O emissions is shown in the following figure. This was modelled with a lognormal distribution and that is evident in the skewness and kurtosis figures. The 90th percentile range is from 15.7 to 28.4 g CO_2eq/MJ.

Figure 10-13 MC Results N_2O Emissions



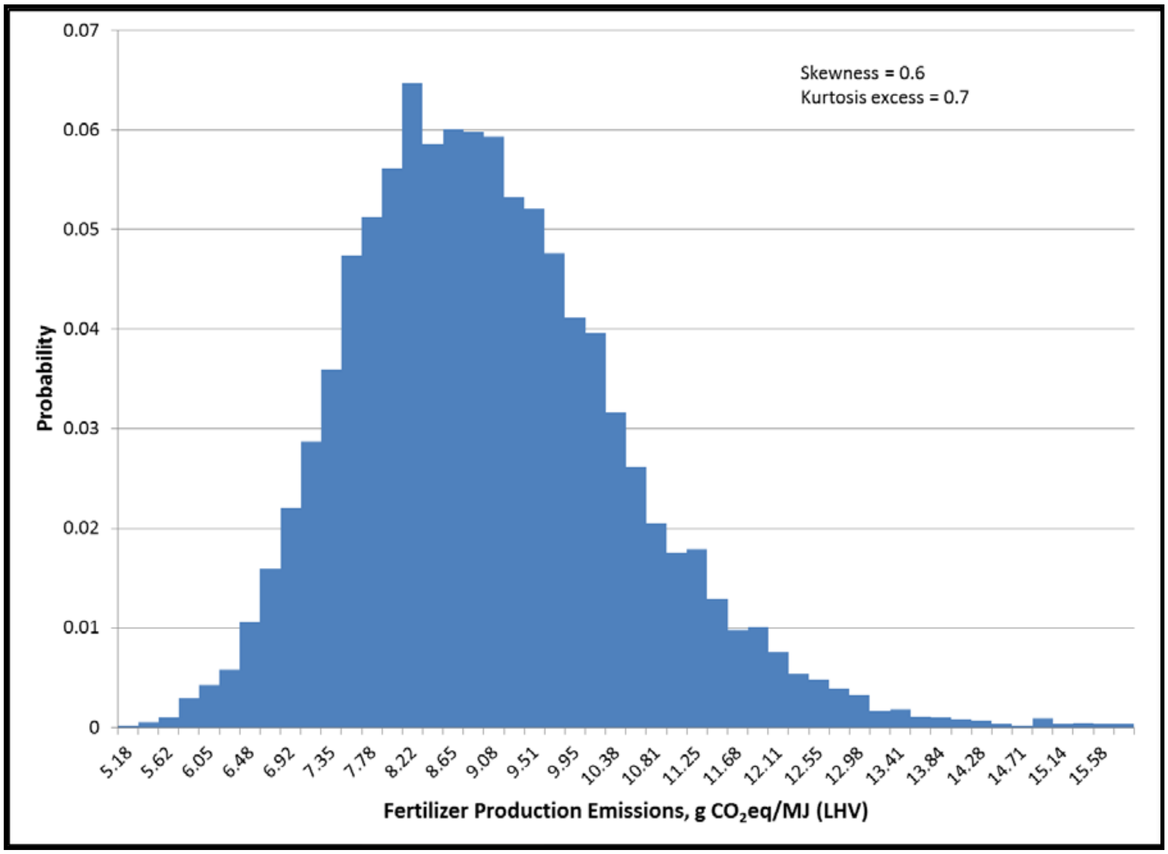
The emissions from the plant are shown in the next figure. There is a slight skewness to the results. The 90th percentile range is from 33.5 to 42.4 g CO_2eq/MJ.

Figure 10-14 Plant Energy Use – MC Results



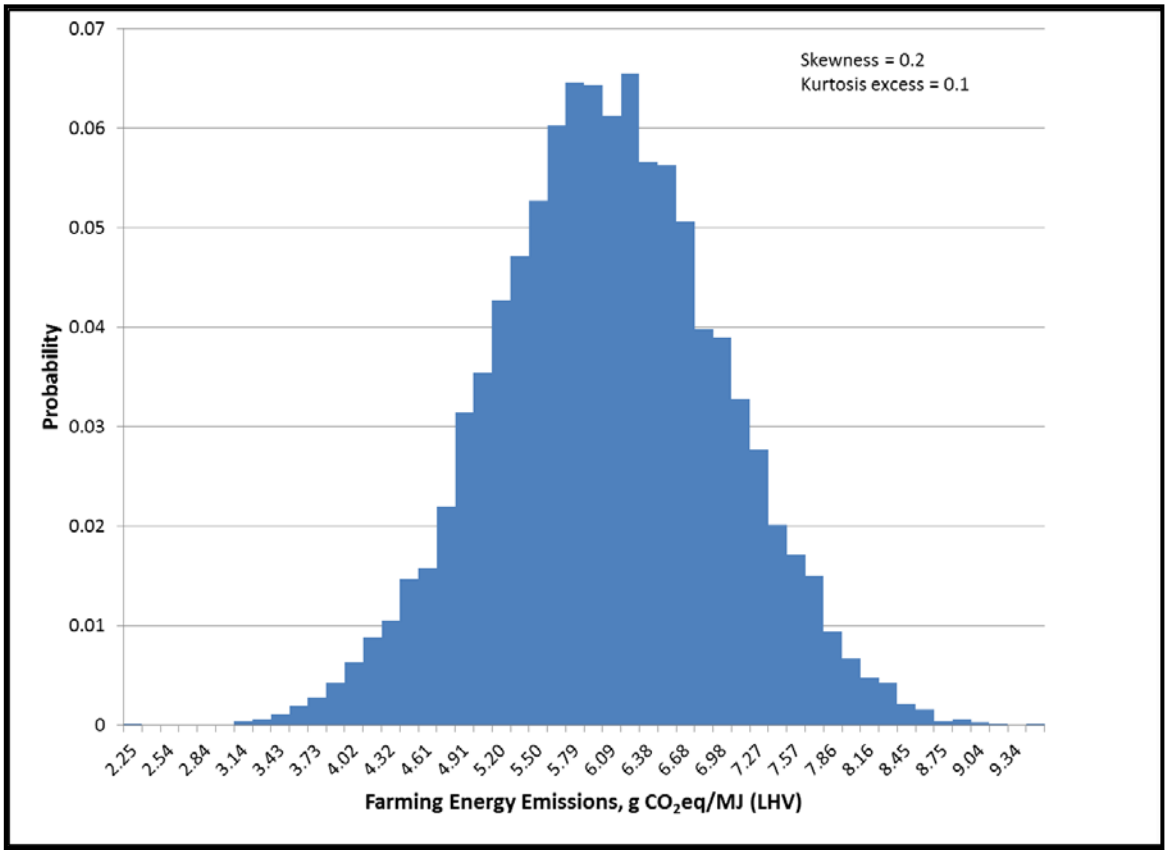
The emissions from the production of fertilizer will be a function of the quantity of fertilizer applied and the emissions per unit of fertilizer. We have only changed the nitrogen fertilizer for this work as these emissions dominate the fertilizer emissions. The fertilizer production emissions are shown in the following figure.

Figure 10-15 MC Results Fertilizer Production Emissions



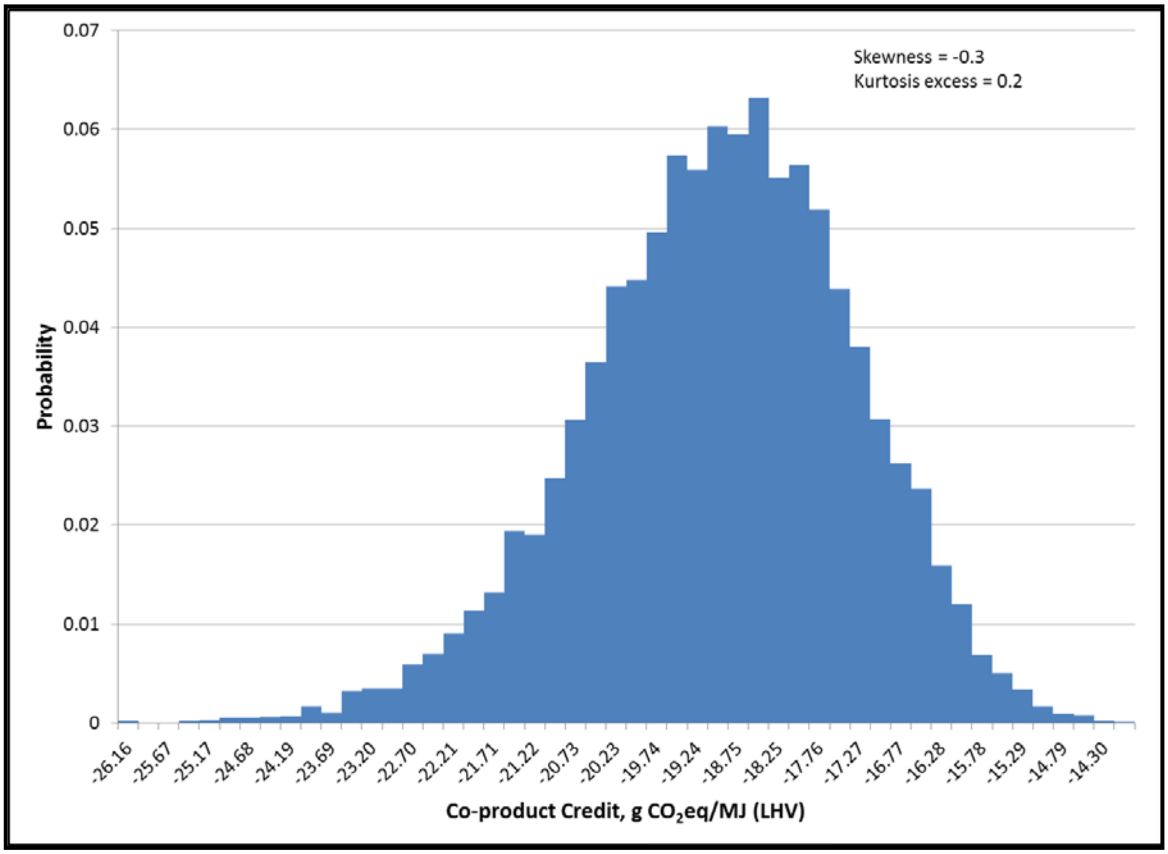
We also adjusted the farming energy. The distribution of these results is shown in the following figure. There is a relatively narrow range here, from 4.4 to 7.5 g CO_2eq/MJ. The zero values for skewness and kurtosis indicate a normal distribution.

Figure 10-16 MC Results Farming Energy



The co-product credit emission savings is a function of the N_2O emission factor, the nitrogen rate applied, the nitrogen fertilizer production emissions and the farming energy. The distribution of the results is shown in the following figure. There is some skewness in these results.

Figure 10-17 MC Results – Co-product Credit



Note that the sum of the ranges for the individual stages is more than the range for the entire lifecycle. This is typical of Monte Carlo analyses.

10.6 SUGARCANE ETHANOL

The sugarcane ethanol pathway results show significant variation in feedstock production emissions, ethanol plant emissions, co-product credits, and in transportation emissions. The transportation emission differences result from different assumptions with respect to modes of transport but some of the other differences are caused by uncertainty with respect to some of the modelling parameters.

10.6.1 N_2O Emissions

There are differences in the N_2O emissions for sugarcane production in the different models. There is probably a higher level of uncertainty on these emissions than there is for corn ethanol because there are so few measurements of N_2O emissions from sugar cane fields. The few sources indicate that the range could be even higher than the 0.3 to 3.0% range suggested by the IPCC.

For the Monte Carlo analysis we have used the 1.25% for EF_1 as the mean value (GHGenius default) and applied a lognormal distribution with a standard deviation of 0.2%.

10.6.2 Harvesting

Brazilian sugarcane production is undergoing a transformation from manual harvesting with field burning to a mechanized harvest with no burning. We have applied a lognormal distribution to the quantity that is mechanically harvested. The distribution has a mean value of 0.44, the default value in GHGenius and a standard deviation of 0.11. It is assumed that all mechanized harvested area is unburned and that all manual harvested area is burned.

10.6.3 Ethanol Plant Methane Emissions

There is uncertainty about methane emissions associated with the vinasse produced by the plant. In the default GHGenius runs this was assumed to be zero because there is insufficient data to set a default value. For the Monte Carlo runs we have set a mean value of 5 g CH_4/GJ and applied a lognormal distribution with a standard deviation of 5. This provides a relatively long tail.

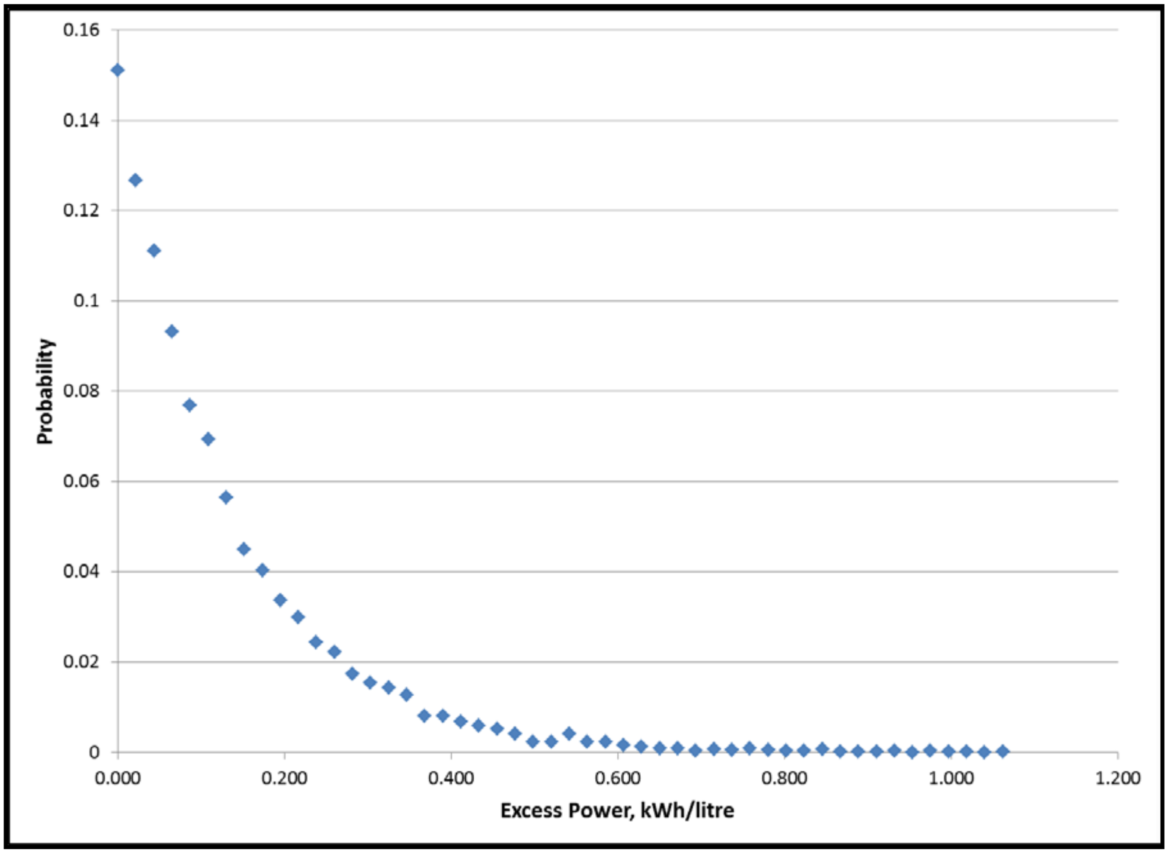
10.6.4 Co-products

The sugarcane mills have the potential to export power to the grid. The quantity of power that is exported depends on the mill design. Older mills, which were built when power exports were not allowed, are relatively inefficient users of steam and power since the bagasse was treated as a waste product that must be disposed of. New plants can improve the combustion efficiency and the energy use in the mill and have power available for export. There is also significant uncertainty about what kind of power would be generated if this mill produced power were not available. Both of these issues are addressed in the Monte Carlo analysis.

10.6.4.1 Power Production

To model the excess power produced an exponential function is used. This is set to provide a mean value of 0.13 kWh/litre. This distribution provides an exponential decay in the probability of a mill producing surplus excess power.

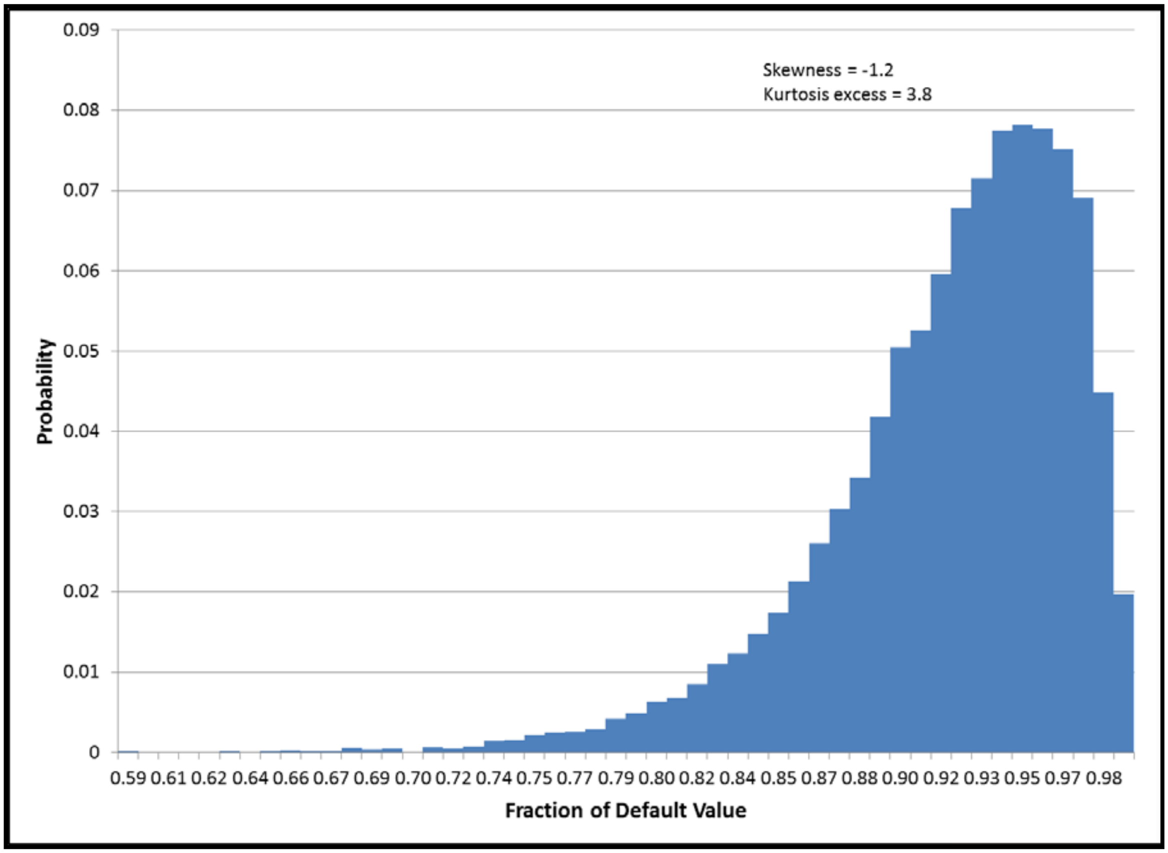
Figure 10-18 Excess Power Quantity Distribution



10.6.4.2 Displaced Power Carbon Intensity

There is also uncertainty with respect to the power that is displaced by the extra production from sugarcane ethanol mills. The overall power intensity of the Brazilian grid is quite low but there is a significant amount of natural gas generation, especially for incremental power demands. There is also some seasonality to the carbon intensity as a lot of the power is produced from hydroelectricity. To model this, a beta distribution is used. This distribution and the parameters chosen allow the maximum value to be 108% of the single cycle natural gas system and the minimum value to be 65% of the default value. The shape of the distribution is shown below.

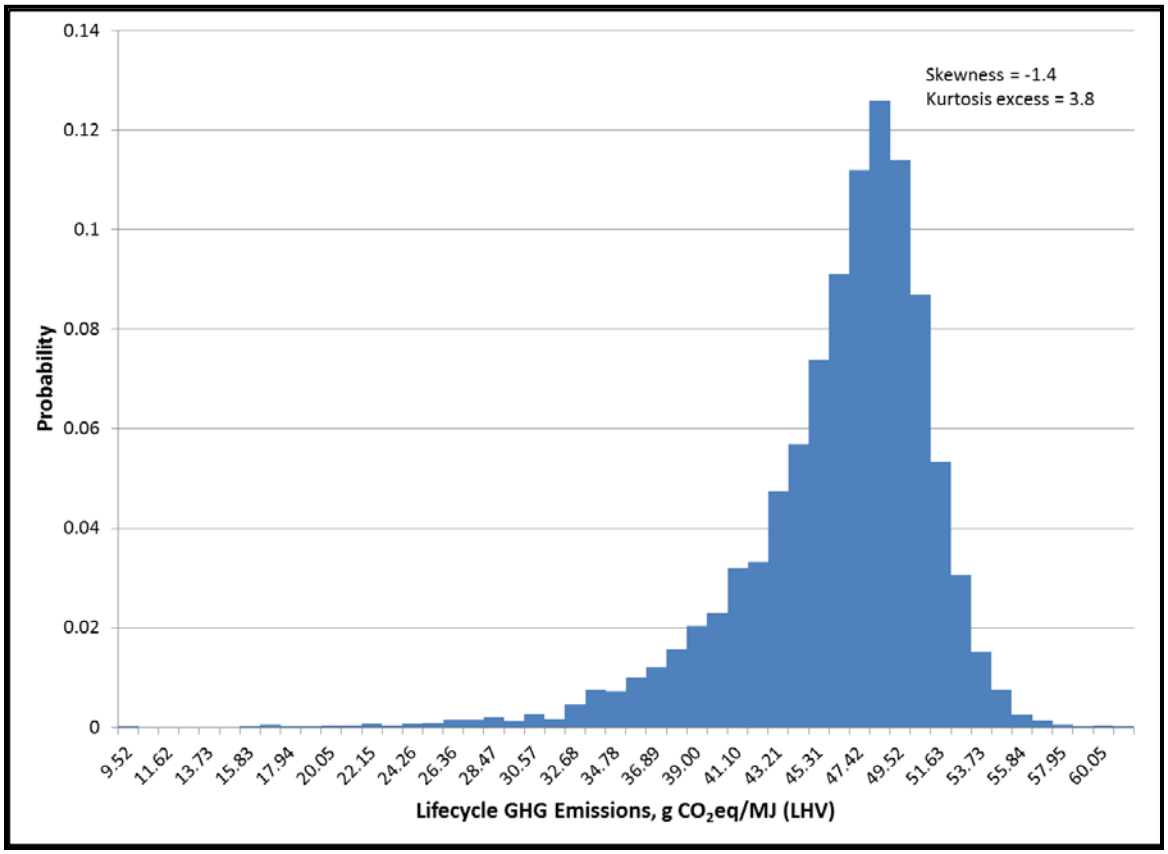
Figure 10-19 Power CI Distribution Function



10.6.5 Results

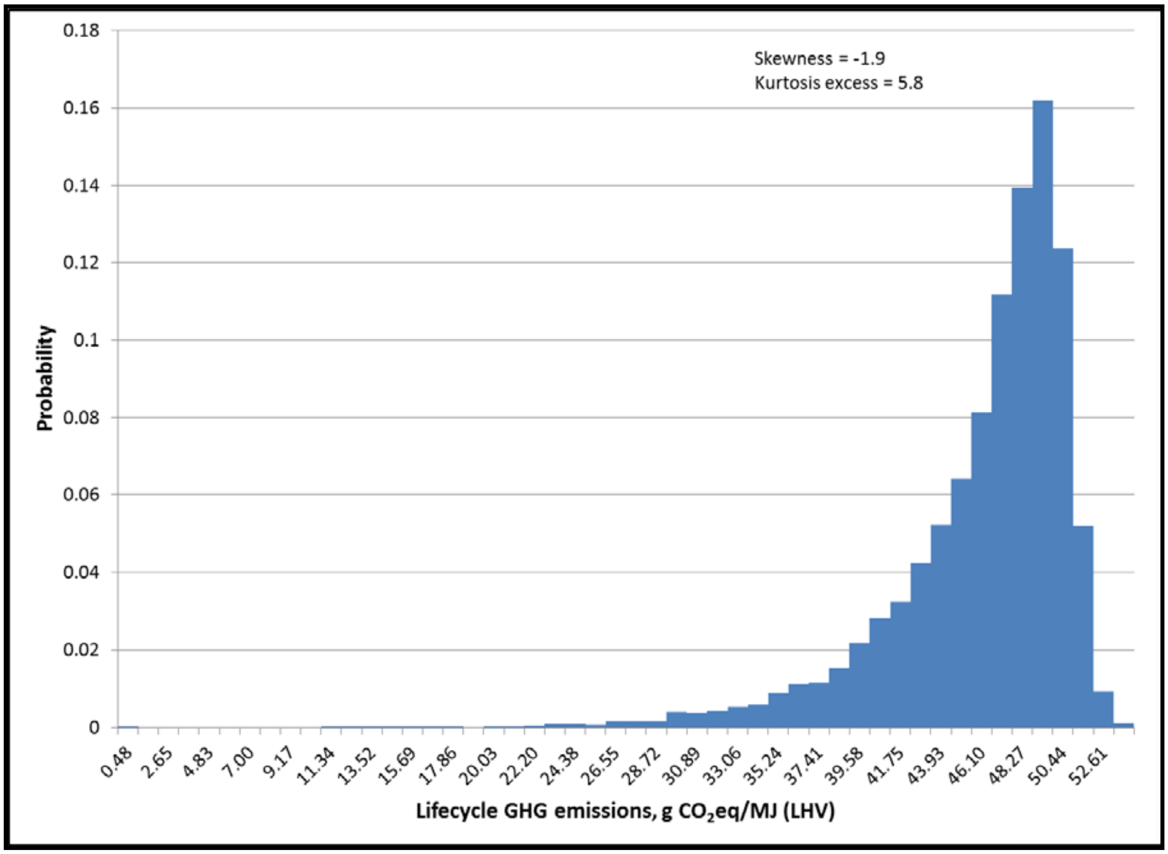
The Monte Carlo results for the sugarcane ethanol pathway are shown in the following figure. There is a significant negative skewness to the distribution. This is primarily the result of the uncertainty surrounding the excess power credit. The 90% probability range is from 36.9 to 51.6 g CO_2eq/MJ (LHV).

Figure 10-20 Sugarcane Ethanol MC Results



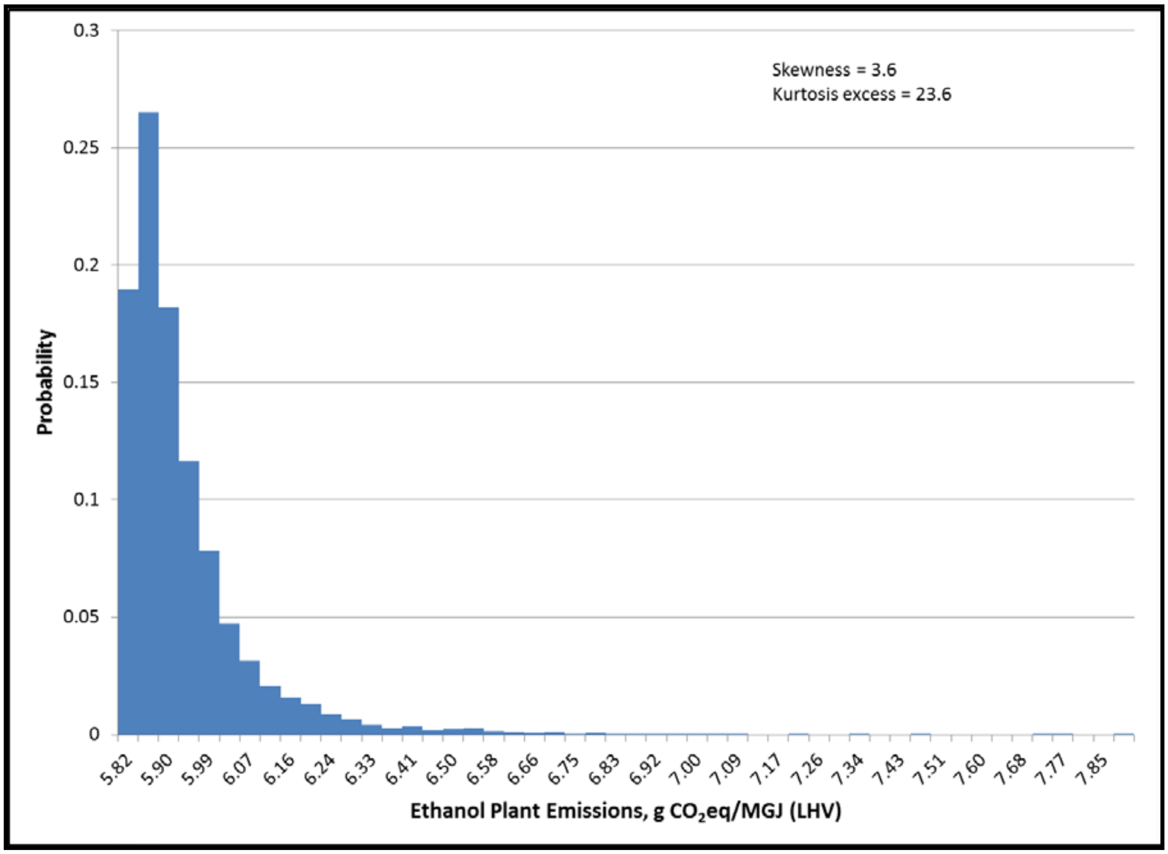
If we change the distribution of the N2O emission factor from a lognormal to a normal distribution it has relatively small impact on the results. The 90% probability range becomes 36.6 to 51.0 g CO_2eq/MJ and the skewness and negative kutosis increase as shown in the following figure.

Figure 10-21 Sugarcane MC Results with Normal Distribution for N_2O



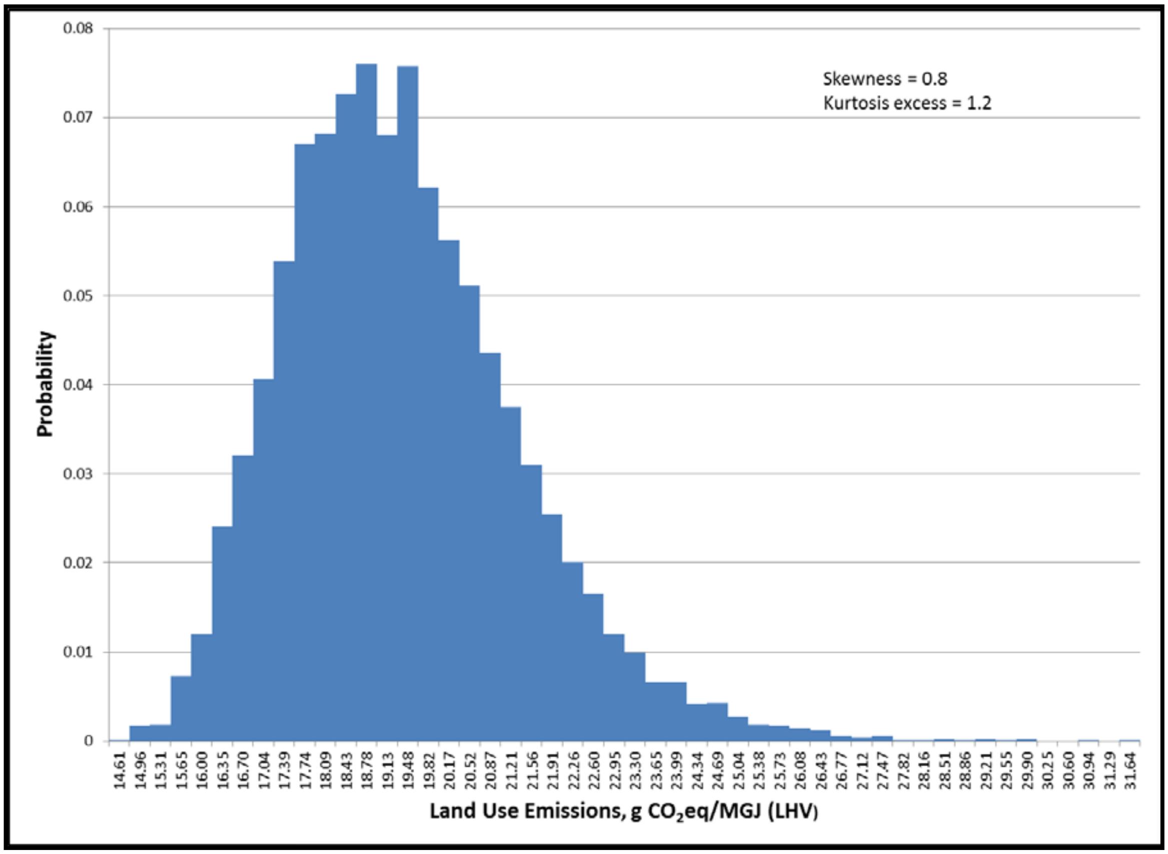
The uncertainty with respect to the methane emissions from the vinasse distribution is shown in the following figure. The high standard deviation chosen for this parameter results in a larger kurtosis excess. The overall impact on the lifecycle emissions is quite small.

Figure 10-22 Ethanol Plant Emissions MC Results



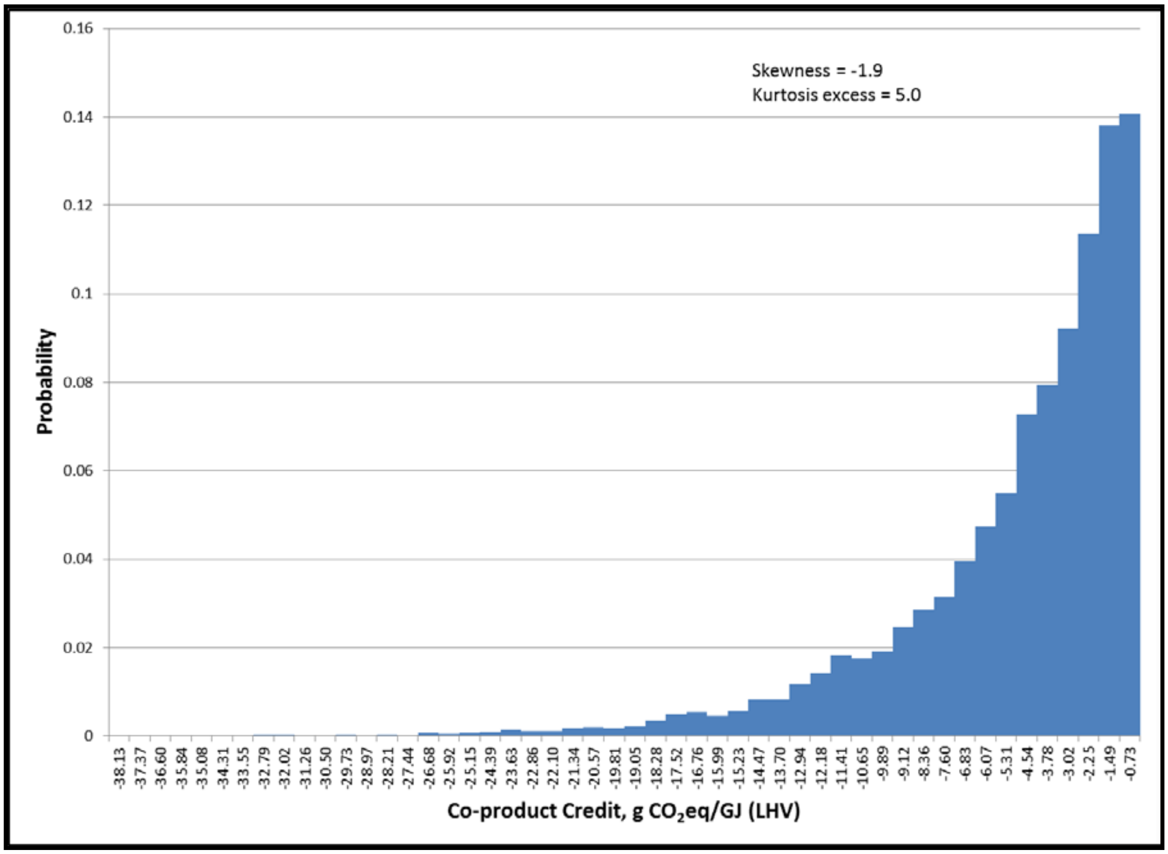
For this pathway we used a lognormal distribution for the N_2O emission factor uncertainty. This produces the following distribution of results. These results include methane and N_2O emissions from the field burning of straw as well as the N_2O emissions from the decomposition of nitrogen fertilizer and crop residues.

Figure 10-23 Land Use Change MC Results



The distribution of the co-product credit is shown in the following figure. This is a function of the uncertainty with respect to the amount of power sold to the grid and the carbon intensity of the displaced power. There is a significant negative skewness and a high kurtosis excess with this distribution.

Figure 10-24 Co-product Credit MC Results



10.7 CELLULOSIC ETHANOL

There are no commercial cellulosic ethanol plants in operation so there is a great deal of uncertainty concerning the emission profile of this pathway. With so little process data it is even difficult to model the uncertainty as it is unknown how close the modelled parameters might be to the actual results.

We have chosen five parameters that have a large impact on the emission profile. For three of the parameters we have chosen a normal distribution and for the other two a lognormal distribution. The parameters and the assumed probability distributions are discussed below.

As with the other pathways, the base GHGenius model is used for the Monte Carlo analysis.

10.7.1 Power Production

The electric power co-product offsets about one third of the lifecycle GHG emissions in GHGenius. Electric power consumption is a difficult parameter to transfer from process modelling to real world performance as the physical layout of the plant can impact power requirements and any safety factors included in the design will often incur a permanent power penalty.

The normal distribution is applied for this parameter. The mean is set to 0.50 kWh/litre. The standard deviation is set to 0.125. For the 10,000 iterations this set a minimum value of 0.06 kWh/litre and a maximum value of 1.01 kWh/litre.

10.7.2 Displaced Power Carbon Intensity

The emission intensity of the displaced power will depend on the location where the plant is operated. The base case used a carbon intensity of 673 g CO_2eq/kWh delivered. A normal distribution has been applied with a standard deviation of 101 g CO_2eq/kWh delivered.

The low end of the range from the MC analyses was 310 and the high end of the range was 1,010 g CO_2eq/kWh delivered. The high end represents a 100% coal power scenario and the low end would be a blend of 45% gas fired powered and the remainder hydro or wind.

10.7.3 Enzyme Consumption

A large amount of effort has been spent in the past decade in reducing the enzyme requirements for cellulosic ethanol systems. In the base case modelled in GHGenius, the enzymes are manufactured on site and the main ingredient is glucose.

For the Monte Carlo simulation we have applied a lognormal distribution to the glucose consumption. A lognormal distribution will have a long tail, as it is more likely that plants will use more enzyme rather than less enzyme than the base case assumes. The mean is the default consumption in the base case and the standard deviation is 30% of the mean. This distribution provides a minimum value of 30% of the mean and a maximum value of 2.8 times the mean.

10.7.4 NaOH Consumption

Caustic soda is used to adjust the pH throughout the process, for process cleaning, and for waste water treatment. This product is generally produced through an electrolysis process and thus can have high GHG emissions in areas where the electric power carbon intensity is high.

A lognormal distribution is applied to this parameter but with a slightly narrower range than used for the glucose. The mean is the default value in GHGenius; the standard deviation is 20% of the mean. This produces a distribution with the minimum value of 46% of the mean and the maximum value as twice the mean value.

10.7.5 Yield

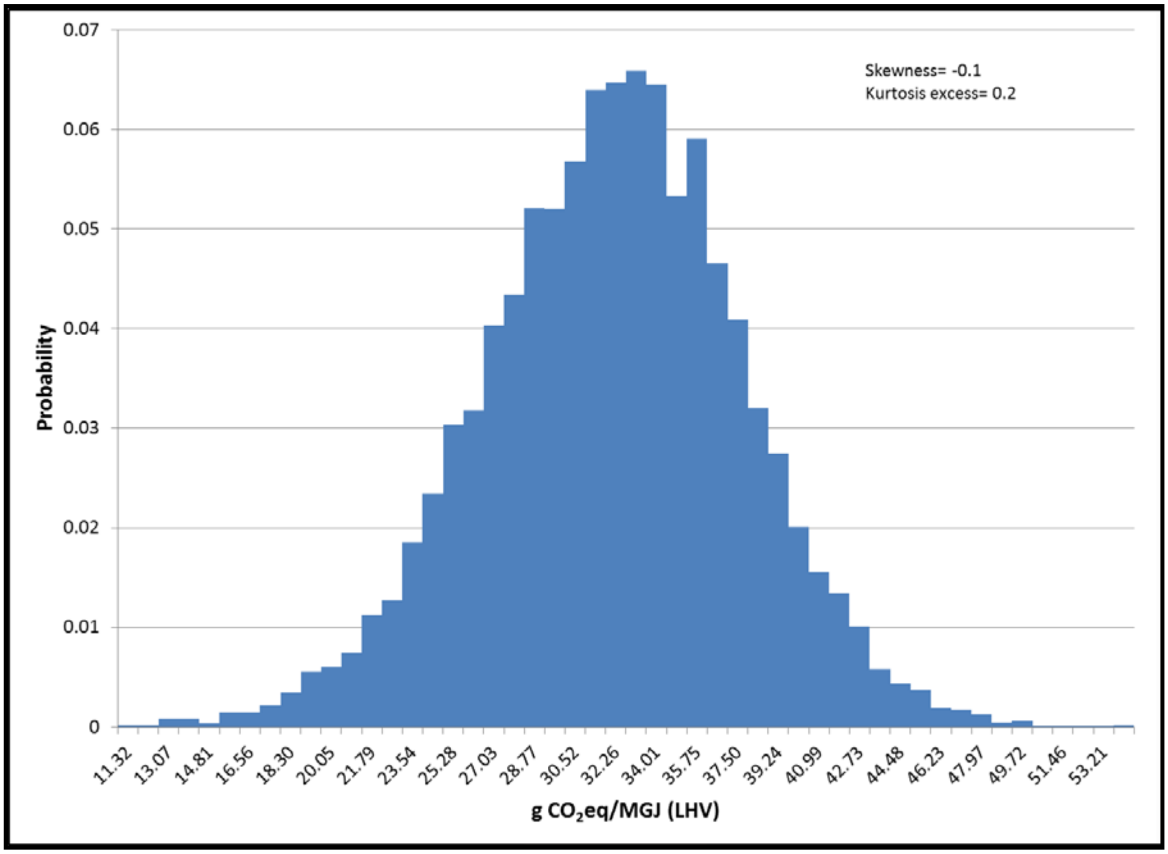
The final parameter used in the Monte Carlo analysis is the yield. The yield is a complex parameter to model since there may be other parameters that are dependent on the yield. Low yields may be accompanied by increased power production and this in turn may mean increased power exports with lower overall GHG emissions. Low yields could also mean higher waste water treatment costs with higher power consumption and higher caustic use and higher overall GHG emissions.

We have modelled the yield as an independent variable, no other process parameters change in the model as a result of changing yield. The yield will therefore only impact the feedstock production emissions. A normal distribution has been applied with the mean being the GHGenius default value (3.01 kg corn stover/litre of ethanol) and the standard deviation is 3.3% of the mean yield. This is a fairly narrow range (2.67 to 3.40 kg stover/litre of ethanol) as it is assumed that commercial plants will have to be quite efficient in order to have acceptable economics.

10.7.6 Results

The graphical distribution of the total emission results of a 10,000-iteration Monte Carlo run is shown in the following figure.

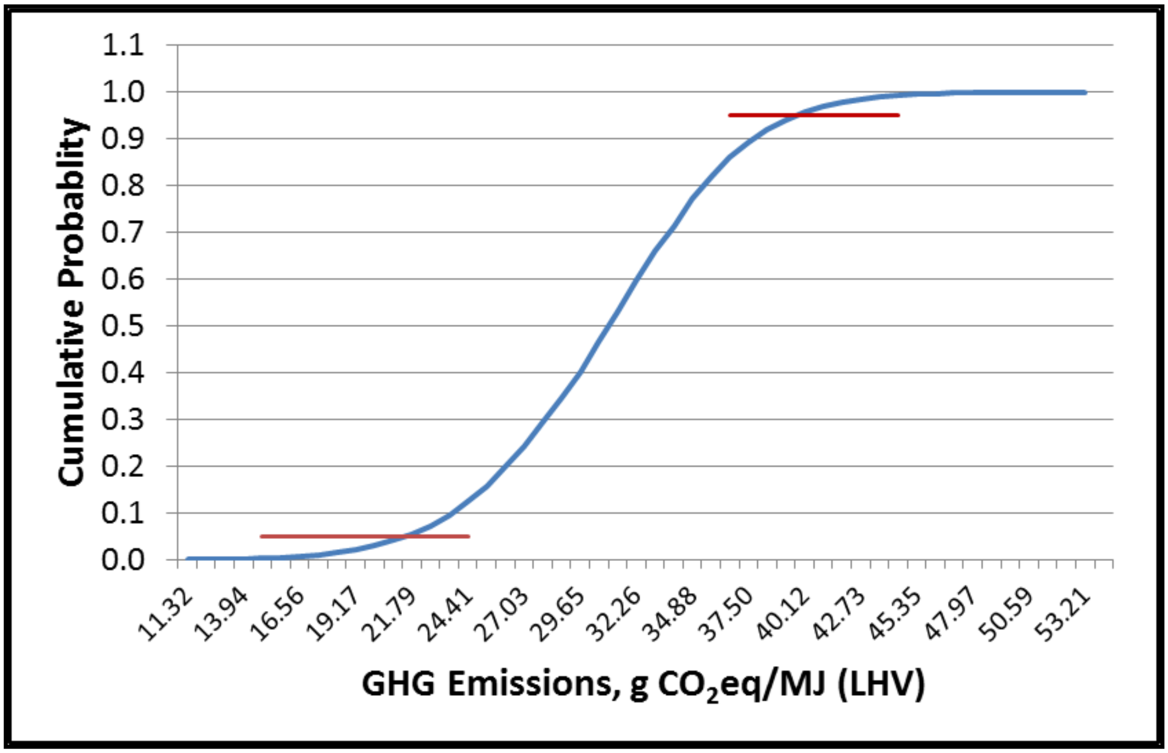
Figure 10-25 Cellulosic Ethanol Monte Carlo Results



The mean of the Monte Carlo runs was 32.55 g CO_2eq/MJ (LHV). The same value as the standard GHGenius run. The standard deviation from the analysis was 5.5 g CO_2eq/MJ (LHV). The distribution has a skewness of –0.1 and a kurtosis excess of 0.2. Both measurements indicate that the results are close to a normal distribution.

The cumulative results are shown in the following figure. There is a 95% probability that the emissions are less than 41 g CO_2eq/MJ (LHV) but greater than 22 g CO_2eq/MJ (LHV).

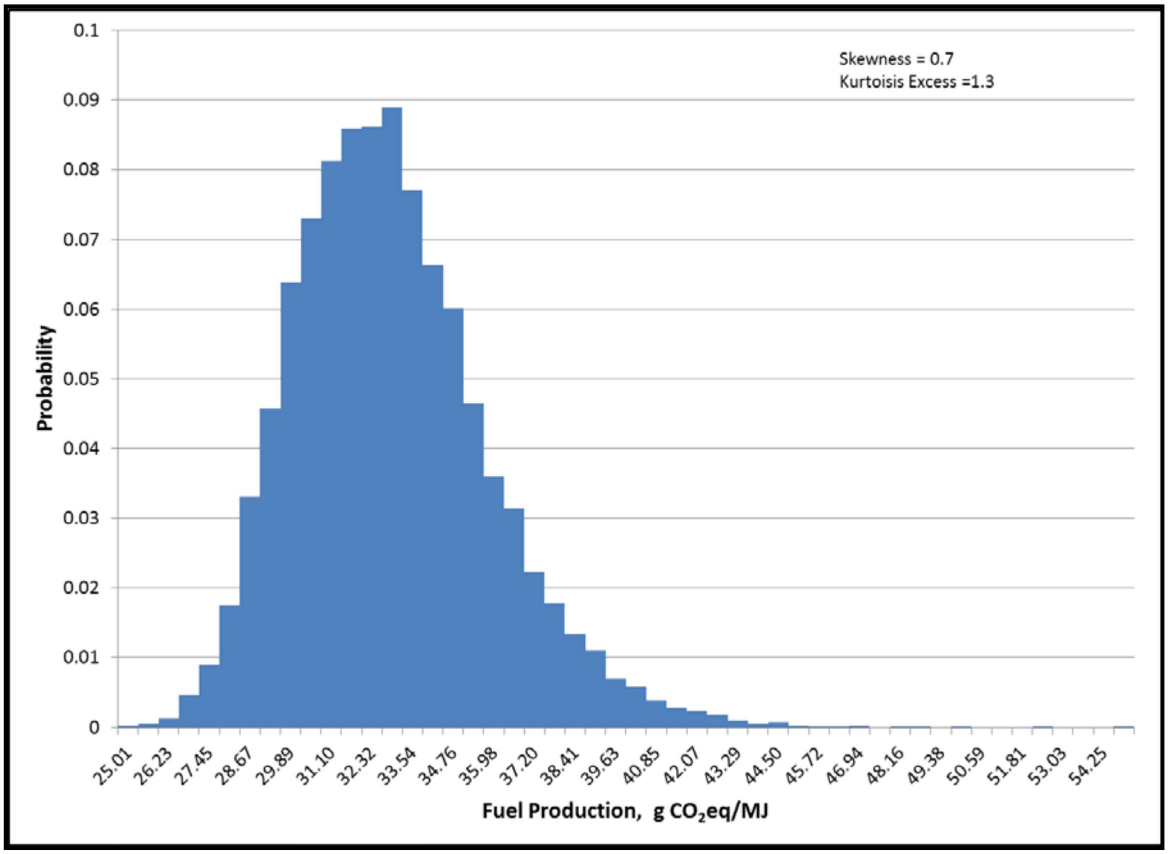
Figure 10-26 Cumulative GHG Emissions – Cellulosic Ethanol



The parameters that were changed had an impact on the production emissions (enzyme, caustic, and yield) and on the co-product credit (quantity of excess power and the carbon intensity of the power).

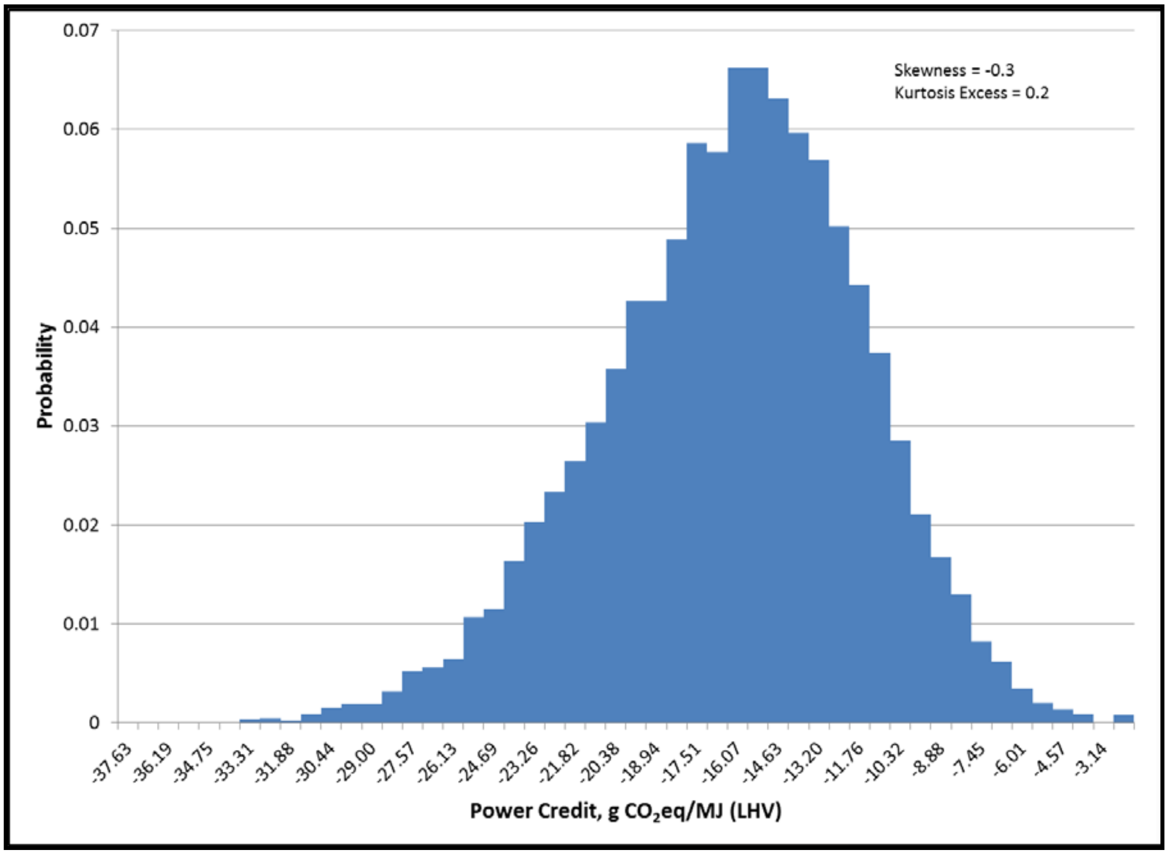
The distribution of the emissions for the fuel production stage is shown in the following figure. It is skewed and has a longer tail, not surprising as both the enzyme and caustic were modelled with lognormal distributions.

Figure 10-27   MC Results - Fuel Production



The emission credit from the excess power is a function of the quantity of power and the carbon intensity of the power. Both were modelled with a normal distribution. The distribution of the results is shown in the following figure. There is some skewness and it is towards larger credits. There is a significant range between the 10 and 90th percentiles, greater than the range in the previous figure that looked at the fuel production emissions.

Figure 10-28 MC Results – Power Credit



10.8 SOYBEAN BIODIESEL

The uncertainty in the soybean biodiesel system is not as well defined as it is with corn ethanol but five important variables were identified in the earlier sections that have a large impact on the results and have some uncertainty associated with them. They are discussed below along with the chosen uncertainty distributions and modelling parameters.

10.8.1 N_2O Emissions

The N_2O emissions from the production of the soybeans make a large contribution to the lifecycle GHG emissions. There are two variables, the nitrogen content of the residue and the EF_1 emission factor, that impact the results unlike most biofuel pathways that just have some uncertainty with respect to the N_2O emission factor.

10.8.1.1 N_2O Emission Factor

In the United States there is a lot of farm land that grows corn and soybeans in rotation. The N_2O emission factor uncertainty for soybeans should therefore be very similar to that of corn. We have used the same lognormal distribution as was used for this parameter for corn and the same relative mean but a slightly larger standard deviation value to see if that has an impact. The mean is set to the 1.5% value that is the default in GHGenius and the standard deviation is 0.20%. This produces a minimum value of 0.86 and a maximum value of 2.6, closer to the IPCC uncertainty range.

10.8.1.2 Nitrogen Content of Residues

The models have a large range in the nitrogen value of the crop residue. As noted, there is very little data in the literature on this parameter, unlike most crops which have a lot of data. The one value that IPCC uses is from a 90 year old reference and the back calculations that others have done using measured N_2O emission rates suggested that the nitrogen content should be higher, at least if the N_2O production follows the same pathways in nitrogen fixing crops as it does in non-nitrogen fixing crops.

We have used a normal distribution to model this parameter. The mean is the default value in GHGenius of 1.69% and the standard deviation is 0.25%.

10.8.2 Field Energy Use

Farming energy use in soybean production appears to be decreasing over time. There are also other non-USDA data sets that suggest that the farm energy use for soybeans is much less than reported by the USDA.

We have applied a lognormal distribution to all of the farm energy inputs for soybean production. The mean value is the GHGenius default value and the standard deviation is set to 30% of the mean value.

10.8.3 Fuel Production

There are two stages to the fuel production process. In the first stage the soybeans are crushed and the oil is extracted from the beans. In the second stage of manufacturing, the oil is converted to biodiesel. In GHGenius the energy use for modelling both stages is derived from relatively recent industry surveys. Both sets of data are included in the Monte Carlo analysis.

10.8.3.1 Crushing Energy Consumption

Soybean crushing energy is modelled with both electric power and natural gas inputs. The Monte Carlo analysis applies a lognormal distribution to both parameters. The mean value is the GHGenius default value and the standard deviation is 10% of the mean. Both the power and the gas are adjusted at the same time so that there is a constant ratio between the two energy sources.

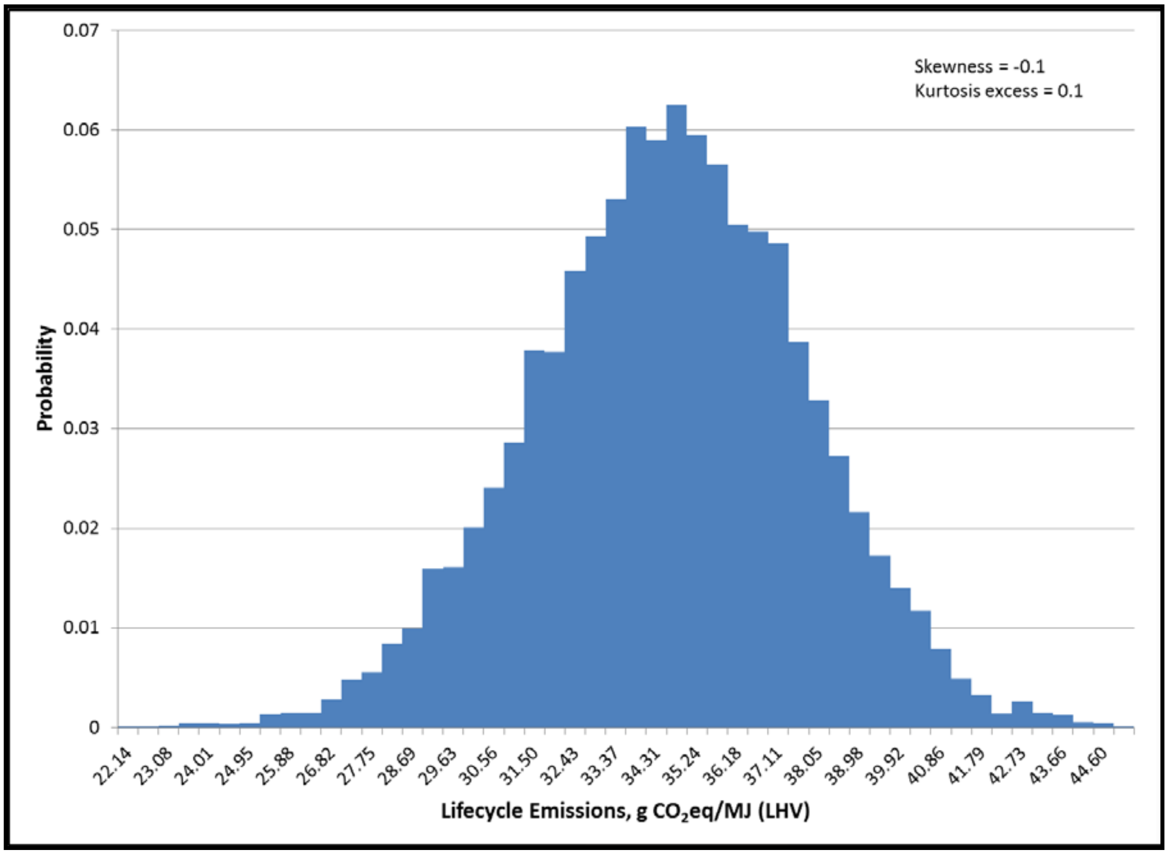
10.8.3.2 Biodiesel Energy Consumption

Biodiesel energy consumption is also composed of an electric power and natural gas component. Identical Monte Carlo parameters are used as were applied to the crushing energy. A lognormal distribution is applied, the mean values are the GHGenius defaults and the standard deviation is 10% of the mean. The crushing energy and biodiesel energy are modelled independently, so while the Monte Carlo parameters are identical, different random numbers are generated for the crushing energy and the biodiesel energy.

10.8.4 Results

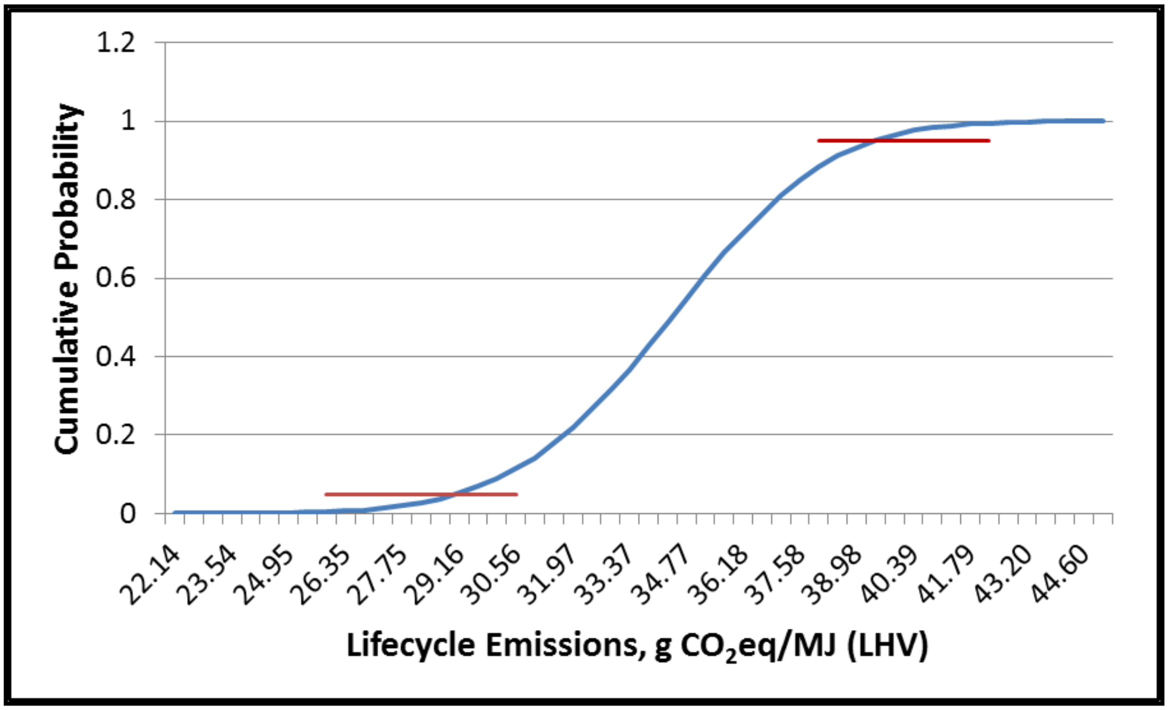
The results for the lifecycle emissions for the production of soybean biodiesel are shown in the following figure. The results indicate that this is essentially a normal distribution and there is very little skewness or kurtosis. The mean value is 34.8 g CO_2eq/MJ with a standard deviation of 2.8 g CO_2eq/MJ. The 90% range is 29.0 to 39.4 g CO_2eq/MJ.

Figure 10-29 Soybean Biodiesel Monte Carlo Results



The cumulative emission results with the 90% range marked are shown in the following figure.

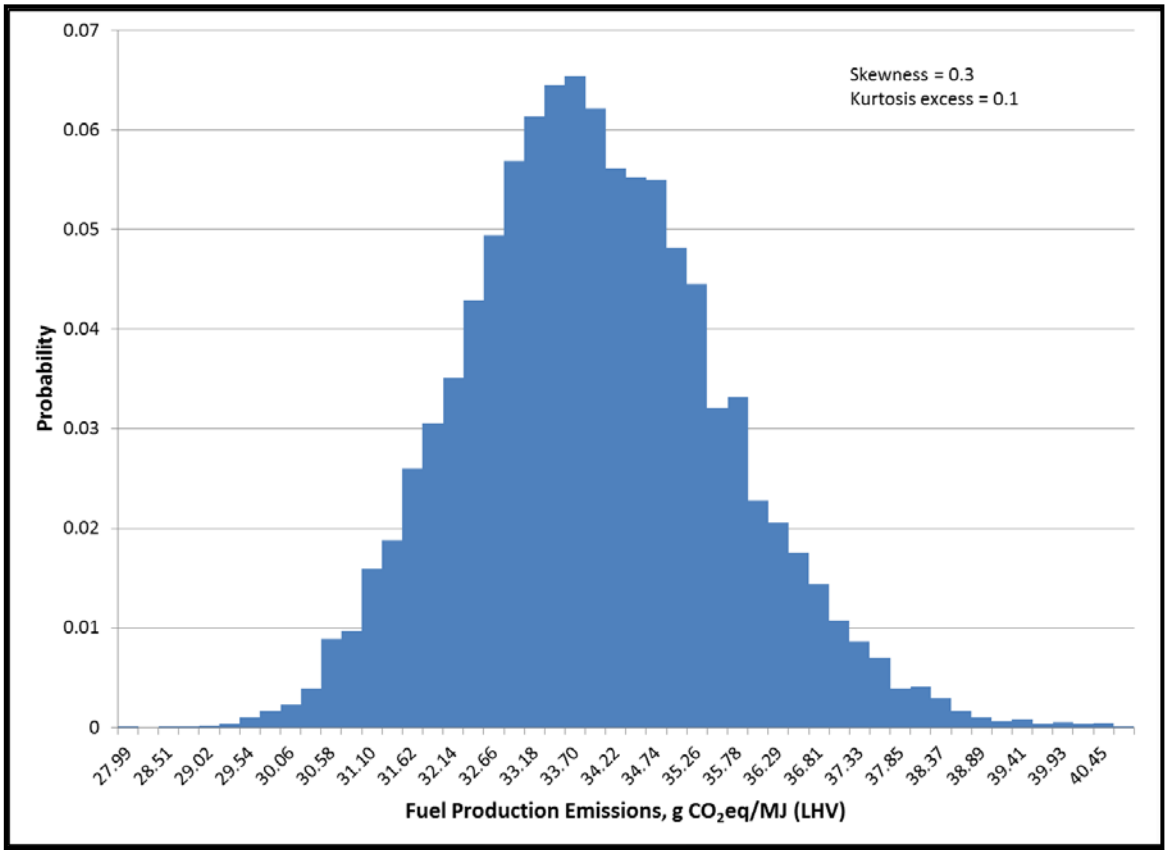
Figure 10-30 Cumulative GHG Emissions – Soybean Biodiesel



10.8.4.1 Fuel Production Stage

There were two variables investigated for the fuel production stage, the crushing energy and the biodiesel production energy. The Monte Carlo results for this stage of the lifecycle are shown in the following figure. Both of the variables were modelled with lognormal distributions and that is evident in the moderate skewness and kurtosis of the combined impact of the two variables. The 90% range is 31.2 to 36.6 g CO_2eq/MJ.

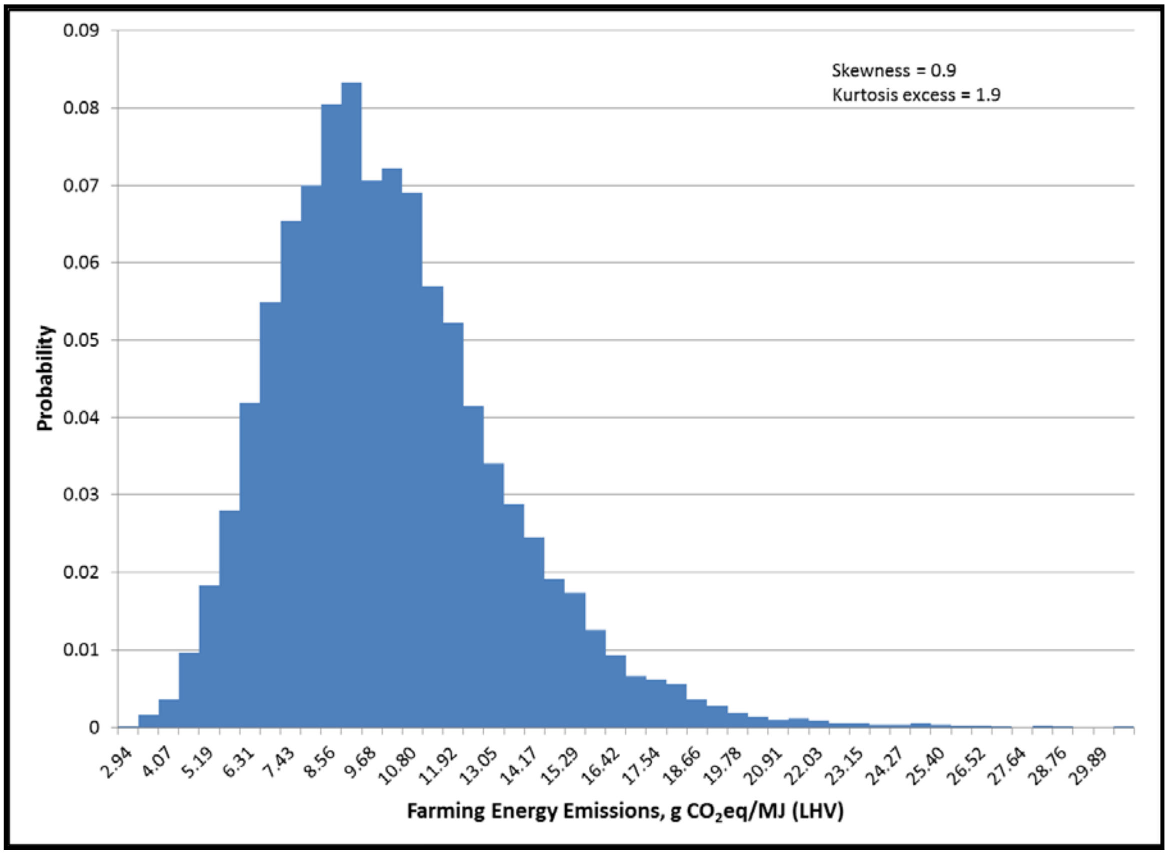
Figure 10-31 Fuel Production Stage MC Results



10.8.4.2 Farming Energy

The farming energy was also modelled with a lognormal distribution. There is more skewness and kurtosis with the one variable than there is with the two lognormal distributions shown in the previous figure. The 90% range is 5.7 to 15.6 g CO_2eq/MJ.

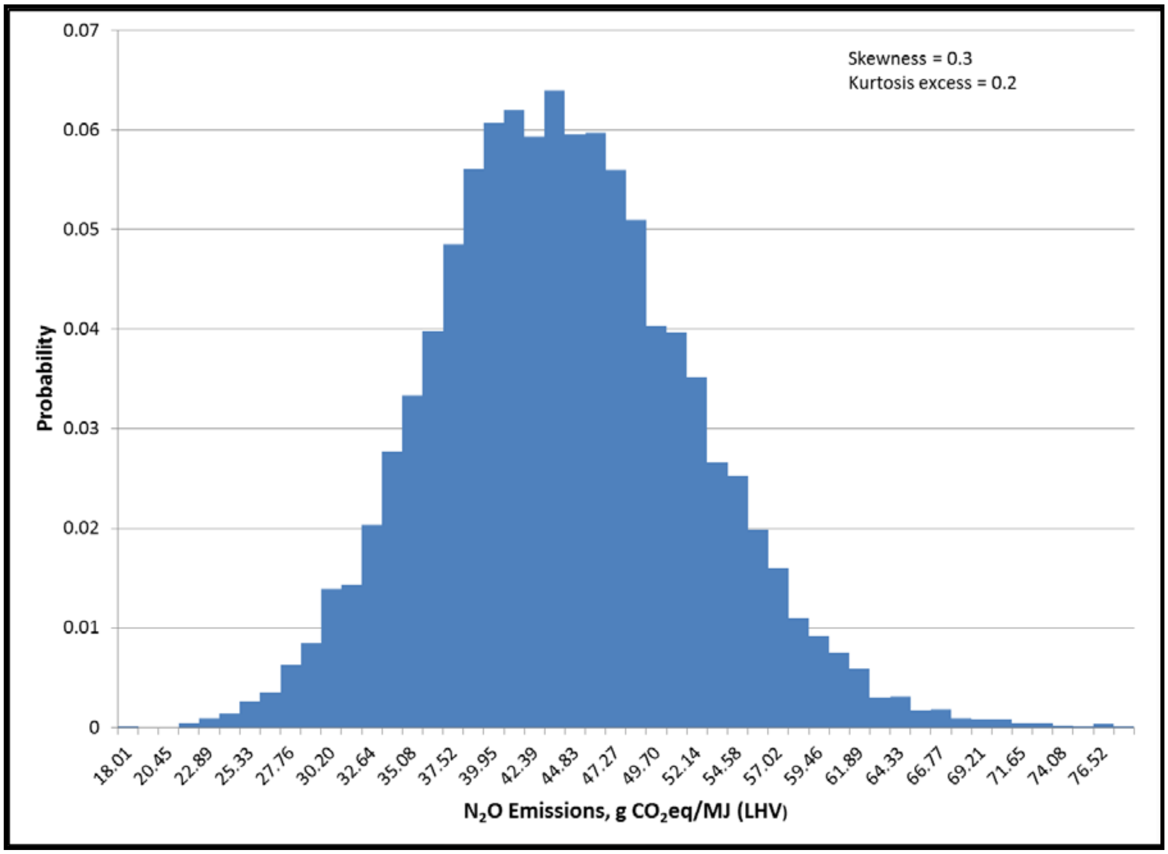
Figure 10-32 Farming Energy MC Results



10.8.4.3 N_2O Emissions

The N_2O emissions are a function of the N_2O emission factor and the nitrogen content of the soybean crop residues. The emission factor is modelled with a lognormal distribution and the nitrogen content with a normal distribution. The results for this stage are shown in the following figure. The results are quite close to a normal distribution. The 90% range is quite wide at 31.4 to 57.0 g CO_2eq/MJ.

Figure 10-33 Soybean N_2O Emissions MC Results



10.9 SUMMARY

There is uncertainty in all of the pathways studied. The results found here for the pathways that have been studied by others are quite similar in terms of the shape of the distribution of the results and the range of the results. Some of the other analyses found in the literature undertook simulations with many more model parameters rather than just the major ones that impact the major sources of emissions and uncertainty, this added complexity does not appear to significantly reduce the level of uncertainty.

The quantitative results that are produced from Monte Carlo analysis and are typically reported include the mean, standard deviation, and the 90% confidence range. The mean value is a function of the other modelling parameters and is subject to variability but a comparison of the standard deviation and the range of the results is informative. These results are shown in the following table.

Table 10-1 Range and Standard Deviations from Monte Carlo Results

Pathway	Mean	Std Deviation	5% Value	95% Value	90% Range
	g CO_2eq/MJ				
Gasoline	26.0	4.6	19.6	33.7	14.1
CNG	26.1	3.0	21.3	30.8	9.5
Corn Ethanol	59.8	4.9	51.6	67.7	16.1
Sugarcane Ethanol	46.9	4.9	36.8	51.6	14.8
Cellulosic Ethanol	32.5	5.5	22.6	40.5	17.9
Soybean Biodiesel	34.8	3.1	29.1	39.4	10.3

These results exclude the combustion emissions. There is much less uncertainty with respect to the combustion emissions compared to the production emissions. The standard deviations and the 90% ranges are relatively close for all of the six pathways modelled.

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