CRC Report No. E-102-2

Review of Critical Parameters for Transportation Fuel Pathways

Final Report

March 2018

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

The Coordinating Research Council, Inc. (CRC) is a non-profit corporation supported by the petroleum and automotive equipment industries. CRC operates through the committees made up of technical experts from industry and government who voluntarily participate. The four main areas of research within CRC are: air pollution (atmospheric and engineering studies); aviation fuels, lubricants, and equipment performance; heavy-duty vehicle fuels, lubricants, and equipment performance (e.g., diesel trucks); and light-duty vehicle fuels, lubricants, and equipment performance (e.g., passenger cars). CRC's function is to provide the mechanism for joint research conducted by the two industries that will help in determining the optimum combination of petroleum products and automotive equipment. CRC's work is limited to research that is mutually beneficial to the two industries involved. The final results of the research conducted by, or under the auspices of, CRC are available to the public.

REVIEW OF CRITICAL PARAMETERS FOR TRANSPORTATION FUEL PATHWAYS

Prepared For:

COORDINATING RESEARCH COUNCIL, INC.
5755 North Point Parkway, Suite 265
Alpharetta, GA 30022

Prepared By

(S&T)^2 Consultants Inc.
11657 Summit Crescent
Delta, BC
Canada, V4E 2Z2

Date: March 13, 2018

EXECUTIVE SUMMARY

The Coordinating Research Council (CRC) is a non-profit organization that directs, through committee action, engineering and environmental studies on the interaction between automotive/other mobility equipment and petroleum products. The formal objective of CRC is to encourage and promote the arts and sciences by directing scientific cooperative research to develop the best possible combinations of fuels, lubricants, and the equipment in which they are used, and to afford a means of cooperation with the Government on matters of national or international interest within this field.

Through CRC, personnel in the automotive equipment and other related mobility industries and in the energy industries can join together, and can join with Government, to work on mutual problems. CRC has no facilities for conducting direct research.

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 vehicle and fuel 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 fuel options. LCA models can be of great assistance for this.

In 2013, the CRC commissioned a study (CRC Project E-102) 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 these inputs, for several specific fuel pathways. Validation of the inputs and resulting outputs from the models was discussed, and pathway variability and overall model uncertainty for the different pathways was assessed. The study was carried out by $(S\&T)^2$ Consultants Inc. and the final report is available from the CRC.

This follow on project, CRC E-102-2, is intended to support the uncertainty analysis that was undertaken in CRC Project E-102 with supporting data from published literature. The objective was to find a range of values and/or parameter distributions outside of the default values for a specific pathway in GREET 2014, GHGenius, and BioGrace. Unlike project E-102, which looked at the well to wheel emissions of the vehicle and fuel pathways, this work considered the well to tank portion of the pathways (with the exception of heavy duty natural gas vehicles).

The CRC has identified three primary tasks for this project: a review of the literature on the corn ethanol pathway, a review of the other pathways, and Monte Carlo simulations of all six pathways in each of the three models.

TASK 1 CORN ETHANOL

Three specific aspects of the corn ethanol pathway have been investigated;

1. The N_2O emissions from corn production,
2. The energy use in corn ethanol plants, and
3. The ethanol co-products.

For all three issues a range of values from the recent literature (2010 to 2015) has been developed and some recommendations for changes in the default values for the models are presented. Trends in the parameters are also noted.

The scope of work requested that the N_2O emission information should be presented in a manner that is consistent with the IPCC (Intergovernmental Panel on Climate Change) methodology. However, the literature search did identify a number of papers that suggest the emissions are not a linear function of the nitrogen applied as the IPCC methodology prescribes.

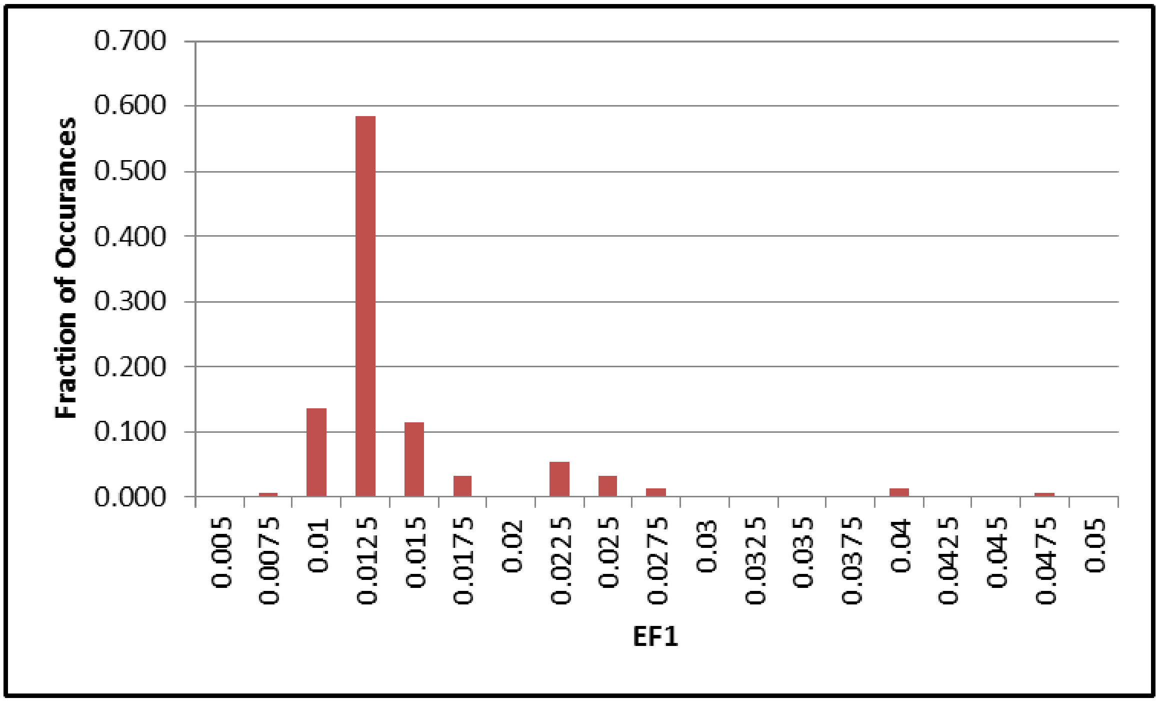
GREET and GHGenius take a similar approach to calculating the N_2O emissions and generally follow the approach recommended by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The N_2O calculations in GREET are slightly less transparent in that the emission factors are embedded in equations in the model and changes in the emission factors require the user to change the equations rather than just changing a cell value as is the case in GHGenius. BioGrace is less transparent in the N_2O calculations unless the user chooses to use the IPCC 2006 methodology. This methodology is not used for the EU RED default values.

In the IPCC methodology the direct emission factor (EF_1) accounts for 75 to 80% of the N_2O emissions and is thus the most significant parameter. The indirect emissions due to leaching are 15 to 20% and the indirect emissions due to volatilization are 5 to 10%.

EF_1 can be influenced by a number of soil and climatic conditions. For IPCC Tier 2 and Tier 3 approaches, the precipitation is the factor with the most influence on EF_1. Thus EF_1 is regionally specific and the models should use values that are reflective of the region being modelled.

The GNOC (Global Nitrous Oxide Calculator) model is a public model that produces a value for EF_1 for a specific location considering soil conditions and climatic conditions. This model was used to look at N_2O emissions for US corn production by agricultural district. The production weighted average for EF_1 was 0.0119, the min was 0.0072 and the max was 0.0474. The distribution of the values is shown in the following figure. Note that the range would be different if the analysis was done at the state level instead of at the agricultural district level.

Figure ES- 1 Distribution of GNOC EF_1 for US Corn



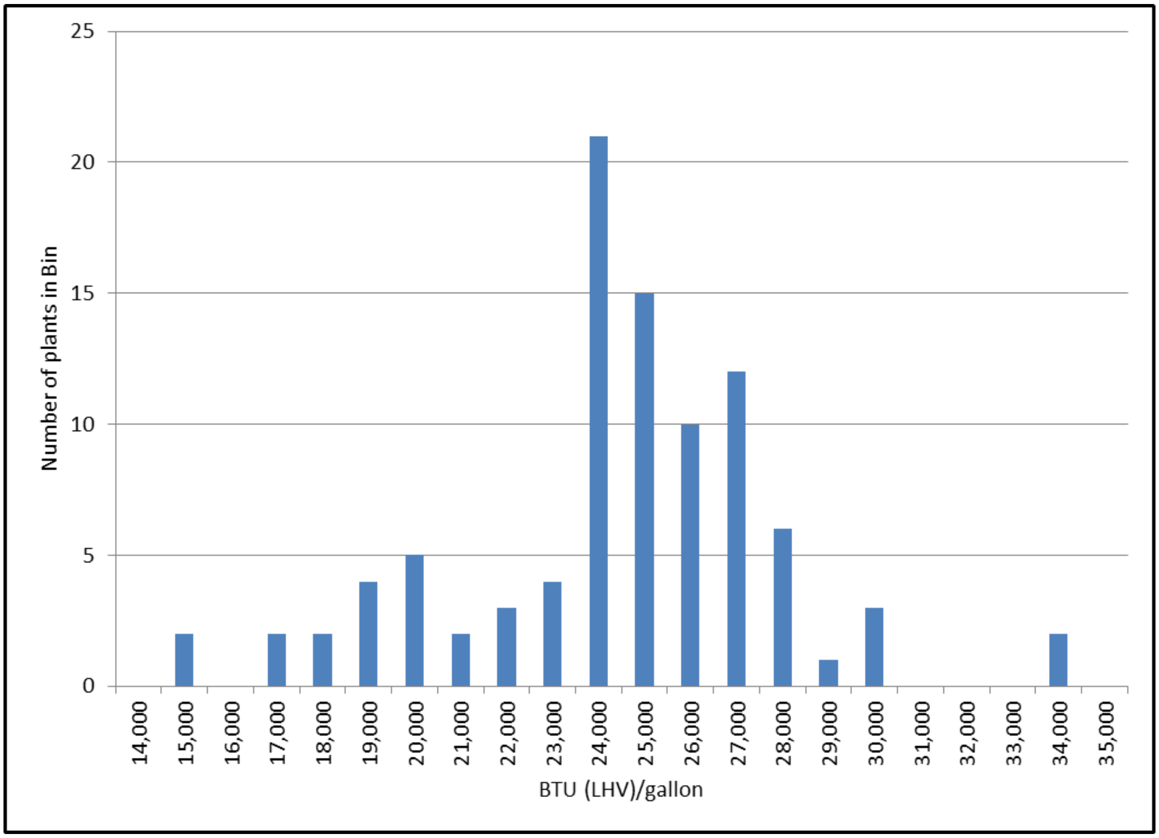
GNOC uses the IPCC Tier 1 emission factor for volatilization and either zero or the IPCC Tier 1 emission factors for leaching. The total N_2O emissions calculated by GREET and GNOC are almost identical. However GREET N_2O emissions are lower than would be calculated using the emission factors developed from the EPA NIR and the USDA GHG Inventory reports.

The default for EF_1 for crop residues in GREET could be increased to the same factor as used for synthetic fertilizer (0.0125) and GREET could consider including a factor to account for corn production on histosols. No changes to GHGenius are recommended.

The thermal energy use for all of the corn ethanol dry mills for the year 2014 was found and production data for about half of them was used to generate energy use per gallon information. The energy use default values in GREET and GHGenius are appropriate and no changes are required.

While the model default values are very close to the 2014 average values, there is a range of energy use for individual plants. Thermal energy requirements for individual plants ranged from 14,088 to 33,500 BTU (LHV)/gal. The distribution is shown in the following figure.

Figure ES- 2 Distribution of Energy Use at Corn Ethanol Dry Mills



The type of energy used in the corn ethanol plants has changed over time and in 2014, 98.3% of the energy used for thermal applications was natural gas. The coal use was only 1.1% and some of the plants that used coal switched to natural gas during 2014. The coal use in dry mill plants is probably close to zero in 2016. The default values in GREET and GHGenius should be changed to at least match the 2014 data.

There is a trend for ethanol plants to use less energy over time.

European ethanol plants do not produce as much electricity as the BioGrace model suggests. There is very limited public data on natural gas use in European ethanol plants but the values in BioGrace are grossly exaggerated and do not reflect the actual operation of the plants with respect to gas used and electricity produced.

Co-products can be dealt with in LCA models several different ways. The ISO recommended approach would be the displacement approach. This is the way that corn ethanol co-products were assessed in the RFS2 program and in the CARB LCFS (California Air Resources Board Low Carbon Fuel Standard) program. It is not the approach use in BioGrace, where energy allocation is used and the co-product credit is only a function of the emissions of producing corn and ethanol and the co-product yield.

GREET and GHGenius use the displacement approach as the default approach for corn ethanol. The GREET calculations for the emissions displaced require information on the species (beef, dairy, swine, and poultry) that the co-products are fed to and the feed displaced (corn, soymeal, and urea) by the co-products for each species. There is also a methane credit for distillers grains fed to beef. This information is combined with the quantity of distillers' grain produced per gallon of ethanol.

There is no regular accounting of DDG consumption by species but there have been estimates made by various researchers. In the GREET calculations the one factor that has the most influence on the final co-product credit is the fraction fed to beef. This is because of the extra credit for avoided methane emissions when the DDG is fed to beef. The GREET default vault value is 40.6%; two values found in the literature were 45 and 54%. GREET should also investigate the potential or a methane reduction for dairy cattle. Both of these changes would increase the co-product credit for corn ethanol. There is insufficient data available to develop a distribution of co-product use by species.

Counteracting this, the GREET value for the quantity of DDG produced is too high. The value in the model was established when ethanol yields were lower and DDG production was higher. As ethanol yields increase, DDG production drops at approximately twice the rate. In GHGenius the quantity of distillers' grains produced is a function of the ethanol yield, GREET should consider a similar approach.

There is a clear trend for reduced DDG production per gallon of ethanol produced. There is also a trend for increased extraction' of corn oil from the distillers' grain.

The range of values found in the literature review for the three corn ethanol parameters are shown in the following table. The plant energy use is from the EPA Flight dataset. The N_2O EF1 is from the GNOC tool, and the % DDG is from the limited literature available. The plant energy use and the N_2O emission factor represents variability in the data set and the % DDG consumed by beef is representative of the uncertainty in the available data.

Table ES- 1 Range of Values for Corn Ethanol Parameters

Parameter	Min	Average	Max
Plant thermal energy use, BTU/gal (LHV)	14,088	23,911	33,500
EF_1 for N_2O	0.0072	0.0119	0.0474
% DDG Consumed by beef	40	-	54

TASK 2 OTHER PATHWAYS

The three specific objectives for Task 2 were to:

1. Conduct a review of literature published between 2010 and 2015, including the literature used to support the default values in GREET 2014, GHGenius 4.03a, and BioGrace, to determine a range of values for key parameters.
2. Determine if there are additional key parameters not identified in E-102 for each of the pathways.
3. Scan the literature to assess potential future trends for the key parameters.

The pathways to be considered were petroleum fuels, natural gas, soybean biodiesel and renewable diesel, sugarcane ethanol and cellulosic ethanol. The findings are presented below.

PETROLEUM FUELS

The majority of the emissions from the production of refined petroleum products come from either the production of the crude oil or the refining of the crude oil into finished products. For both stages, energy use and fugitive emissions contribute to the production emissions.

The three models have very different levels of details in terms of how the GHG emissions associated with energy use for crude oil production are determined. GREET has been expanding this area in recent models with progressively more detail in the 2014, 2015, and 2016 versions. However 70% of the crude oil production still uses an original estimate of energy use from the 1990s literature. This value could be improved though the use of OPGEE (Oil Production Greenhouse gas Emissions Estimator) values or even the IOGP (International Association of Oil & Gas Producers) combined value for oil and gas production.

Primary data or even aggregated primary data is very scarce on a global basis. There is the IOGP data, which has a 15-year time series for 35 to 40% of the world's production but it combines oil and gas production and doesn't have the level of specificity that the models generally require.

It may be possible to extract some data from the EPA FLIGHT (Environmental Protection Agency Facility Level Information on Greenhouse Gases Tool) database but it must be extracted manually and the detail on what is reported at each facility is likely going to vary.

With the lack of availability of primary data, the OPGEE model is gaining in popularity as a tool to estimate the GHG emissions from oil production around the world. However, OPGEE is an engineering model and for many production fields the full data set required for the model is not available and default values are used. This will have a negative impact on the certainty of the results produced by the model. The full LCA models can be tuned to produce similar results to the OPGEE model.

Results from the OPGEE model indicate that there is a huge range in the energy required to produce crude oil ranging from less than 1% of the energy in the produced oil to more than 30% of the energy in the produced oil, with an average of 3.2%. The data from the IOGP has an average energy use for oil and gas production of 3% as well. However, since oil refineries are generally larger than individual oil fields aggregated data is probably a better measure of the range of energy use. The range of energy use for crude oil production is likely in the range of 2 to 10% of the energy in the crude for any given refinery.

There remains significant uncertainty with respect to methane emissions from crude oil production. The best data sources are the IOGP (~23 g CH_4/MM BTU) and the national inventory reports of UNFCCC (United Nations Framework Convention on Climate Change) Annex 1 countries (US is 150 g CH_4/MM BTU). There is a significant variation in the reported values from these two sources.

Top down estimations of methane emissions are generally much higher than the bottom up approaches that are used in inventory systems and in the models. With such a wide variation it is impossible to suggest a better range of values for use in the models.

There are generally good data sets on energy use in refineries at the national level and sometimes at the sub national levels. Refinery energy use is a function of many parameters and GHGenius and GREET are capable of adjusting energy use based on crude oil density and sulphur. Allocated energy use in the GREET model is between 10 and 12% of the energy in the finished products for diesel and gasoline. Unallocated energy use in GHGenius is between 6.7% and 11.4% of the energy produced.

There will be a range of values between refineries but due to the fungible nature of the products information on individual refineries is not particularly valuable.

Most of the information on vented and fugitive methane emissions from refineries is based on emission factors. The few actual measurements of methane from refineries are much higher than the emission factor based approach. The impact on the lifecycle GHG emissions of petroleum fuels is relatively small.

The available data shows that energy used for producing crude has increased in the past two decades but has been relatively stable for several years. Fugitive methane emissions from crude oil production have a downward trend over the past decade.

There are no apparent trends in refinery energy use or refinery methane emissions apparent from the long term data sets available.

The ranges of values found in the literature for the four parameters investigated are shown in the following table. None of the data sets identified were robust enough to report average values and thus the range of values represents primarily uncertainty although there is also clearly variability in all four parameters. Min and max values are not necessarily from the same data source.

Table ES- 2 Range of Values for Petroleum Parameters

Parameter	Min	Max
Crude oil energy use, energy consumed/energy recovered	2%	35%
Crude oil fugitive emissions, g CH_4/mm BTU	28	360
Refinery energy use, BTU consumed/BTU delivered	0.067	0.114
Refinery fugitive emissions, g CH_4/mm BTU	0.33	0.33

NATURAL GAS

This review is focused on three key parameters, fugitive emissions from the complete supply chain, the energy used for CNG (Compressed Natural Gas) compression, and the efficiency of the engines when operated on CNG.

There has been a large amount of work undertaken in recent years and reported in the literature on methane emissions throughout the natural gas supply chain. Most of the work has found a wide range in the results with the average being skewed by a relatively few "super emitters". The models use average values for the supply chain and given the fungible nature of the supply chain this is the appropriate approach for modeling. GREET and GHGenius both rely on the US NIR (National Inventory Report) emission data for natural gas fugitive emissions.

For natural gas compression there is very little information on fugitive emissions for the fuel dispensing stage of the lifecycle. There are several papers that identify the emissions but not the unit throughputs. Only one 2017 paper has quantified the emissions per unit of fuel. The average loss rate was 0.09% and while the range was provided for each component for all of the stations monitored, the overall range was not provided.

The three models use a similar approach to determining the compression energy requirements and all have similar inputs and results. However, there is very limited data available to support the values in the models. The one report that was identified that had compiled the inlet pressure conditions for 18 CNG stations had an average value 3 times higher than what is used in the models. However, most of the stations did have values that were similar to the model inputs, and the average was skewed by a few stations that had inlet pressures up to eight times the average value.

GREET and GHGenius both use the relative energy use between natural gas and liquid fuel engines to determine the combustion emissions. The most recent real world data from the United States for natural gas vehicles has very similar relative energy use as is currently in the models for normal driving cycles. There does appear to be some driving cycles, such as refuse trucks, where the CNG engines perform better than the diesel engines. These duty cycles are characterized by a lot of start and stop driving cycles and new diesel engines have difficulty maintaining temperatures for the emission control systems. Urban buses may have a similar problem but no recent information was found on the real world performance of these vehicles. The range of relative energy use is therefore dependent on the vehicle applications and within applications there is insufficient information available to determine representative ranges.

Of the three areas investigated, the only trend that is apparent is the reduction in fugitive methane emissions from the natural gas supply chain. There is a long term trend to reduced losses from the transmission and distribution portions of the supply chain. The methane losses from the gas production stage appear to have peaked about 10 years ago and have declined in the past decade. All four parameters are variable and uncertain.

Table ES- 3 Range of Values for Natural Gas Parameters

Parameter	Min	Max
Fugitive emissions, g CH_4/mm BTU	188	350
CNG Energy use, kWh/kg	0.25	0.57
CNG Fugitive emissions, % throughput	0	0.4%
Relative engine efficiency, diesel/NG	0.75	1.1

SOYBEAN BIODIESEL/RENEWABLE DIESEL

Three areas of uncertainty and variability were identified in the previous work (E-102): N_2O emissions, farm energy use, and the energy use for oilseed crushing and biodiesel/renewable diesel production.

There remains considerable uncertainty over the nitrogen content of the soybeans residues. Many of the papers in the literature continue to use the IPCC default value, which contains a value from a 1925 reference. All of the authors who have looked at the issue consider this to be too low. One of the challenges is that some of the root nodules decompose in the growing year and so any analysis that is done at the end of the year will miss that N in a measurement of residue nitrogen content.

The recent GREET update identified literature which had N_2O emissions ranging from 0.7 to 4.84 kg N_2O/ha. GREET now has a value of 1.84 kg N_2O/ha. Other sources identified in the recent literature are within this range

For farm energy use, GREET and GHGenius both use data from the USDA ARMS (Agricultural Resource Management Survey) program. A detailed look at the data from that program shows large variations in energy use from state to state with much of the variation apparently caused by energy used for irrigation. The energy used ranged from 379 MJ/acre to 3,317 MJ/acre, with an average of 825 MJ/acre. Energy used in soybean production in non-irrigated states is lower than the average and is in line with data from state level surveys.

There is only one set of public data on the energy use for soybean crushing and that is the 2008 NOPA (National Oilseed Processors Association) data, which was updated in 2015 with revised power consumption. There does appear to have been an issue with unit conversions or interpretation of the data set as the values in GREET, which were taken from a secondary energy source, do not align with the original NOPA data.

New data is available for biodiesel plant energy use. This data indicates slightly higher energy use than what is currently in GREET and GHGenius but much less than is in the BioGrace model.

For renewable diesel production only one data set was identified in the literature that is based on actual plant data. The feedstock, hydrogen, and electricity consumption are all higher than the values used in GREET, but so is the quantity of co-products produced.

In the parameters that were evaluated only the farm energy use has a long term trend. More no till agriculture, more efficient farm equipment and higher yields all lead to less energy use per unit of production. The other parameters, N_2O emissions and plant energy use, either have insufficient data available to identify trends or show no trend from the available data.

The range in the parameters is shown in the following table. The N_2O emission range is from the GNOC tool applied to the US Corn Belt, and the farm energy is the state level data from the 2012 USDA ARMS survey. The range reflects geographical variability and the average value is the average for all US soybean production. The soybean crushing energy min and max are different values from a US and a European survey, and the min and max values for biodiesel energy requirements are the differences between the GREET and BioGrace models.

Table ES- 4 Range of Values for Soybean Biodiesel Parameters

Parameter	Min	Average	Max
EF1 for N_2O	0.0072	0.0119	0.0474
Farm energy, BTU/bu	8,196	19,646	70,114
Soybean crushing energy, MJ/tonne seed	845	-	947
Biodiesel production energy, BYU/lb biodiesel	372	-	1,788

SUGARCANE ETHANOL

Four sugar cane ethanol parameters were investigated, the N_2O emissions in the sugar cane production stage, the energy used for mechanical harvesting, methane emissions from vinasse distribution, and the quantity of co-product electricity produced. All four parameters were subjects of literature searches. In most cases the literature searches turned up limited real world information.

The N_2O emissions are a function of the quantity of N applied and the emission factor. There remains very little information available on N_2O emissions for Brazilian sugarcane, especially compared to crops such as corn and soybeans in other parts of the world. The information that is available would suggest that the synthetic N fertilizer rates in GREET (0.8 kg) and GHGenius (1.1 kg) are too low and should be increased to about 1.2 kg N/tonne of cane.

The data on N_2O emission factors is limited in the literature. GREET uses a factor that is less than the IPCC Tier 1 default values. Many of the papers did use the Tier 1 default values in their analyses. There were also a few papers that did attempt to measure the N_2O emissions and develop overall emission factors. The range for an overall N_2O emission factor would be from 1.22% (GREET) to 1.84% (Otto et al).

Industry average data for fuel use in the sugarcane production stage is not available in the public domain. This is not unusual, as other crops have the same issues. The available literature has a wide range from 2.2 to 3.7 l diesel/tonne of cane. The values that are used in the models are in the middle of the range.

There has been additional research on methane emissions from sugarcane vinasse since the issue was first identified in the earlier CRC work. GREET 2016 has added this emission source to the sugarcane pathway. However the value used in GREET covers only a portion of the total methane sources and it appears that the information in the paper that was used for the data may have been misinterpreted as using GWP factors from the 5th Assessment report rather than the 3rd report that the original authors actually used. Since not all mills transport the vinasse in open channels the range for this source should be from zero to 90 g CH_4/tonne of cane.

The quantity of electricity that is exported to the grid in Brazil from sugarcane processing facilities is increasing. In 2015 40% of the mills exported power. A breakdown of power exports by the type of sugarcane mill was not identified but ethanol plants likely export between 25 and 35 kWh/tonne of cane (0.3 to 0.4 kWh/gal of ethanol) on average. The value in GREET 2016 is much higher than the industry average value. The range of power exported to the grid is from zero to 177 kWh/tonne of cane. The industry average is likely about 30 kWh/tonne in 2015.

There is an underlying trend for more of the sugar cane to be harvested mechanically and without burning. This suggests that more nitrogen will be used and more diesel fuel will be used as the trend develops. There is also a trend to more electricity being exported from the mills to the grid. This trend increases the co-product credits for the process and will offset the trend to higher nitrogen and diesel fuel use. The N_2O emission factor, while variable is also very uncertain. The other parameters have plant variability but due to the lack of good data the average values are also uncertain.

Table ES- 5 Range of Values for Sugarcane Ethanol Parameters

Parameter	Min	Max
N_2O EF_1	0.9%	5.6%
Harvesting Energy, BTU/tonne cane	75,000	125,000
Methane Emissions, g CH_4/tonne cane	0	90
Power sold, kWh/tonne cane	0	177

CELLULOSIC ETHANOL

The modelling of the cellulosic ethanol pathway in GREET 2014 onward is much more comprehensive than it was in GREET 2013. However, the default values used in GREET, GHGenius, and BioGrace continue to have a high degree of uncertainty.

The recent peer reviewed literature does not contain any information from the few operating demonstration plants, as the process developers consider this kind of information confidential.

The CARB applications that have been submitted for three of the operating demonstration plants are heavily redacted but they do indicate that different process philosophies are being used by different developers. There is an order of magnitude difference in the overall CI for the three applications. The limited information that can be discerned from the applications confirms that the chemical usage and the electric power production are parameters that are variable and have a significant impact on the results. It is not possible to confidently predict a range of values for these two sets of parameters.

There is no information available in the literature that would allow any potential future trends for the important parameters to be developed.

Insufficient information was identified in the literature to determine ranges for the parameters investigated. All remain uncertain.

TASK 3 MONTE CARLO AND SENSITIVITY ANALYSES

Monte Carlo simulations and sensitivity analysis was undertaken on the six pathways for the parameters that were investigated as part of the literature review. The same values for the parameters were used in each model. This also involved some harmonization of the models where it was feasible to align the systems being modelled. Due to the different structures of the models a complete harmonization of the modelling frameworks is not possible.

For the corn ethanol pathway, the GREET and GHGenius models provide very similar carbon intensity results (after aligning the system boundaries to exclude changes in soil carbon) and the distribution of the Monte Carlo results is also very similar. The BioGrace model uses energy allocation for the co-product and as a result provides lower GHG emissions than the other two models. Harmonizing the production system to use purchased power rather than exporting power and using the same thermal energy and N_2O emission factors as the other two models, increased the GHG emissions compared to the RED default value. BioGrace did produce a different Monte Carlo distribution than GREET and GHGenius but it doesn't appear to be related to the different method for allocation emissions to the co-product.

The literature search did not find a significant amount of data on the distribution of the key parameters investigated for the pathways other than the corn ethanol pathway. As a result, the definition of the probability distribution functions for the input parameters for the other five pathways are mostly estimates.

The structures of the petroleum pathways in GREET and GHGenius are quite different and it is not possible to fully harmonize the two models. However, using the four parameters investigated in the literature search and using the same input values for those parameters in each of the models did produce quite similar Monte Carlo distributions. Changes in the refining efficiency produced larger changes in the GHG emissions than changes in the energy used to produce crude oil but the quality of the refinery efficiency data is much higher than the quality of the data on crude oil energy use so the uncertainty of the crude oil energy use may still have a greater impact on the overall results.

The GREET and GHGenius natural gas pathways are quite similar and relatively easy to harmonize. The largest difference in the CNG pathways between the models is in the distribution of the natural gas where GHGenius has higher methane emissions. One of the very recent papers in this area would indicate that these emissions in GHGenius are too high and in GREET are too low. Updating both models would bring the results even closer together.

Aligning the transportation assumption for the soybean biodiesel pathway between the models greatly reduced the soybean biodiesel GHG emissions in BioGrace and brought the emissions into the same range as the other models. The energy allocation approach used in BioGrace compared to the mass allocation for oilseed crushing used in GREET and GHGenius will produce higher GHG emissions and that is seen in the results.

The soybean renewable diesel results for GREET and GHGenius are quite close in magnitude and in the Monte Carlo distribution. It is easier to align the renewable diesel pathways in the two models than the biodiesel pathways due to the lack of significant fossil carbon inputs to the process and the need to deal with the fossil carbon in the fuel and co-products. BioGrace does not have a soybean renewable diesel pathway.

The sugarcane ethanol pathways were also aligned with similar transportation scenarios to eliminate that variability between the models. The normalized Monte Carlo results for the three models are very similar. Most of the differences between the models are due to different assumptions regarding lime and limestone.

The literature survey found very little real world data on cellulosic ethanol production systems. Even when the yield, power produced, and two of the key chemical inputs were harmonized there are significant differences in the results between GREET and GHGenius. The distributions of the normalized Monte Carlo results were also quite different.

TABLE OF CONTENTS

List of Tables

LIST OF FIGURES

1. INTRODUCTION

The Coordinating Research Council (CRC) is a non-profit organization that directs, through committee action, engineering and environmental studies on the interaction between automotive/other mobility equipment and petroleum products. The formal objective of CRC is to encourage and promote the arts and sciences by directing scientific cooperative research to develop the best possible combinations of fuels, lubricants, and the equipment in which they are used, and to afford a means of cooperation with the Government on matters of national or international interest within this field.

Through CRC, personnel in the automotive equipment and other related mobility industries and in the energy industries can join together, and can join with Government, to work on mutual problems. CRC has no facilities for conducting direct research.

More information on the CRC can be found on their website, https://crcao.org/about/index.html.

1.1 OBJECTIVES

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 vehicle and fuel 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 fuel options. LCA models can be of great assistance for this.

In 2013, the CRC commissioned a study (CRC Project E-102) to better quantify sources of uncertainty and variability in selected LCA models that are being used to regulate fuels by conducting 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 was discussed, and pathway variability and overall model uncertainty for the different pathways was assessed. The study was carried out by $(S\&T)^2$ Consultants Inc. and the final report is available from the CRC.

The follow on project, CRC E-102-2, is intended to support the uncertainty analysis that was undertaken in CRC Project E-102 with supporting data from published literature. The objective is to find a range of values and/or parameter distributions outside of the default values for a specific pathway in GREET 2014, GHGenius 4.03a, and BioGrace V4c. The literature cited for the default values for these specific models is to be included in this work. GREET has annual model releases, so GREET 2015 and 2016 are now available. This work also considered the literature cited for changing the default values in these two updated models.

Unlike project E-102, which looked at the well to wheel emissions of the vehicle and fuel pathways, this work only considered the well to tank portion of the pathways with one exception, the relative efficiency of the heavy duty natural gas engine relative to the diesel engine.

1.2 Scope of Work

The CRC has identified three primary tasks for this project; the tasks are briefly described below.

1.2.1 Task 1: Review of Literature for the Corn Ethanol Pathway

There are three specific objectives for this task. The first is to review the literature for N_2O emissions for corn production, the second is to review the literature on energy use in the corn ethanol plants, and the third is to consider co-product issues.

The time horizon for the literature review is the period from 2010 to 2016. The literature review should include the literature cited in each of the models, as well as the available literature from the time period under consideration. Google Scholar was the primary tool used for the literature searches for all pathways.

The search terms used in Google Scholar were meant to be specific and return papers that contained meaningful information. The report appendices contain information on the search terms used for each pathway, the number of results, and the top ranked results for each set of search terms. Not all papers that were returned in the search actually contained any primary data that the search was looking for. The important papers that did have useful information on the specific topic are summarized in the main body of the report. These papers are included in the references.

The goal of the literature review is to identify the range of values that could be used in the different models. The range of values provided should be representative of the areas covered by each of the models. The N_2O emission values should be consistent with the IPCC methodology used by the models and the actual calculation methodology used by the models themselves. The energy use values should include the type of energy (coal, natural gas, electric power, etc.) as well as the quantities of energy consumed. The energy use should also consider the different ethanol plant configurations in the different regions covered by the models.

1.2.2 Task 2: Review of Literature for other E-102 Pathways

The CRC Project E-102 also looked at the following pathways in the different LCA models:

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

The scope of work is to undertake a literature review to find the range of values for the key parameters, to determine if there are additional key values to the ones identified in E-102, and to scan the literature to assess future trends for the key parameters.

1.2.3 Task 3: Monte Carlo Simulations

Task 3 involved using the information generated in Tasks 1 and 2 and running Monte Carlo simulations, using the same uncertainty parameters, in each the three LCA models. Some harmonization of the models was done prior to running the Monte Carlo simulations in order to produce the most comparable results possible.

2. CORN ETHANOL PATHWAY

Corn ethanol is the world's largest volume renewable fuel and is thus an important pathway. This review covers three aspects of the corn ethanol pathway where there is some uncertainty and variability surrounding the input data. The three areas are the N_2O emissions associated with corn production, the type and quantity of energy used in the ethanol plant, and the treatment and value attributed to the co-products. Each of these three areas has been investigated and is reported on in the following sections.

2.1 CORN PRODUCTION N_2O EMISSIONS

Corn production N_2O emissions are derived from the decomposition of nitrogen fertilizers and crop residues. These emissions are usually the second largest contributor to the corn ethanol lifecycle emissions after the ethanol plant energy use.

Emissions of N_2O from agricultural soils consist of direct and indirect emissions. The emissions of N_2O from anthropogenic nitrogen inputs occur directly from the soils to which the nitrogen is added, and also indirectly through two pathways:

i) volatilization of nitrogen from synthetic fertilizer and manure as NH_3 and NOx and its subsequent deposition off-site; and

ii) leaching and runoff of synthetic fertilizer, manure and crop residue N. Changes in crop rotations and management practices such as summerfallow, tillage and irrigation, can also affect direct N_2O emissions by altering mineralization of organic nitrogen, nitrification and denitrification.

The IPCC methodology for determining the direct and indirect emissions are discussed below.

2.1.1 Direct Emissions

The IPCC (IPCC, 2006) equation for the direct emissions is:

$$N_2O=(F_{SN}+F_{ON}+F_{CR}+F_{SOM})*EF_1$$

Where:

N_2O = annual direct N_2O–N emissions from N inputs to managed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}

F_{ON} = annual amount of animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr^{-1}

F_{CR} = annual amount of N in crop residues (above-ground and below-ground), returned to soils, kg N yr^{-1}

F_{SOM} = annual amount of N in mineral soils that is mineralized, in association with loss of soil C from soil organic matter as a result of changes to land use or management, kg N yr^{-1}

EF_1= Emission factor. Tier 1 value is 0.01

The treatment of manure in an LCA can vary. The FAO livestock LCA guidelines recommend that the emissions from manure should be included in the livestock LCA unless there is significant revenue derived from the sale of manure. GREET is usually run with no manure addition as manure application was added to GREET 2015 as part of the land management modeling changes. GHGenius does allow for the modelling of N_2O emissions from manure application for field crops and includes some manure addition in the base case.

2.1.2 Indirect Emissions

Indirect emissions will result from the volatilization of applied nitrogen and from nitrogen that is leached from the soil. The calculated emissions from volatilization in the Tier 1 IPCC methodology are:

$$N_2O_{(ATD)}–N = (F_{SN} \bullet Frac_{GASF} + F_{ON} \bullet Frac_{GASM}) \bullet EF_4$$

Where:

$N_2O_{(ATD)}$–N = annual amount of N_2O–N produced from atmospheric deposition of N volatilized from managed soils, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertilizer N applied to soils, kg N yr^{-1}

$Frac_{GASF}$ = fraction of synthetic fertilizer N that volatilizes as NH_3 and NOx, kg N volatilized (kg of N applied)$^{-1}$

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils, kg N yr^{-1}

$Frac_{GASM}$ = fraction of applied organic N fertilizer materials (FON) that volatilizes as NH_3 and NOx, kg N volatilized (kg of N applied or deposited)$^{-1}$

EF_4 = emission factor for N_2O emissions from atmospheric deposition of N on soils and water surfaces, [kg N–N_2O (kg NH3–N + NOx–N volatilised)$^{-1}$]

The IPCC Tier 1 default values are for $Frac_{GASF}$ (0.10), $Frac_{GASM}$ (0.20), and EF_4 (0.01).

The equation for the indirect leached emissions is:

$$N_2O_{(L)}–N = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \bullet Frac_{LEACH} \bullet EF_5$$

Where:

$N_2O(L)$–N = annual amount of N_2O–N produced from leaching and runoff of N additions to managed soils in regions where leaching/runoff occurs, kg N_2O–N yr^{-1}

F_{SN} = annual amount of synthetic fertilizer N applied to soils in regions where leaching/runoff occurs, kg N/yr.

F_{ON} = annual amount of managed animal manure, compost, sewage sludge and other organic N additions applied to soils in regions where leaching/runoff occurs, kg N yr^{-1}

F_{CR} = amount of N in crop residues (above- and below-ground), including N-fixing crops, and from forage/pasture renewal, returned to soils annually in regions where leaching/runoff occurs, kg N yr^{-1}

F_{SOM} = annual amount of N mineralized in mineral soils associated with loss of soil C from soil organic matter as a result of changes to land use or management in regions where leaching/runoff occurs, kg N yr^{-1}

$Frac_{LEACH}$-(H) = fraction of all N added to/mineralized in managed soils in regions where leaching/runoff occurs that is lost through leaching and runoff, kg N (kg of N additions)$^{-1}$

EF_5 = emission factor for N_2O emissions from N leaching and runoff, kg N_2O–N (kg N leached and runoff)$^{-1}$

The IPCC Tier 1 default values are, for $Frac_{leach}$ (0.30), and EF_5 (0.0075).

The total N_2O emissions are the sum of the direct and the indirect emissions. When the IPCC Tier 1 default values are used the overall emission factor for nitrogen fertilizer is 1.325% and for crop residues it is 1.225%, as shown below.

$$\text{Direct } N_2O = (F_{SN}+F_{ON}+F_{CR}+F_{SOM}) \bullet 0.01$$

$$\text{Indirect } N_2O \text{ from Volatile} = (F_{SN} \bullet 0.01 + F_{ON} \bullet 0.02) \bullet 0.10$$

$$\text{Indirect } N_2O \text{ from leaching} = (F_{SN} + F_{ON} + F_{CR} + F_{SOM}) \bullet 0.30 \bullet 0.0075$$

For synthetic nitrogen fertilizer the value is 0.01 (direct) +0.001 (indirect vol) +0.00225 (indirect leach)=0.01325 or 1.325%.

For crop residue the value is 0.01 (direct) +0.00225 (indirect leach)=0.01225 or 1.225%.

2.1.3 Existing Model Values

GREET and GHGenius take a similar approach to calculating the N_2O emissions and generally follow the approach recommended by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. BioGrace is less transparent in the N_2O calculations unless the user chooses to use the IPCC 2006 methodology. This methodology is not used for the EU RED default values.

2.1.3.1 GREET 2015

In GREET, the synthetic fertilizer emission factor is a combination of the direct and indirect emissions and includes a direct emission factor (EF_1) of 0.012, an indirect factor for volatilized emissions of 0.01 kg N_2O–N/kg N volatized ($Frac_{gas}$)* 0.10 kg N volatized/kg N applied (EF_4), and indirect leaching factor of 0.0075kg N_2O–N/kg N leaching & runoff (EF_5)* 0.30 kg N leaching & runoff/kg N applied ($Frac_{leach}$).

For the synthetic nitrogen fertilizer all of the values except EF_1 are IPCC Tier 1 default values. The EF_1 value is based on a review of the literature from which the GREET developers developed a statistically best-fit distribution, a Weibull distribution, with goodness-of-fit tests such as Kolmogorov Smirnov and Chi-Squared tests, to address the uncertainty in fertilizer-induced N_2O emissions. The parameters (alpha, beta and gamma) of the developed Weibull distribution are 0.907, 0.0105 and 0, respectively. This distribution function results in a mean value of 1.20%, a 10 percentile (P10) value of 0.088%, and a 90 percentile (P90) value of 2.631% (Wang et al , 2012).

For the crop residues the emission factor is based on all IPCC Tier 1 values, including EF_1. There are no volatilization emissions from crop residues in the IPCC approach. This was a change made for GREET 2015. The crop residue emission factor probably should use the same EF_1 as synthetic nitrogen and should be 0.01425 rather than 0.01225.

The GREET N_2O emission calculation becomes very simple, as is shown below.

$$\text{Corn } N_2O \text{ emissions} = (F_{sn}*.01525 + F_{cr}*.01225)*44/28$$

The crop residue N in GREET is 141.6 grams/bushel. The simple N_2O emission factor (all N_2O emissions divided by synthetic fertilizer) in GREET 2015 is 1.93%. No changes were made in GREET 2016 for these emission factors.

2.1.3.2 GHGenius 4.03a

GHGenius also uses the IPCC methodology for the N_2O calculations. The N_2O emission factors are regionalized in GHGenius. The US factors are discussed here. The emission factors used are compared to those used in GREET in the following table.

Table 16-1 GHGenius and GREET 2015 N_2O Emission Factors

Emission factors	GREET 2015	GHGenius
EF_1 Syn fert	0.012	0.0125
EF_1 crop residue	0.010	0.0125
EF_4	0.01	0.01
EF_5	0.0075	0.0075
$Frac_{gasf}$	0.10	0.10
$Frac_{leach}$	0.30	0.30

GHGenius also includes N_2O emissions resulting from a loss of soil carbon (F_{SOM}) but for US corn production there is only a small gain in soil carbon so this factor is zero. One additional factor is that GHGenius includes N_2O emissions from the cultivation of histosols (peat soils). It is estimated that 1% of US corn is grown on these soils and that there are emissions of 8000 g N_2O/ha/year from these soils (an IPCC factor).

The crop residue nitrogen in GHGenius is 131 g N/bushel of corn. It is calculated based on the nitrogen content of the above and below ground residue, and the mass of crop residue that remains in the field. It is assumed that 5% of the total crop reside is removed from the field. This could be stover that is used for feed, bedding, or other applications. Without this factor the residue contribution is essentially the same as GREET.

The differences between the two models are EF_1 (0.0005 higher in GHGenius for fertilizer and 0.0025 higher for crop residue) and the inclusion of N_2O emissions from cultivated histosols in GHGenius. The simple N_2O emission factor in GHGenius is 2.03%.

2.1.3.3 BioGrace

BioGrace offers two options for N_2O emissions. There is the default value, which has a simple N_2O emission factor of 1.58%, or users can use the IPCC approach. The simple approach is not transparent and provides no insight into how it is calculated.

The model uses a 185% higher crop residue N factor than GHGenius or GREET and this accounts for the higher N_2O emissions. The crop residue factor is calculated from IPCC default values whereas the values in GREET and GHGenius are based on multiple published studies of US corn production and analysis. The IPCC approach uses all Tier 1 default values and returns a simple N_2O emission factor of 2.22%. This higher factor is driven by much more residue per unit of corn produced.

2.1.3.4 Model Summary

The N_2O emission parameters for each of the models are summarized in the following table for ease of comparison.

Table 1-2 N_2O Emission Parameter Summary

	GREET 2015		GHGenius 4.03a		BioGrace	
	Fert	Crop Res	Fert	Crop Res	Fert	Crop Res
EF_1	0.012	0.010	0.0125	0.0125	0.01	0.01
$Frac_{GASF}$	0.10	0.0	0.10	0.0	0.10	0.0
EF_4	0.10	0.0	0.10	0.0	0.10	0.0
$Frac_{LEACH}$	0.30	0.30	0.30	0.30	0.30	0.30
EF_5	0.0075	0.0075	0.0075	0.0075	0.0075	0.0075
Crop residue N, g/bu		141.6		131		401
Overall N	1.93%		2.03%		2.22%	

The differences between the models are small except for the quantity of nitrogen in the crop residue.

2.1.4 Literature Search

The literature search has focussed on the period from 2010 to 2016. In Appendix 1 the search terms, number of papers returned, and a listing of some of the most relevant papers for each search term is presented. By including the search terms “Literature Survey” and “Meta-analysis” the search also focussed on studies that included more than one site and therefore would be more representative of regional values. However there were very few of the papers that were returned by the search that had data that would be useful for the models.

From the search it is obvious that this is a complex issue and that the emissions depend on more than just the rate at which the nitrogen is applied. Agronomic and climatic conditions have definite roles to play.

There is a growing body of knowledge that suggest the linear approach employed by the IPCC may not be the best approach to use and that emissions can increase rapidly when excess nitrogen is applied. A few of the papers are discussed below.

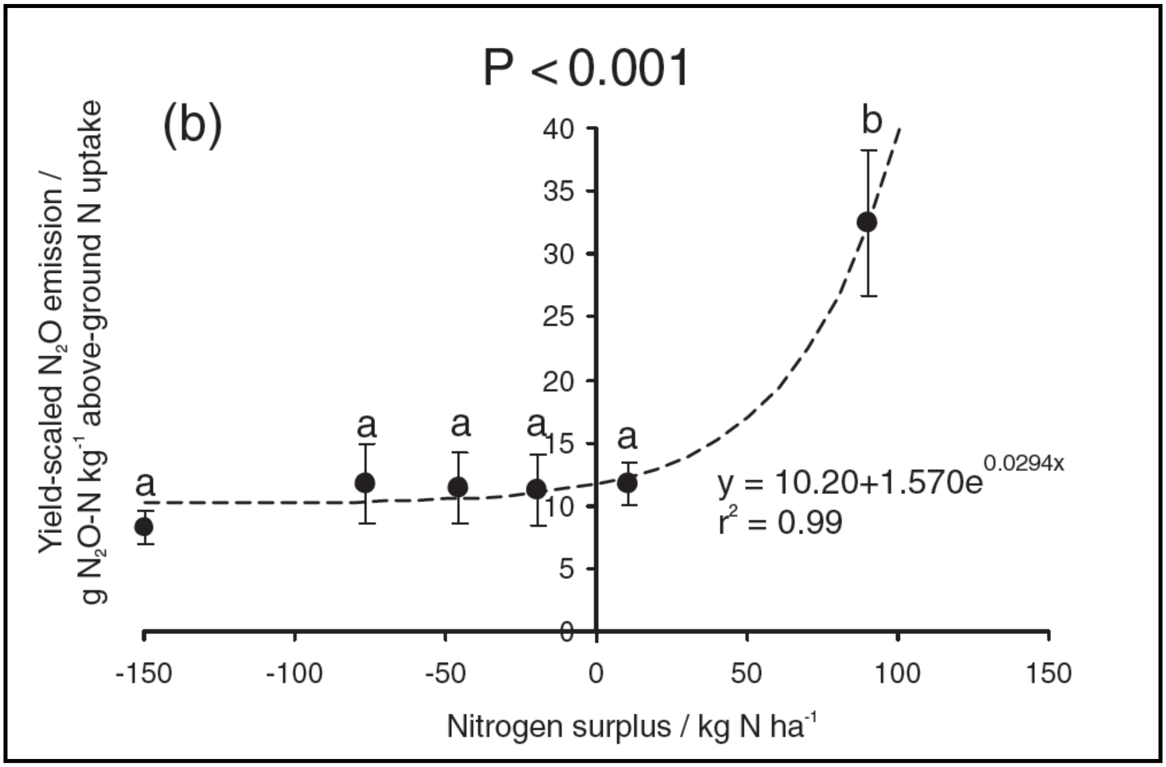
2.1.4.1 Van Groenigen et al 2010. Towards an agronomic assessment of N_2O emissions: a case study for arable crops

This paper took a different approach to estimating N_2O emissions than that used in the IPCC guidance and the models. The approach does require more data than is currently available in most cases.

The paper analyzed 19 independent studies that included 147 data points. The authors postulate that, in a world with a growing demand for food, fuel and fibre, expressing N_2O emissions as a function of land area or fertilizer application rate is not helpful and may even be counterproductive. Emissions should be assessed as a function of crop N uptake and crop yield. When N_2O emissions are correspondingly placed within such an agronomic framework, crops growing close to their yield potential in intensive forms of agriculture with high Nitrogen Use Efficiency (NUE) may lead to smallest yield-scaled N_2O emissions.

The following figure shows the finding graphically.

Figure 1-1 N_2O Emissions vs. Nitrogen Surplus



The non-linear relationship between N_2O emissions and nitrogen application rates is a potential explanation of the side variation seen in many of the published site studies. The authors recommend routine reporting of crop N uptake rates in N_2O emission studies.

2.1.4.2 Lesschen at al 2011. Differentiation of nitrous oxide emission factors for agricultural soils

This paper developed an approach to determining N_2O emissions that depend not only on N input sources but also on environmental conditions. The experiment investigated the effects of 16 sources of N input, three soil types, two land-use types and annual precipitation on the N_2O EF. The derived EF inference scheme performed on average better than the default IPCC EF. The use of differentiated EFs, including different regional conditions, allows accounting for the effects of more mitigation measures and offers countries a possibility to use a Tier 2 approach.

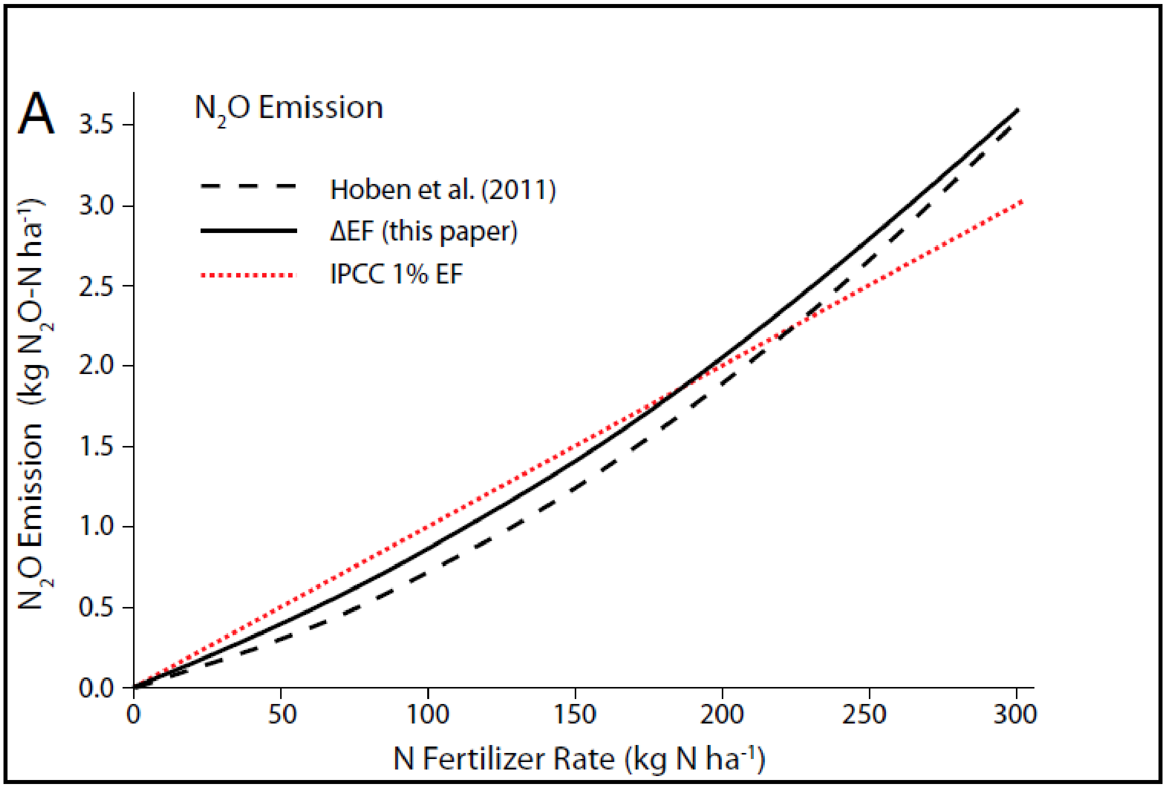
The paper demonstrated that, despite high uncertainties in N_2O emissions and poor quantification for some factors, differentiated N_2O EFs can perform better than a single default EF. The use of differentiated EFs accounts for the regional variation in soils, land use, crop management and climate conditions, which will result in more realistic spatial patterns of N_2O emissions. However, the total estimated direct N_2O soil emission in Europe is more or less the same for the IPCC 1% EF and the EF inference scheme developed in this paper although the variation among countries is much larger.

2.1.4.3 Shcherbak et al 2014. Global metaanalysis of the nonlinear response of soil nitrous oxide (N_2O) emissions to fertilizer nitrogen

The findings of this paper were that Nitrogen (N) fertilizer rate is the best single predictor of N_2O emissions from agricultural soils, but it is a relatively imprecise estimator. Accumulating evidence suggests that the emission response to increasing N input is exponential rather than linear, as assumed by Intergovernmental Panel on Climate Change methodologies. They performed a metaanalysis to test the generalizability of this pattern. From 78 published studies (233 site-years) with at least three N-input levels, they calculated N_2O emission factors (EFs) for each nonzero input level as a percentage of N input converted to N_2O emissions. They found that the N_2O response to N inputs grew significantly faster than linear for synthetic fertilizers and for most crop types. N-fixing crops had a higher rate of change in EF (ΔEF) than others. A higher ΔEF was also evident in soils with carbon >1.5% and soils with pH <7, and where fertilizer was applied only once annually. The results suggest a general trend of exponentially increasing N_2O emissions as N inputs increase to exceed crop needs.

The authors developed a quadratic equation and compared it to the IPCC methodology. The results are shown below.

Figure 1-2 Comparison of Direct Emissions from IPCC and Quadratic Model



2.1.5 Public Data Sources

There are public data sources for N_2O emissions available as a result of the reporting that UNFCCC Annex 1 countries undertake and there are public models available. The data from some of these sources is discussed below.

2.1.5.1 *United States*

Two data sources are available for the United States: the EPA National Inventory Report that is prepared annually for submission to the UNFCCC and a more detailed USDA GHG Inventory report that is prepared every five years. The methodology is harmonized between the reports and the primary difference is the frequency and the level of detail available.

2.1.5.1.1 EPA NIR

The N_2O emissions for crop production are included in the National Inventory Report that is prepared annually by the EPA. The report describes the methodology used and provides some detailed information that allows for a comparison with the values used in the IPCC methodology.

The method for the direct N_2O emissions is based on using results from process-based models and measured N_2O emissions in combination with scaling factors based on U.S. specific empirical data on a seasonal timescale combined with a Tier 1 approach for some of the minor crops. Corn is in the group of crops that utilize the Tier 3 approach.

The process-based modeling (a combined approach using the DAYCENT and DNDC models) combined with field data analysis are used to derive base emission rates for the major cropping systems and dominant soil texture classes in each USDA Land Resource Region. In cases where there are insufficient empirical data to derive a base emission rate, the base emission rate is based on the IPCC default factor. The base emission factors are adjusted by scaling factors related to specific crop management practices that are derived from experimental data.

For indirect emissions, the EPA uses the IPCC equation. The IPCC defaults are used for estimating the proportion of nitrogen that is subject to leaching, runoff, and volatilization. In land parcels where the precipitation plus irrigation water input is less than 80 percent of the potential evapotranspiration, nitrogen leaching and runoff are considered negligible and no indirect N_2O emissions are estimated from leaching and runoff.

An analysis of the data in the NIR yields the emission factors shown in the following table.

Table 1-3 US NIR N_2O Emission Factors

Parameter	IPCC Tier 1	Value
Direct Emissions, EF_1	0.010	0.0115
Indirect Emissions, volatilization, EF_4	0.001	0.0009
Indirect Emissions, leaching, $Frac_{LEACH}*EF_5$	0.00225	0.0016
Total	0.01325	0.0140

The emission factors derived from the EPA data may not be exactly the factors that should apply to corn production as they are aggregated for a number of crops (alfalfa hay, barley, corn, cotton, dry beans, grass hay, grass-clover hay, oats, onions, peanuts, potatoes, rice, sorghum, soybeans, sugar beets, sunflowers, tomatoes, and wheat) and some of these are grown in areas where corn is not grown.

2.1.5.1.2 USDA GHG Inventory 2008-2013

The USDA GHG inventory is published every five years and the most recent report was published in September 2016. This report has more disaggregated data than the US EPA report but uses the same methodology. The emissions for corn and soybean production are combined and reported as row crops. The direct and indirect emissions (volatilization and leaching) are reported for each major land resource area (MLRA) that had row crops and the total N input for the row crops is also reported. From this data it is possible to calculate the emission factors that would be used in the IPCC equations that the models use. The results are shown below.

Table 1-4 US USDA N_2O Emission Factors

Parameter	IPCC Tier 1	Value
Direct Emissions, EF_1	0.010	0.0150
Indirect Emissions, volatilization, EF_4	0.001	0.0023
Indirect Emissions, leaching, $Frac_{LEACH}*EF_5$	0.00225	0.0013
Total	0.01325	0.0186

The emission factors are higher than those calculated from the EPA data but they are specific to corn and soybeans and thus more regionally precise. The emissions do include some N_2O resulting from the mineralization of soil N resulting from a loss of soil carbon but this additional source of N contributes less than 1% of the N for the row crop category.

2.1.5.1.3 ICF USDA Corn Ethanol Report

ICF (Flugge et al, 2017) reviewed the EPA RFS2 GHG analysis considering new information that has become available since 2010. They did not have access to the EPA models but they did make some estimates of the changes that the new data may have on the lifecycle GHG emissions for corn ethanol.

The N_2O emissions were calculated using the IPCC Tier 1 default emission factors. The difference in the emissions for corn farming and fertilizer N2O emissions between the EPA RIA and the ICF estimates were small and were attributed to the use of a lower GWP for N_2O from the 4th Assessment Report.

2.1.5.2 Canada

The Canada IPCC Tier 2 methodology estimates direct N_2O emissions from synthetic nitrogen fertilizer application on agricultural soils, and takes into account moisture regimes and topographic conditions. Emissions of N_2O are estimated by ecodistrict and are scaled up to regional, provincial and national levels.

A modified IPCC Tier 1 methodology is used to estimate indirect N_2O emissions from leaching, runoff and erosion of fertilizers, manure, and crop residue nitrogen from agricultural soils. Indirect N_2O emissions from runoff and leaching of nitrogen at the ecodistrict level are estimated using $FRAC_{LEACH}$ multiplied by the amount of synthetic fertilizer nitrogen, non-volatilized manure nitrogen and crop residue nitrogen and by an emission factor of 0.0075 kg N_2O-N/kg N (EF_5).

The default value for the fraction of nitrogen that is lost through leaching and runoff ($FRAC_{LEACH}$) in the Revised 1996 Guidelines is 0.3; however, $FRAC_{LEACH}$ can reach values as low as 0.05 in regions where rainfall is much lower than potential evapotranspiration (IPCC, 2006), such as in the Prairie region of Canada. Accordingly, it is assumed that $FRAC_{LEACH}$ would vary among ecodistricts from a low of 0.05 to a high of 0.3. For ecodistricts with no moisture deficit during the growing season (May through October), the maximum $FRAC_{LEACH}$ value of 0.3 recommended by the IPCC (2006) Guidelines is assigned. The minimum $FRAC_{LEACH}$ value of 0.05 is assigned to ecodistricts with the greatest moisture deficit. For the remaining ecodistricts, $FRAC_{LEACH}$ is estimated by the linear extrapolation of the two end-points described above.

Since the emission factors are available at the regional level it is possible to take the regional crop production data and develop average crop specific N_2O emission factors for those factors that don't follow the IPCC default values. Those values for corn production in Canada are shown below. For the corn producing areas EF_1 ranges from 0.0091 to 0.0169, and $Frac_{LEACH}$ ranges from 0.175 to 0.30.

Table 1-5 Canada N_2O Emissions Factors for Corn

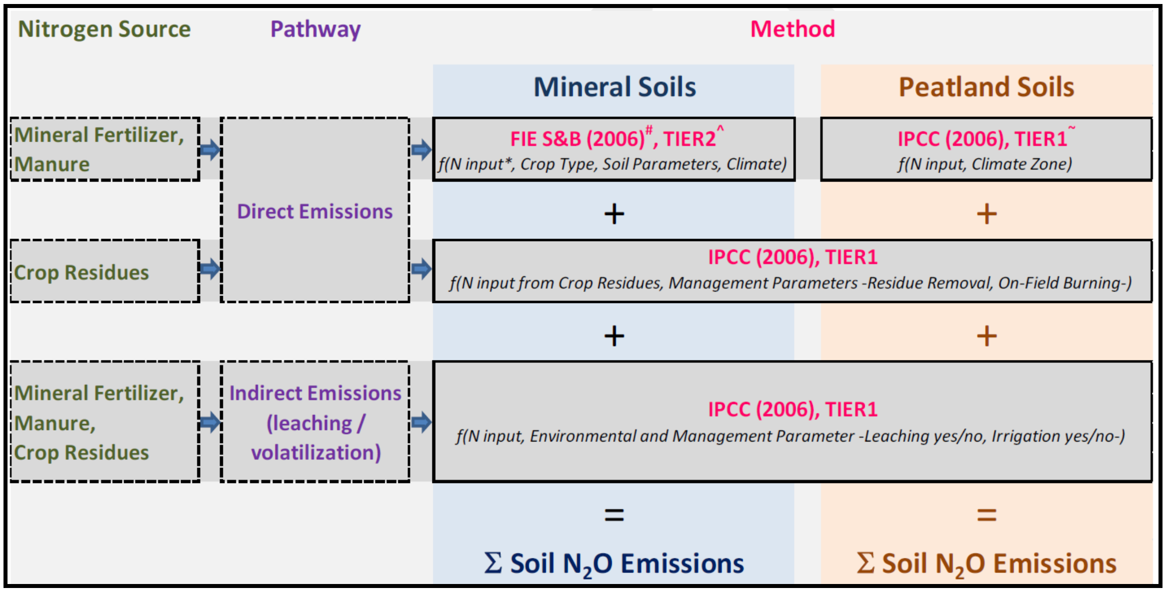
Parameter	IPCC Tier 1	Value
Direct Emissions, EF_1	0.010	0.0146
Indirect Emissions, volatilization, EF_4	0.001	0.001
$Frac_{LEACH}$	0.30	0.26
Indirect Emissions, leaching, $Frac_{LEACH}$*EF_5	0.00225	0.00195
Total	0.01325	0.01775

2.1.5.3 JRC GNOC

The Global Nitrous Oxide Calculator (GNOC) online tool has been developed in the context of the "Assessment of GHG default emissions from biofuels in EU legislation". The tool facilitates the calculation soil N_2O emissions from biofuel crop calculation for each location globally. The online calculations are consistent with the method applied in the assessment of GHG default emissions. The user is provided with default environmental and management data, which is required for the calculations at the selected location.

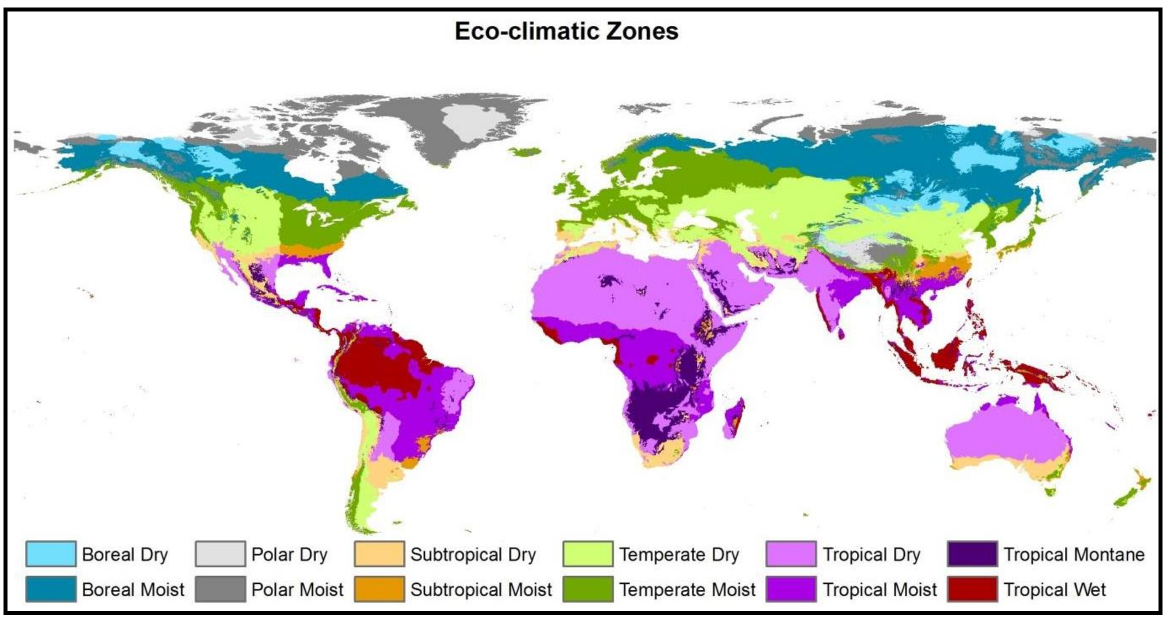
The emissions calculations are based on IPCC (2006) combining Tier 1 and Tier 2 approaches. IPCC distinguishes different pathways (direct, indirect) and different nitrogen sources (e.g. mineral fertilizer, manure, crop residues, drained organic soils). For the indirect pathways (leaching/runoff and volatilization), the GNOC follows the IPCC Tier 1 approach for all nitrogen sources. The same holds for direct emissions from crop residues and drained organic soils. For the direct emissions from mineral fertilizer and manure application, the IPCC Tier 1 single emission factor is disaggregated taking into account differences in management and environmental conditions. The disaggregated (Tier 2) emission factors are based on the fertilizer induced emission concept applying the statistical model developed by Stehfest and Bouwman (2006). The concept is shown in the following figure.

Figure 1-3 GNOC Calculator Method



The soil parameters in the model are from the Harmonized World Soil database version 1.1 and the climate classes are from the "Ecological Zones from Climatic Criteria (Eco-Climatic Zones)" map created by the FAO. These zones are shown in the following figure.

Figure 1-4 Eco-Climatic Zones



The 2015 US corn production area by Agricultural District was obtained from the National Agricultural Statistics Service for both rain fed and irrigated corn. For each Ag District with more than 100,000 acres of corn production or irrigated corn area greater than 50,000 acres, a central point in the district was selected in the GNOC calculator and a common set of inputs (10,000 kg/ha of corn production and 180 kg N/ha) were entered into the calculator to obtain the N_2O emissions representative of that district. A total of 146 data sets were obtained. The disaggregated N_2O direct and indirect emissions were recorded for each district. The same basic approach was used for the rain fed and irrigated areas, except that irrigation was selected as an input for the irrigated area. Area weighted values were calculated for each of the emission sources.

This approach covered 94% of the US corn production area.

A single point estimate was also made for organic soils since they represent only 1% of the corn production. The calculator uses the same 8,000 g N_2O/ha/year as used in GHGenius. At 1% of the area, this has a minimal impact on the results. The results are shown in the following table.

Table 1-6 GNOC N_2O Emission Factors

Emission Factor	Value
EF_1 Syn fert	0.0119
EF_1 crop residue	0.01
EF_4	0.01
$Frac_{gasf}$	0.10
EF_5	0.0075
$Frac_{leach}$	0.144

If the N_2O emissions are rolled into the EF_1 factor, that becomes 0.0122. Other than EF_1 the only other differences is that leaching does not occur on all soils due to the dry climatic conditions and the average $Frac_{LEACH}$ value is 0.144 instead of 0.30.

This methodology which factors in soil and climatic conditions, as well as crop type, produces emission factors that are very close to those used in GREET and GHGenius. The one difference is that the absolute values include the higher estimate of N in the crop residues that is used in BioGrace and is 65% higher than the value used in GREET and GHGenius. The values for Canada are not shown since they are for a different region.

2.1.6 N_2O Emission Findings

The emission factors used in the model are compared to the emission factors calculated from the public data sets in the following table.

Table 1-7 N_2O Emission Comparison

	GREET	GHGenius	EPA NIR	USDA	GNOC
EF_1 Syn fert	0.012	0.0125	0.0115	0.0150	0.0119
EF_1 crop residue	0.010	0.0125	0.0115	0.0150	0.010
EF_4	0.01	0.01	-	-	0.01
$Frac_{gasf}$	0.10	0.10	-	-	0.10
EF4*$Frac_{gasf}$	0.001	0.001	0.0009	0.0023	0.001
EF_5	0.0075	0.0075	-	-	0.0075
$Frac_{leach}$	0.30	0.30	-	-	0.144
$Frac_{leach*}$ EF_5	0.00225	0.00225	0.0016	0.0013	0.00108
N_2O/syn fert	1.93%	2.03%	2.26%	2.65%	1.91%

The GREET and GNOC have no allowance for cultivation on organic soils which is one of the reasons that they have lower N_2O emissions. The GREET model should be using the same direct emission factor for crop residues as for synthetic fertilizer in order to be consistent with the IPCC methodology.

The most detailed, regionally specific, N_2O emission calculations are those from the USDA GHG inventory. The only issue with these factors is that they include the N_2O emissions from the application of manure. Should these emissions be included in the system boundary for the livestock sector or should they be included in the crop production system boundary?

The guidelines for the environmental assessment of livestock systems developed by the FAO Livestock Environmental Assessment and Performance (LEAP) Partnership caution that manure can be a debit or a credit to the livestock system and that care must be taken to avoid double counting when the manure is used as fertilizer for feed systems. In the LCA for feed ingredients, the FAO include the transportation and distribution of the manure in the feed system boundary.

The default approach in the LEAP guidelines is to consider manure as a residue co-product. Emissions and resource use of manure storage are then allocated to the animal farm. Only transport from the animal farm and application of manure is allocated to the plant production system. In this approach the N_2O emissions associated with the application of the manure is attributed to the livestock production. It essentially assumes that the manure would have been produced whether it is used for fertilizer or not. The only exception that is discussed is when the economic value of the manure is high enough that it can be treated as a co-product rather than a residue, in this case some of the N_2O emissions could be allocated to the feed system.

In the USDA analysis, manure accounts for about 8% of the nitrogen input for the row crops. Removing this from the simple N_2O emission calculation would reduce the emissions to 2.44% of the applied synthetic fertilizer. The models could consider higher values for EF_1 and lower values for the $Frac_{leach^*}$ EF_5 term.

2.2 ENERGY USE

Energy use in corn ethanol plants is the largest single contributor to the GHG emissions of corn ethanol. Ethanol plants in North America and the E.U. can be very different in terms of the energy used to operate the facilities. The U.S. and Canada use a variety of energy inputs in the form of coal, natural gas, and electricity to operate their ethanol facilities. The LCA models used in the U.S. and Canada (GREET and GHGenius, respectively) incorporate fuel mix shares based upon publicly available studies on ethanol plants.

This portion of the work considers the type and quantity of energy used in the different countries and compares the value used in the models to recent available data.

2.2.1 Existing Model Values

The existing values in the models are described below.

2.2.1.1 GREET 2015

The corn ethanol pathway data in GREET was updated in the GREET 2014 (Wang et al, 2014) model and there were no changes to the data in the 2015 or 2016 model. There are two industry average corn cry mill plants (plants with and without corn oil extraction) although the difference in energy use between the two is very small.

The data in GREET was based on the study by Mueller and Kwik (2013). That paper is summarized later in the report. The data in the GREET model is slightly different than mentioned in the update report. The values are shown in the following table.

Table 1-8 GREET Energy Use

	Report	GREET 2015
Thermal Energy, BTU/gal	24,000	23,954
Natural gas %		92.0
Coal, %		8.0
Electricity, kWh/gal	0.75	0.748

The GREET energy use values do not change between 2010 and 2020 in the model.

2.2.1.2 GHGenius

The energy use data in GHGenius is based on two historical reviews of energy use (Hettinga, 2007 and Christensen, 2008) and then the historical data was used to develop an exponential equation to vary the energy use by the year that the model is set for. The natural gas equation is defined by a value for the year 1999 (10 MJ/litre) and is reduced by 1.8% per year. The value for the year 2014 is 7.6 MJ/litre (HHV) (24,550 BTU/gal LHV). The default values for Canada are 100% natural gas and for the United States the default is 80% natural gas and 20% coal.

Electric power is handled in a similar manner with the Canada 1999 value being 0.22 kWh/litre and declining at 2% per year. The US value for 1999 is 0.25 kWh/litre and it declines at the same rate. The 2014 value is 0.166 kWh/litre (0.63 kWh/gal).

2.2.1.3 BioGrace

BioGrace has one pathway for corn ethanol, whereas they have five pathways for wheat ethanol. The difference in the wheat pathways is all related to fuel source and the presence of combined heat and power. The corn ethanol pathway only has a combined heat and power pathway. While the RED regulations specify that the CHP size should be the smallest size necessary to supply the thermal load, the size will depend on the technology employed. In BioGrace the CHP plant for corn ethanol exports a significant quantity of power to the grid.

BioGrace uses the values developed for the RED default cases. The data for yield, power, and thermal energy were taken from the 1995 Shapouri et al report on estimating the net energy balance of corn ethanol. These values are 37,000 BTU/gal for thermal energy and 1.2 kWh/gallon for electricity. In accordance with the RED methodology, BioGrace increases the natural gas and power values by 40% to ensure that the default values capture essentially all plants. It is not clear from the original source if the 37,000 referred to the energy of the natural gas or steam. It was also probably reported on a HHV basis, as that is the way it is sold in North America. Thus it is likely that the 37,000 BTU is already overstated because it was interpreted as being LHV and the steam input before it is increased again by 40% and the efficiency of steam production.

The exported power in BioGrace for the corn ethanol pathway is shown in the following table for the default scenario and a scenario without the 40% excess energy.

Table 1-9 BioGrace Power Produced

Scenario	Power, kWh/litre
Default	2.7
No extra Energy	1.9

2.2.1.4 Summary

Since each of the models use different units for energy use, they are compared in the following table using the same metrics as used in GREET (BTU (LHV)/US gallon). The values are for 2014 for GHGenius and GREET.

Table 1-10 Corn Ethanol Energy Use

	GREET 2015	GHGenius 4.03a	BioGrace
Thermal Energy, BTU/gal	23,954	24,550	52,000
Electric Power, BTU/gal	2,552	2,144	5,670
Electric Power, kWh/gal	0.748	0.63	1.6

The GREET and GHGenius values are quite close and are half of the values used in BioGrace. The original source for the BioGrace values is over 20 years old and was based on some personal communications at that time. The old data is then increased by 40% in the BioGrace model whereas in reality the energy use in ethanol plants has decreased over time.

2.2.2 Literature Search

The literature search has focussed on the period from 2010 to 2016. In Appendix 2, the search terms, number of papers returned, and a listing of some of the most relevant papers for each search term is presented. Very few papers that contain any primary data or aggregated primary data were identified. Many of the papers use data from the period before 2010 or data contained in the various versions of GREET.

Three papers with primary data were found although only the first paper showed up searches of peer-reviewed papers. The second paper is an update of the first and is the basis for the values currently in GREET and the third paper was a conference presentation.

2.2.2.1 Mueller 2010

The Energy Resources Center at the University of Illinois at Chicago conducted a survey of corn ethanol technologies, ethanol and co-product yields, energy use, water use, and logistics (Mueller, 2010). The survey focuses on dry mill technologies. The survey responses represent 66% of the installed dry mill ethanol capacity during the year 2008 (90 plants).

On average, a dry-mill corn ethanol plant in 2008:

- utilizes 25,859 Btu/gallon (LHV, anhydrous ethanol) of thermal energy and 0.74 kWh of electricity per anhydrous gallon of ethanol,
- produces 2.78 gallons of anhydrous ethanol per bushel,
- co-produces at once 5.3 lbs of DDGS and 2.15 lbs of WDG as well as 0.006 gallons of corn oil,
- uses 2.72 gallons of water per anhydrous gallon of ethanol produced and discharges 0.46 gallons of water per anhydrous gallon of ethanol,

- sources corn for ethanol production within a 47.1 mile radius from the plant,
- natural gas constitutes 92% of thermal energy supply by plant count.

2.2.2.2 Mueller and Kwik 2013

This was a follow up study to the 2010 report, which used data from 2008. This data was from the year 2012. The work included an assessment of over 50% of operating dry grind corn ethanol plants. On average, 2012 dry grind plants produce ethanol at higher yields with lower energy inputs than 2008 corn ethanol. The results are shown in the following table.

Table 1-11 2012 Survey Results

	2008	2012
Yield (anhydrous/undenatured, gallon/bushel)	2.78	2.82
Thermal Energy (Btu/gallon, LHV)	26,206	23,862
Electricity Use (kWh/gallon)	0.73	0.75
DDG Yield (dry basis) including corn oil (lbs/bu)	15.81	15.73
Corn Oil Separated (lbs/bushel)	0.11	0.53
Water Use (gallon/gallon)	2.72	2.70

This report was used as the basis of the GREET 2014 model update.

2.2.2.3 Christianson & Associates, PLLP 2016

Christianson & Associates, PLLP offers a subscription-based benchmarking service that allows “currently producing” ethanol plants to access a database of anonymized industry data, insights, and reports. 108 facilities throughout the US and Canada have used the service to gain information and insight to measure, assess, compare, and enhance profitability.

The program offers guaranteed confidentiality for all participants. Data is collected, verified, and released to subscribers on a quarterly basis. Plants enter financial and production data quarterly on a secure website within 30 days of quarter end. C&A analysts review data and reports are released within 45 days of quarter end.

From time to time some of the data is released to the public. Energy and yield data for 2004 to 2007 was included in a report prepared for the RFA (2008). More recently data for 2005, 2010 and 2015 was included in a conference presentation. They claim about a 30% participation rate in the program. The average values are summarized in the following table.

Table 1-12 Christianson & Associates 2016

Parameter	2005	2010	2015[1]
Undenatured ethanol yield, gal/bushel	2.68	2.73	2.77
Natural Gas, BTU/gallon (HHV)	31,208	28,588	27,043
Natural Gas, BTU/gallon (LHV)	28,180	25,815	24,420
Electricity, kWh/gal	0.77	0.70	0.67

[1] Three quarters only.

2.2.2.4 USDA 2015 Energy Balance Corn Ethanol

The USDA released a report on the Energy balance of Corn Ethanol early in 2016. This report updated corn production parameters from the 2012 USDA ARMS (Agricultural Resource Management Survey) survey but did not revisit the energy use in the ethanol plants. The report uses the same data that was used in the 2010 report, which was a 2008 survey of 18 dry mill biorefineries conducted by the National Agricultural Marketing Association. The 2008 survey found average thermal energy use of 29,421 BTU/gallon (LHV) and average electricity use of 0.757 kWh/gallon at facilities drying their distillers' grains co-product.

2.2.2.5 Europe

Public data on the number, size, and configuration of European fuel ethanol plants is scarce. In their 2014 report on the industry, ePure (2014) reported the production capacity of beverage and fuel ethanol plants and the number of plants by country. The fuel ethanol production capacity was reported to be 7 billion litres. The fuel ethanol industry apparently operated at 65% of capacity in 2014. That information along with the fuel ethanol production reported by Eurostat for 2014 is shown in the following table.

Table 1-13 European Ethanol Plants

Country	Production Capacity	No. Plants	Avg Size	2014 Fuel Production
	Million litres		Million Litres	
France	2,300	19	121	975
Germany	1,400	12	117	897
United Kingdom	900	5	180	519
Poland	750	14	54	181
Spain	600	5	120	486
The Netherlands	575	2	288	0
Hungary	520	3	173	372
Belgium	500	3	167	325
Czech Republic	350	6	58	132
Italy	300	6	50	1
Sweden	275	6	46	175
Austria	250	2	125	262
Slovakia	240	1	240	134
Romania	200	3	67	15
Lithuania	100	2	50	13
Latvia	50	2	25	0
Bulgaria	50	2	25	27
Finland	50	4	13	24
Ireland	40	1	40	0
Denmark	30	1	30	0
Total	9,480	99	96	4,538

ePure reported that 38% of the feedstock in 2015 was corn. From the table it is apparent that the average size of the European ethanol plants is much smaller than the size of the North America plants and that the plant size can vary significantly from one country to another.

A search for the largest ethanol plants was undertaken and a number of European plants that have co-generation facilities were identified. The plant, ethanol production capacity, and cogen capacity are summarized in the following table. Another dozen large ethanol plants (>100 million litres/year production capacity) were identified that did not have a large cogeneration production capacity. A few additional plants produced some power via steam pressure reduction and through anaerobic digestion systems that operate on stillage and/or imported straw.

Table 1-14 European Plants with Cogeneration Capacity

Name	Country	Ethanol Capacity, million l/year	Cogeneration Capacity, MWH	Potential power kwh/litre
Alco Biofuel[2]	Belgium	150	110,000	0.73
Abengoa[3]	Netherlands	480	400,000	0.83
Abengoa[4]	Spain	200	204,000	1.02
Abengoa[5]	Spain	200	204,000	1.02
Abengoa[6]	Spain	150	135,000	0.90
BioWanze	Belgium	300	>168,000	>0.56

The BioWanze plant burns wheat bran and natural gas to produce the steam and power. The power production at these plants is much less than the 2.7 kWh/litre default value in BioGrace and the 2.2 kWh/litre that BioGrace models as being exported power. The consumed power probably varies from 0.2 to 0.4 kWh/litre resulting in the potential to export 0.4 to 0.8 kWh/litre of ethanol, much less than modelled in BioGrace.

2.2.3 Public Data Sources

There are two public data sources that have information on the energy use in US ethanol plants. The sources and the data extracted from them are discussed below.

2.2.3.1 EPA 2014 Greenhouse Gas Emissions from Large Facilities

In 2008 the EPA issued the Mandatory Reporting of Greenhouse Gases Rule (74 FR 56260), which requires reporting of greenhouse gas (GHG) data and other relevant information from large sources and suppliers in the United States. The purpose of the rule is to collect accurate and timely GHG data to inform future policy decisions.

Some categories began reporting their yearly emissions with the 2010 reporting year. 2010 emissions were reported to EPA via the electronic greenhouse gas reporting tool (e-GGRT) in September 2011. Additional sources began reporting yearly emissions in September 2012, bringing the total to 41 source categories reporting.

In January 2012, EPA made the first year of GHGRP reporting data available to the public through its interactive Data Publication Tool, called Facility Level Information on GreenHouse gases Tool (FLIGHT). EPA will continue to update the tool and release additional data each reporting year.

The data for the year 2014 is available on the FLIGHT website (https://ghgdata.epa.gov/ghgp/main.do). 8,080 facilities are included in the 2014 data. They

[2] http://www.alcobiofuel.com/2-new-projects-at-the-bio-ethanol-plant-in-the-port-of-ghent/
[3] http://www.alcobiofuel.com/
[4] http://www.abengoabioenergy.com/web/en/acerca_de/oficinas_e_instalaciones/bioetanol/europa/bioetanol_gali/index.html
[5] http://www.abengoabioenergy.com/web/en/acerca_de/oficinas_e_instalaciones/bioetanol/europa/biocarburantes_cast_leon/index.html
[6] http://www.abengoabioenergy.com/web/en/acerca_de/oficinas_e_instalaciones/bioetanol/europa/ecocarburantes_esp/index.html

are sorted by sector (nine sectors) and within each sector there are subsectors. Ethanol production is included in the "Other" sector. There are 172 reports for 2014 and four additional ethanol plants were found in the "Other" sector. Plants with less than 25,000 tonnes of CO_2eq are not required to report.

Thirteen plants were removed from the dataset as they either did not report any emissions in 2014, the data was not verified, they were not starch ethanol plants, or more than just an ethanol plant was located on the site. In total, data was collected for 163 plants. All plants were dry mills. The production capacity of these plants using the 2016 EIA plant capacity data is 11.78 million gallons.

In addition to the reported GHG emissions some plants also reported their energy use by type and quantity. Even if they didn't report the energy use, they reported the method that was used to generate the GHG emissions and they all used EPA emission factors based on the type of energy, so the energy used could be calculated from the available data. The energy use reported and the emission factors used higher heating values.

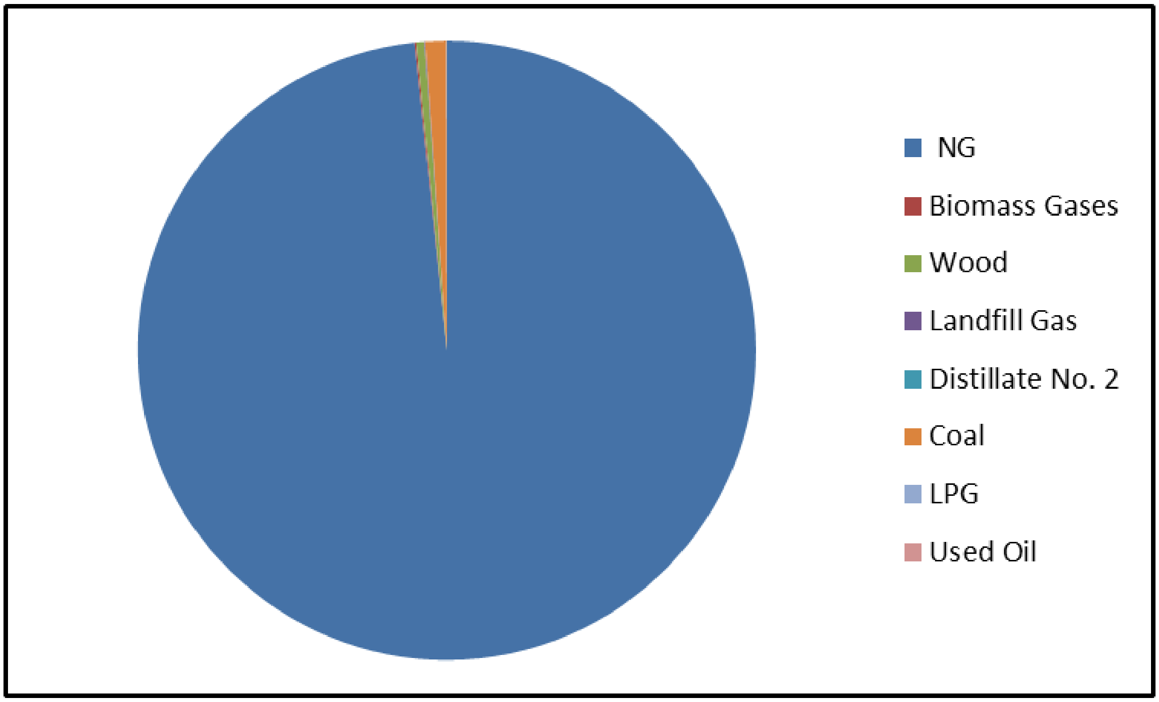
2.2.3.1.1 Type of Energy Used

The plants reported their energy use by fuel. A total of 315.3 million mmBTU was used in these plants that generated 16.72 million tonnes of GHG emissions, although no allowance is made for biogenic CO_2 in the EPA emission factors. The GHG emissions include CO_2, CH_4, and N_2O. Some of the methane is fugitive methane from wastewater treatment plants, although this only totalled 9,635 tonnes of CO_2eq. All 163 plants used some natural gas. The energy use data is summarized in the following table and figure.

Table 1-15 2014 Energy Use

Fuel	mmBTU (HHV)	Number of plants	% of total
Natural gas	309,989,808	163	98.32%
Biomass Gas	303,320	46	0.10%
Wood	1,303,012	1	0.41%
Landfill gas	138,463	2	0.04%
No 2 distillate	6,837	6	0.00%
Coal	3,471,354	3	1.10%
LPG	59,705	6	0.02%
Used Oil	73	1	0.00%
Total	315,272,572	163	100%

Figure 1-5 Ethanol Plant Energy Use



There is much less coal used than has been represented in GREET and GHGenius. None of the three coal plants used coal exclusively and two of the three plants were in the process of replacing coal with natural gas and thus when the 2015 data is released coal will likely represent much less than 1% of the total energy use.

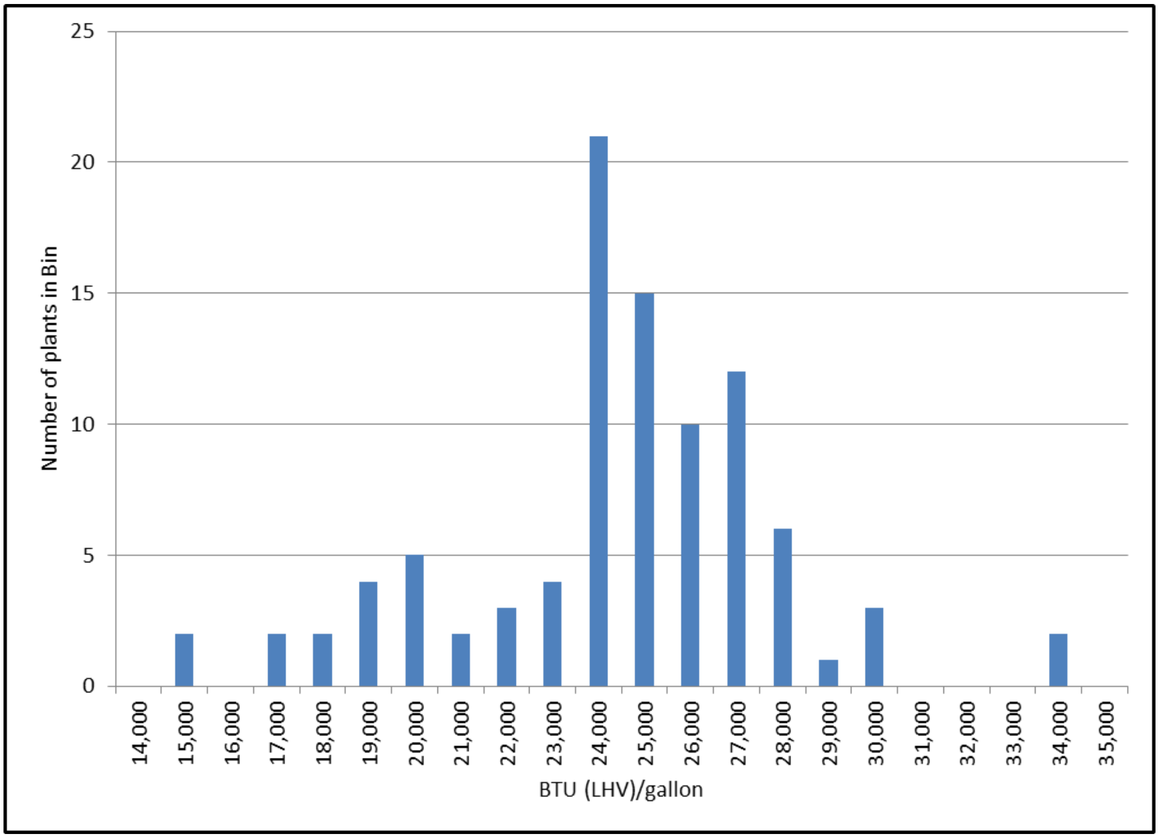
2.2.3.1.2 Energy Intensity

The FLIGHT data does not report any ethanol production rate but many ethanol producers do make this information public. The public data may not be consistent as some producers may report the undenatured volumes and others may report denatured volumes, but the difference would be small.

We have been able to find 2014 production data for ninety four plants. These plants reported 7.58 billion gallons of production and thus represent 64% of the production in the data set. The average energy intensity is 26,480 BTU/gallon (HHV). This would be 23,911 BTU/gal (LHV) and 7.4 MJ/litre (HHV). This is very close to the values used in GREET 2015 and GHGenius 4.03a.

Some of the plants in the data set may be generating some of their own electricity with small co-gen plants and these plants would have higher natural gas but lower electric power requirements. The distribution of the results is shown in the following figure.

Figure 1-6 Distribution of Energy Intensity



2.2.3.2 EPA Efficient Producer Applications

The EPA developed the Efficient Producer petition process for corn starch and grain sorghum ethanol producers that demonstrate superior process efficiency through reduced onsite energy consumption, increased fuel output and/or use of biomass or biogas from certain sources to reduce process energy greenhouse gas emissions. Ethanol producers who are not grandfathered or have expanded production must demonstrate that the GHG emission reduction is greater than 20% in order to create RINs.

As of September 30, 2016 the program has approved sixty-five producers. These producers must meet certain criteria established by the EPA and supply one year of detailed data to the EPA in order to be evaluated and accepted by the program.

The first few applicants had their actual energy use published in their approval letters but most of the approval levels now report the emissions per million BTU for feedstock production and for ethanol production. The emission factors that are used are the same emission factors used by the EPA in the RFS2 rulemaking and are based on GREET 1.8d. The published data does allow the ethanol yield and the emissions from the fuel and power use to be determined.

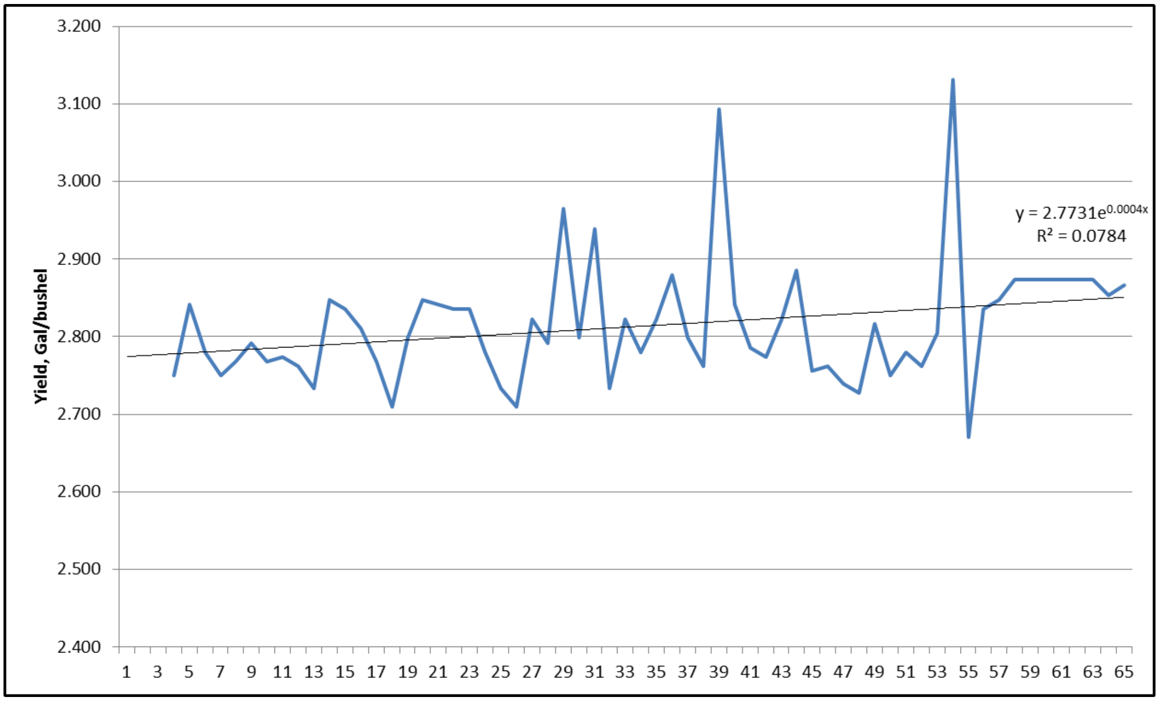
2.2.3.2.1 Yield

The Upstream emissions reported by the EPA in the approval letters are directly proportional to the ethanol yield. The emissions in the base case analyzed by the EPA in the 2010 rulemaking were 47.6 kg CO_2eq/mm BTU (LHV) and this was based on an ethanol yield of

2.71 gallons/bushel. The ethanol yield for the 62 plants that the EPA reported upstream emissions for can be calculated as 2.71*47.6/reported upstream emissions.

The average value for the yield calculated this way was 2.81 gallons/bushel. When the approvals are listed chronologically there does seem to be a trend to higher yields over the two year period, although the trend is not statistically significant, as shown in the following figure.

Figure 1-7 Efficient Producer Ethanol Yield



In order for corn ethanol to meet the 20% reduction in GHG's from the gasoline baseline, the ethanol GHG emissions need to be 3.14 kg CO_2eq/mm BTU lower than the EPA corn ethanol base case. The average yield of the 61 approvals reduced the emissions by 1.73 kg CO_2eq/mmBTU. None of the plants were able to achieve the 20% reduction with just the improvement in the yield.

The ethanol yields in the three models are summarized in the following table. The data is for the year 2014. GREET and GHGenius yields are programmed to increase over time. The BioGrace value is taken from the same 1995 report that was used for the energy inputs.

Table 1-16 Ethanol Yields in Models

Model	Yield, gal/bushel	Yield, Litres/tonne as received
GREET 2015	2.81	419
GHGenius 4.03a	2.72	406
BioGrace	2.49	372

The ethanol yield in GREET is aligned with the EPA data but the value in GHGenius and in BioGrace could be increased for better alignment with the US data.

2.2.3.2.2 Energy Use

The ethanol plant power and gas use are the two factors that produce the process emissions in the EPA analysis. Both the natural gas use and the electric power consumed contribute to these emissions. The base case emissions calculated by the EPA are based on power consumption of 0.66 kWh/gal and natural gas use of 28,658 BTU/gal (LHV). The first three approvals issued by the EPA provided enough information to calculate the power and gas use but all of the approvals since then have provided just the combined emissions for the power and the gas.

The EPA baseline emissions were 32.4 kg CO_2eq/mm BTU and the average of the 65 approvals has been 28.0 kg CO_2eq/mm BTU, a 4.4 kg CO_2eq/mm BTU improvement and more than enough to move the plants past the 20% reduction threshold.

There is a calculation issue with the EPA methodology. The applicant is required to enter the natural gas meter readings in volume and then the EPA applies the GREET energy density. However all natural gas transactions are measured at 60F and the GREET energy density is reported for 32F. The natural gas energy that is calculated by the EPA is therefore about 5.5% too high.

If we assume an average electric power requirement then we can calculate the equivalent natural gas from the data supplied by EPA. These combinations are shown in the following table. The natural gas use in the table has been corrected to the incorrect energy density.

Table 1-17 Natural Gas and Power Use from Efficient Producer Approvals

Assumed Power Use, kWh/gal	Calculated Natural Gas Use, BTU/gal (LHV)
0.60	23,276
0.65	22,758
0.75	21,721
0.85	20,684

If the average electric power use is 0.65 kWh/gal then the natural gas use is 22,701 BTU/gal (LHV). This is less than the average value calculated from the GHG reporting dataset but a lower value should be expected since no one would apply to be an efficient producer unless they could demonstrate that they met the threshold.

There is some overlap between the two EPA datasets and, in general, the values calculated from both datasets are aligned after they are adjusted for similar units. Some variation could be expected since the efficient producer data could represent production in 2012, 2013, 2014, or 2015 in some case.

2.2.3.2.3 ICF USDA Corn Ethanol Report

ICF (Flugge et al, 2017) reviewed the EPA RFS2 GHG analysis considering new information that has become available since 2010. They did not have access to the EPA models but they did make some estimates of the changes that the new data may have on the lifecycle GHG emissions for corn ethanol.

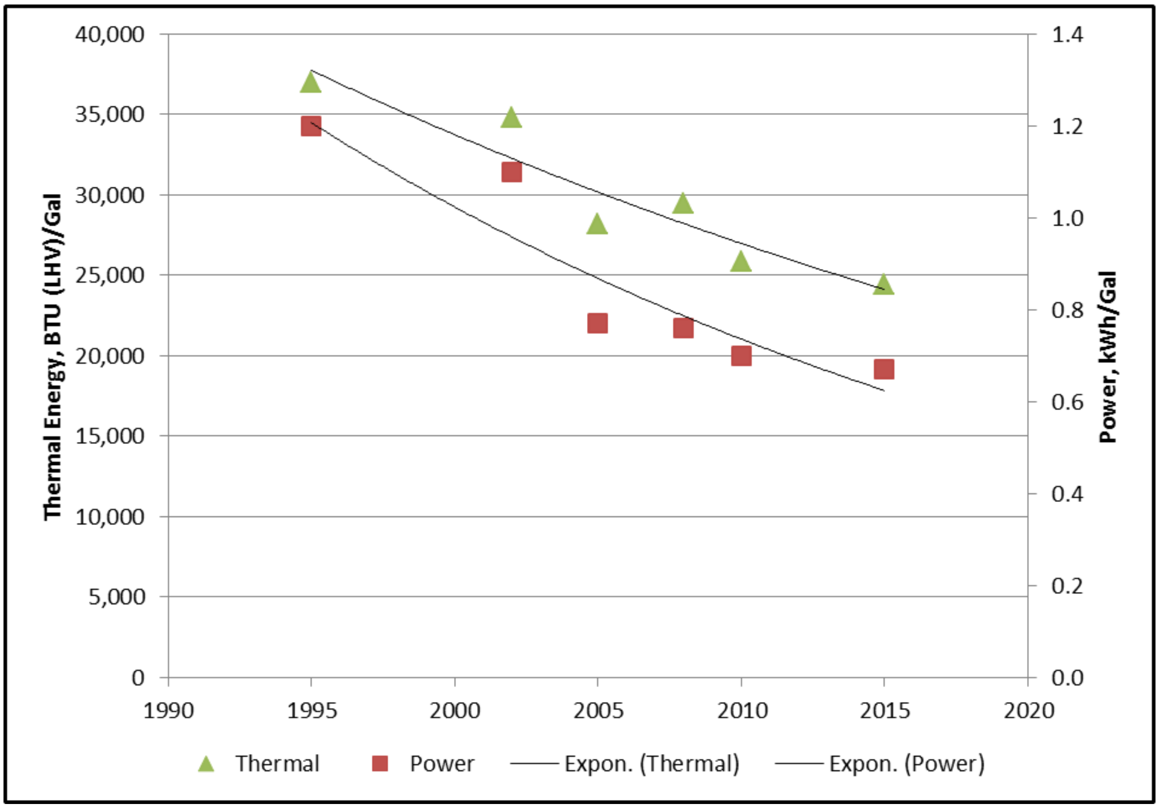
The ICF modeling utilizes the GREET 2014 corn ethanol pathway data which use process-level data from Mueller and Kwik (2012). This data is presented in section 2.2.2.1.

2.2.4 Energy Use Findings

There are three primary findings of the review of energy in corn ethanol plants.

1. The number of coal fired dry mill ethanol plants in 2014 was only 3 out of 163 in the data set and two of those were in the process of moving to natural gas during 2014. Very small quantities of other fuels are used but natural gas supplied more than 98% of the thermal energy requirements of US dry mill ethanol plants. Note that plants that purchase steam from an adjacent facility would not have GHG emissions to report and would not be included in the data set analyzed.
2. Thermal energy use at US dry mill ethanol plants has also declined over time. Combining the new data on energy use with the data collected in earlier USDA reports that looked at the energy balance of corn ethanol producers the trends shown in the following figure. The thermal energy use has declined at about 2.2% per year and the electric power at a 3.3% per year rate. Future rates could be lower as experience curve theory suggests the energy intensity is reduced for every doubling of production. A more mature industry takes longer to double in size that a new rapidly growing industry. The available data supports this slowing of improvement in energy intensity.

Figure 1-8 Long Term Energy Use Trends



The thermal energy use from the three different sets of data are summarized and compared to the GREET model in the following table. The EPA Efficient Producer value assumes that the electric power use is 0.65 kWh/hour, similar to the value in the Christiansen survey.

Table 1-18 Thermal Energy Use

Source	BTU/gal (LHV)
GREET 2015	23,954
Christiansen Benchmarking Survey	24,420
EPA FLIGHT data	23,911
EPA Efficient Producer applications	22,758

The EPA efficient producer value would be expected to be lower than the other since plants with high energy use would not likely apply to the program. The other values are consistent with the values in GREET 2015 and there would not appear to be any need to change the value at this time. The energy use vs. time curve in GHGenius could be adjusted slightly towards lower energy use.

3. For European plants there is a much larger diversity in terms of plant size and feedstocks than there are in US plants. Corn usage has grown and it is now the largest feedstock followed by wheat, sugar beet and other cereal crops. Some European ethanol plants do have combined heat and power systems but they are all smaller than the system modelled in BioGrace and have less power to export. In addition, the data used in the BioGrace model is at least 20years old and does not represent a state of the art facility.

2.3 CO-PRODUCTS

The type of co-products, intended end-use of co-products (process fuel vs. animal feed) and the method adopted to allocate environmental burden among co-products can significantly impact the overall greenhouse gas footprint of the fuel pathway. A range of plausible cases for fuel CI can be developed, depending upon the choice of the parameters selected.

2.3.1 Co-product Treatment in LCA

There are multiple ways of dealing with the treatment of co-products in LCA work and this remains an important issue for LCA practitioners. 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:

Allocation Procedure (4.3.4.2)

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.

The implications of some of the trends that are reported later under the different allocation systems are discussed below.

2.3.1.1 Mass Based Allocation

Mass and energy based allocation are the simplest systems to implement. As the ethanol yield increases, the emissions burden assigned to the ethanol will increase and the co-products become a smaller part of the equation due to carbon dioxide production increasing with the increased ethanol production. Mass allocation is not dependent on which co-products are produced and thus the trend to higher levels of oil extraction has no impact on the analysis since it doesn’t change the mass of the co-products. The oil is either included with the DGS or a portion is sold as a separate product but the sum of the mass of the individual co-products does not change.

2.3.1.2 Energy Content Allocation

Energy content allocation behaves the same way as mass. As the ethanol yield increases the emissions burden assigned to the co-products decreases. Changes in the type of co-products produced do not change the allocation, as the co-product energy in relation to the ethanol energy remains the same.

2.3.1.3 Displacement Allocation

With the displacement approach, the ethanol is credited with emissions that are displaced by the co-products. This leads to a much more complex treatment of the co-products and requires much more information on how the co-products are used.

2.3.2 Existing Model Values

The values and the approaches used in the models are discussed below.

2.3.2.1 GREET 2015

GREET has the most complex treatment of co-products of the models. It can do allocation by energy and mass and it can use the displacement approach. In the displacement approach the model can use different ratios of use between animal species and different products displaced for each species.

The use by species in GREET 2015 came from data from the RFA website in 2008. The GREET information and the latest values from the RFA website (where the estimates are provided by the Distillers' Grain marketing companies) are shown in the following table.

Table 1-19 DDG Use by Species

	GREET 2015	RFA 2016
	%	
Beef	40.6	45
Dairy	40.6	31
Swine	12.8	15
Poultry	6.0	8
Other	0	1

These values could be updated in the model.

In GREET 2015, when the displacement approach is used, the displaced products include corn, soybean meal, urea, and soy oil. The displacement ratios in GREET do vary with the animal species and between wet and dry product, as shown in the following table.

Table 1-20 GREET Displacement Ratios

	Corn	Soy Meal	Urea	Total
	Lbs/lbs DG			
Beef	1.203	0.000	0.068	1.271
Dairy	0.445	0.545	0.000	0.990
Swine	0.577	0.419	0.000	0.996
Poultry	0.552	0.483	0.000	1.035
Total Dry	0.751	0.320	0.024	1.096
Beef	1.276	0.000	0.037	1.313
Dairy	0.445	0.545	0.000	0.990
Total Wet	0.861	0.273	0.019	1.152
Composite	0.781	0.307	0.023	1.111

The emissions for each of these products in GREET 2015 and thus the emissions displaced by the co-products are shown in the following table.

Table 1-21 Displacement Credits GREET 2015

Product	g CO_2eq/lb.
Corn	134.2
Soybean Meal	235.0
Urea	580.9
Soy oil	235.0

There is also a methane avoidance credit for DG that is fed to cattle. The aggregate value is 2,260 g CO_2eq/mmBTU of ethanol.

The final co-product credit in GREET is the sumproduct of the individual products displaced and the emissions for each of the displaced products. The value for a corn dry mill with corn oil extraction is 14,007 g CO_2eq/MM BTU ethanol (LHV).

There are no changes to the ethanol co-products in GREET 2016.

2.3.2.2 GHGenius 4.03a

GHGenius allows the user to use the displacement approach or to allocate the emissions of feedstock and fuel production by mass or energy content. The displacement approach is used for the BC LCFS.

The displacement values used for corn ethanol are shown below. They are essentially the same as the GREET aggregate values.

Table 1-22 GHGenius Displacement Values Corn Ethanol

Displaced Product	Lbs Displaces/pound DDG
Corn	0.78
Soybean Meal	0.31
Total	1.09

In addition, there is a credit for methane reduction from the livestock of 3,270 g CO_2eq/mmBTU (LHV) (2,792 g CO_2eq/GJ of ethanol HHV).

The total co-product credit for US corn ethanol in GHGenius 4.03a is 17,596 g CO_2eq/MM BTU ethanol (LHV).

2.3.2.3 BioGrace

The BioGrace model follows the current RED guidelines and uses the energy allocation method to allocate some of the feedstock and fuel production emissions to the co-products except for surplus electricity. In this case the excess power receives a displacement credit for the electricity as if it were produced by a natural gas combined cycle gas turbine plant (124 g CO_2e/MJ of electric power). The net plant emissions are then allocated between the ethanol and the co-products on an energy content basis.

2.3.3 Literature Search

Since the drivers of the co-product credit in GREET are the aggregate displacement ratios and the emissions for the displaced products, the focus of the literature search was on the displacement ratio for each species and the use of the co-products be the different species. The time period of the search was 2010 to the present. Very few relevant references were found.

2.3.3.1 Hoffman and Baker 2011

This USDA publication developed a method to estimate the potential use of U.S. DDGS and its substitutability for corn and soybean meal in U.S. feed rations. Findings demonstrated that, in aggregate (including major types of livestock/poultry), a metric ton of DDGS can replace, on average, 1.22 metric tons of feed consisting of corn and soybean meal in the

United States. Over time, DDGS may substitute for less corn and more soybean meal as the share of beef cattle consumption of DDGS declines slightly (although increasing in absolute terms), with offsetting share increases in dairy cattle, swine, and poultry. Feed market impacts of increased corn use for ethanol are smaller than that indicated by the total amount of corn used for ethanol production because of DDGS.

The displacement ratio is slightly higher than is used in GREET 2015. The Hoffman substitution ratios are shown in the following table.

Table 1-23 Hoffman Substitution Ratios

Specie	Corn	Soy Meal	Total
		Lb./lb DDGS	
Beef	1.20	0.00	1.20
Dairy	0.73	0.63	1.36
Swine	0.70	0.30	1.00
Poultry	0.61	0.44	1.05

The primary difference between these values and the GREET values is with the dairy ratios. The Hoffman ratio is significantly higher than the GREET.

2.3.3.2 Agricultural Marketing Resource Center

The Agricultural Resource Marketing Center (AMRC) publishes a DDGS balance sheet on an annual basis. This includes estimates of export and domestic usage of DDGS and the quantity consumed by the four livestock species. The last report was published in Dec 2015 and has data since 2011/2012 and forecasts through to 2016/17. The five-year average substitution ratios are shown in the following table.

Table 1-24 AMRC Substitution Ratios

Specie	Corn	Soy Meal	Total
		Lb./lb DDGS	
Beef	1.00	0.00	1.00
Dairy	0.45	0.34	0.79
Swine	0.85	0.11	0.96
Poultry	0.55	0.20	0.75

These are much more conservative displacement rates than determined by Hoffman and used in GREET.

The AMRC also estimated how much of the co-product is used by the four species. That information is shown in the following table.

Table 1-25 Fraction Consumed by Species

Species	2011-12	2012-13	2013-2014	2014-2015	2015-2016
Beef	53.4%	53.6%	53.6%	53.6%	53.6%
Dairy	34.1%	33.9%	33.9%	33.9%	33.9%
Swine	6.9%	7.2%	7.2%	7.2%	7.2%
Poultry	5.6%	5.3%	5.3%	5.3%	5.3%

The year-to-year variations are quite small, suggesting that there is no significant trend in the usage. The beef consumption is higher than estimated in GREET, at the expense of dairy and swine consumption.

There was a study that was a joint effort between the National Agricultural Statistics Service and the Nebraska Corn Development, Utilization & Marketing Board (an agency of the State of Nebraska) in 2007 (NASS, 2007).

Approximately 9,400 livestock operations in Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin were surveyed to get a better understanding of co-product usage. This did not include any poultry operators. It is not possible to determine the exact amounts used for each animal group, since only the peak number of animals is provided but the usage based on peak animals was 72% beef, 10% dairy, and 18% swine. This was also not a national survey.

2.3.3.3 Klassing for ICCT, 2012

This paper took a very detailed approach. The objective of this study was to determine the shifts in feedstuff usage that occur when regionally-specific "least-cost" diets are provided to animals throughout the US as a result of including DDGS at typical levels. This was done by using a realistic range of feedstuff prices to formulate least cost diets according to industry standards. This process was replicated across the primary production regions for a given species. A "US composite" was then tallied by weighting the different least cost solutions according to the actual animal production rates in each region. This process was done for each the major livestock groups: beef cattle, dairy cattle, broilers, egg laying chickens, turkeys and swine.

This paper did not include any impact of increased feed efficiency. The author believes that the observed increase in feed efficiency is not present when more complex diets are used in regions outside of the high plains. The aggregate result across all species and all regions is shown in the following table for the 2010 DDG volume and when the DDG is used at 50% of the maximum inclusion rate.

Table 1-26 Klassing Displacement Ratios

Feedstock Displaced	Displacement Ratio
Corn Dent Yellow	0.661
Soybean meal, 48.5%	0.046
Canola meal	0.059
Wheat Silage	0.000
Brewers' grain, dried	0.016
Wheat	0.068
Wheat flour middlings	0.038
Alfalfa Hay, mid bloom	-0.031
Rice bran with germ	0.055
Corn gluten feed	0.027
Wheat, mill run	0.040
Feather meal, hydrolyzed	0.006
Bakery waste, dried	0.023
Cottonseed meal	0.054
Wheat flour	0.008
Urea	0.032
Calcium phos. dibas	0.008
Meat with bone meal	0.006
Soybean hulls	0.006
Salt	0.003
Mineral mix - NRC	0.005
DL-methionine 99%	0.001
Threonine	0.001
Sorghum-Sudan grass, mid bloom	-0.035
L-lysine HCl 95%	0.000
Fat	0.013
Vitamin mix - NRC	-0.006
Whey, liquid	-0.004
Mixed grass & legume silage	-0.013
Grass Silage	-0.013
Limestone, ground	-0.003
Wheat Straw	-0.036
Soybean seeds meal 44%	0.000
Corn Silage, well eared	-0.036
Total	0.999

The challenge here is that most of these products are not included in GREET or GHGenius. There are also a number of products that are added when the DDGS is added. Many of the products that are added are low value products like silage and straw.

The ratio of energy feeds to protein feeds is quite close to the values used in GREET and GHGenius.

2.3.4 Co-product Production

Starting in October 2014 the National Agricultural Statistics Service (NASS) publishes a monthly Grain Crushings and Co-Products Production report with the amount of agricultural commodities consumed in dry and wet mill production as well as monthly production of co-products for the U.S.

NASS built and maintains a list of all known ethanol mills. An operation profile was completed for each facility to determine the presence of dry and/or wet alcohol mill during 2014. Operations that will mill were asked for the nameplate production capacity.

All operations on the list that produce alcohol are selected for the monthly Dry Mill Producers of Ethanol Survey and/or Wet Mill Producers of Ethanol Survey which ask for quantities of grain used as feedstock and co-products produced. The surveys currently cover 200 facilities with 14.8 billion gallons of capacity.

The dry mill survey asks for corn and sorghum consumed, but for some months the sorghum quantities are redacted due to confidentially reasons. The co-products that are reported are shown in the following table along with the average values for 2015, the only year for which 12 months of data is available. The survey results are issued monthly and are available at http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1899.

Table 1-27 2015 Dry Mill Co-product Production

Product	Actual Weights	Dry Weight Estimate, tons
Corn (1000 Bushels)	4,677,945	
Sorghum (1000 CWT)	17,918	
Total Tons	131,878,360	116,050,000
Co-product, tons		
Condensed distillers solubles (CDS - syrup)	1,754,642	666,764
Corn oil (Corn Distillers Oil - CDO)	1,399,993	1,399,993
Distillers dried grains (DDG)	5,118,994	4,504,715
Distillers dried grains with solubles (DDGS)	22,499,301	19,799,385
Distillers wet grains (DWG) 65% or more moisture	14,931,311	4,479,393
Modified distillers wet grains (DWG) 40% to 64% moisture	4,882,354	2,441,177
Total	50,586,595	33,291,427

Converting the data to the GREET equivalent inputs produces the results in the following table along with the values in GREET 2015. The estimated moisture content of the wet products in the survey are 65%, the same value used in GREET.

Table 1-28 GREET Co-product Values

Co-product	GREET 2015	Survey Results - 2015
	Actual weights Lb/gal	
Corn Oil	0.188	0.212
Dry Products (ex corn oil)	4.02	4.16
Wet Products	5.28	3.25

The survey indicated higher production of corn oil and dried products than is used in GREET 2015 but lower rates of wet products and less total mass. The values in GREET are inconsistent with the ethanol yield modelled in GREET 2015. They are calculated using a formula (cell G461 and G462 on the Input sheet) that is consistent with an ethanol yield of 2.65 gal/bushel.

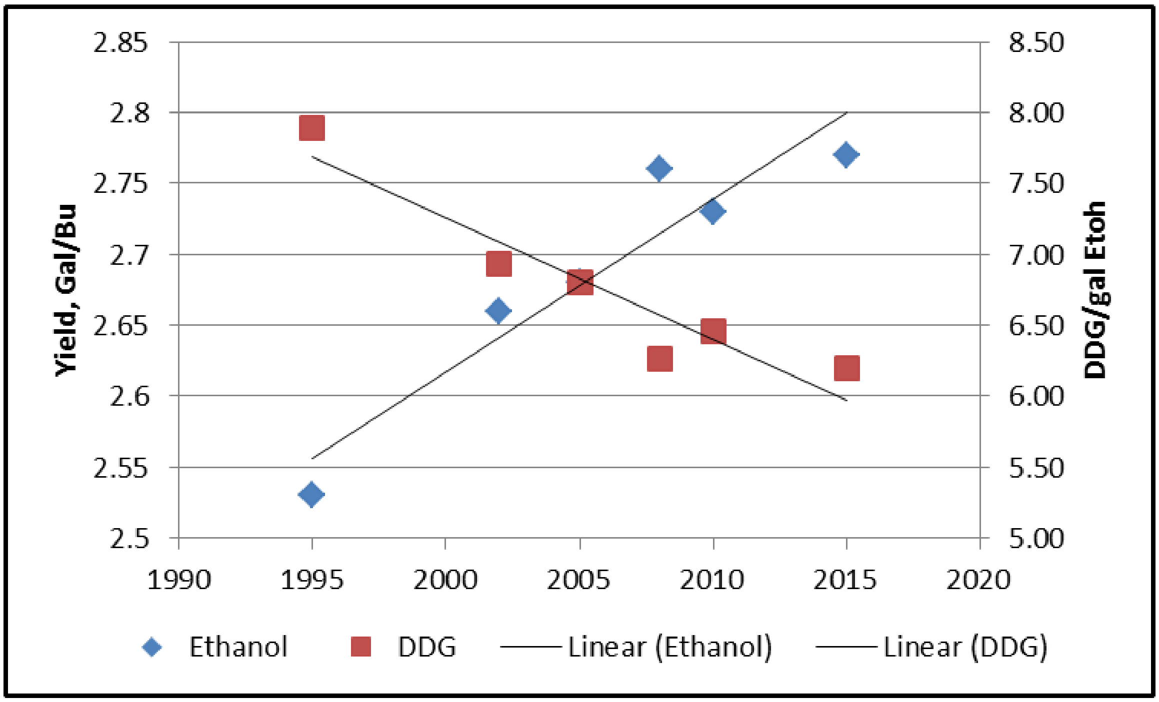
2.3.5 Co-product Trends

The available NASS data is only available for 23 months and there is the potential for seasonal variations so it is difficult to determine any trends from such a small data set. There is a longer-term ethanol yield data set that can be used to estimate the co-product yield.

2.3.5.1 Co-product Mass

The long-term trend in co-product mass can be calculated from the long-term yield information. The starch in the corn is hydrolyzed and then fermented to ethanol and carbon dioxide, where the unconverted mass becomes the co-product. With the molecular weight of ethanol and carbon dioxide being close it means that the mass of the co-product declines by twice the increase in mass of ethanol produced. The long-term ethanol yield from USDA energy balance reports and the Christensen benchmarking report identified earlier is shown in the following figure along with the estimate co-product yield.

Figure 1-9 Yield and Co-product Trends

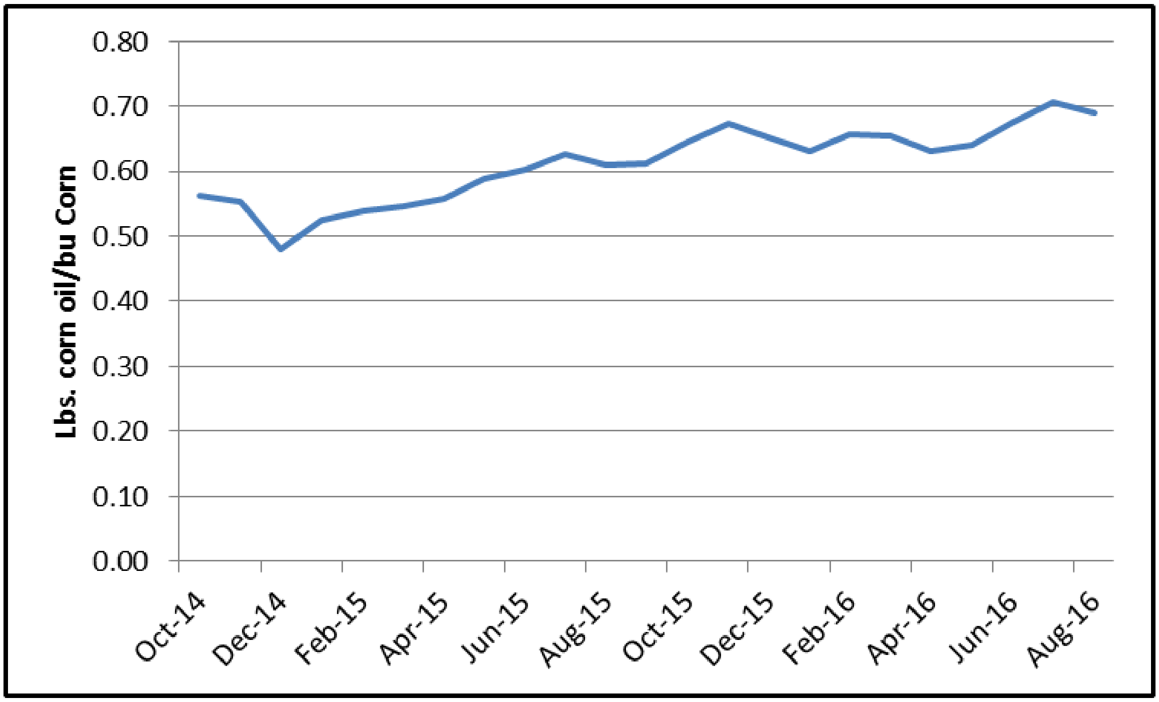


As ethanol yield increases, the quantity of co-products produced from a bushel of corn decreases and decreases even faster when expressed per gallon of ethanol.

2.3.5.2 Corn Oil Yields

The one exception to the issue of trends from the NASS data set may be corn oil yield. Corn oil extraction is a relatively new innovation for dry mills with the first applications occurring about a decade ago and growing to the point where most corn dry mills now extract corn oil. There are two pounds of oil in a bushel of corn. The technologies that are employed only extract a portion of the oil but plants are working to increase the oil extracted as it has much higher economic value as oil than as distillers' grains. Given the relatively short implementation period and the low levels of extraction some trend in corn oil production is realistic and this is shown in the following figure.

Figure 1-10 Corn Oil Extraction Rates



The industry is currently extracting about one third of the oil in the corn as corn oil, with the remaining left in the distillers grains. The quantity of corn oil extracted has increased in the 23 months that the NASS survey has been reporting information.

2.3.5.3 Species Fed

In GREET the dry and wet DG is used in different species and thus each animal species has different quantities of the four co-products that are displaced. This means there can be different co-product displacements as the ratio of wet and dry co-products produced changes and as the overall meat demand changes. The other variable in the GREET corn ethanol pathway is that the displacement ratios are different for domestic consumption and for exported consumption. There are a significant number of variables that can change and influence the results.

Table 1-29 Displacement Credits GREET 2015

Product	g CO_2eq/mm BTU
Beef	20,134
Dairy	13,840
Swine	12,900
Poultry	13,725

The large difference between the species is a function of the methane credit for beef. It is not clear why there is no methane credit for the dairy since they are also ruminants and they produce large amounts of methane.

The AMRC data does not show any significant trends in which animals are consuming the co-products.

2.3.5.4 Exports

The difference in the DG credit between domestic usage and exports is minimal in GREET, as shown below. Thus any difference in the domestic/export ratio would not have an impact on the co-product credit in GREET.

Table 1-30 Displacement Credits GREET 2015

Product	g CO_2eq/mm BTU
Domestic	14,007
Exports	14,005
Average	14,007

2.3.5.5 Wet vs. Dry

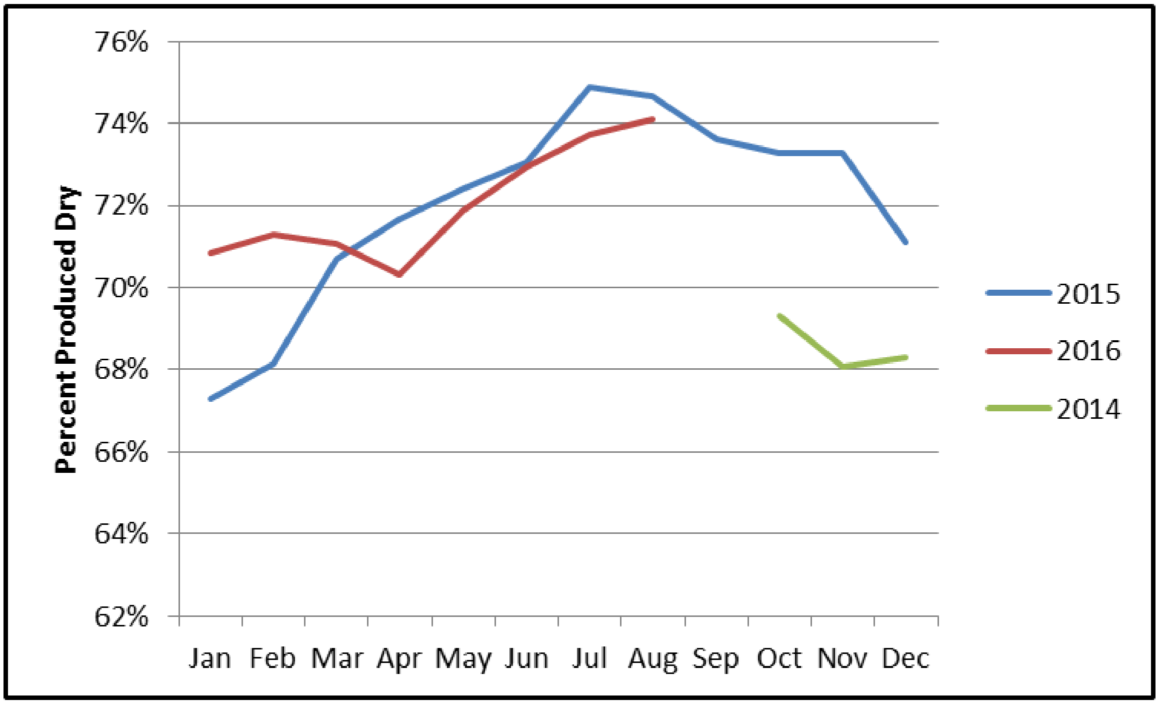
The difference between wet and dry is also minimal and is one of the reasons for the small difference between domestic use (wet and dry) and export use (dry only).

Table 1-31 Displacement Credits GREET 2015

Product	g CO_2eq/mm BTU
Dry	14,107
Wet	14,012

From the limited NASS data available, it is possible that there is a seasonal trend in the fraction sold wet but it is not possible to identify any long term trends, as shown in the following figure.

Figure 1-11 Dry DG Production



2.3.6 Co-product Findings

A number of findings can be drawn from the investigation of co-products. These are summarized below.

1. The quantities of wet and dry distillers grains in GREET 2015 should be updated with the data from the monthly NASS surveys. The current data in the model is inconsistent with the modelled ethanol yields. This will lower the co-product credit in the model.
2. The long-term trend to higher ethanol yields will mean that less co-product is produced. This has some different implications for the different allocation approaches. In the case of the mass approach, the loss of co-product mass is only half compensated by the increase in ethanol mass since more CO_2 is also produced? The impact on the energy allocation is less severe because the energy efficiency of the fermentation is higher than the mass efficiency. The impact on the displacement approach is similar to the mass allocation impact since the mass of the co-products drives the displacement calculations.
3. The quantity of corn oil being extracted is higher than in GREET and appears to be increasing. Extraction rates are far below the theoretical maximum value. Higher corn oil production leads to a higher co-product credit in GREET.
4. The co-product use by the different species should be re-evaluated in GREET as the original data source has updated values and there are different values in the AMRC annual estimates.
5. The displacement ratios for dairy cattle should be investigated as a more recent USDA report has a much higher value. The possibility of including a methane credit for dairy should also be investigated.

6. Other than a lower mass of co-products due to higher ethanol yields and more corn oil being extracted there does not appear to be any trends in how the coproducts are being used that would impact the carbon intensity of corn ethanol in GREET.

2.4 CORN ETHANOL SUMMARY

Three specific aspects of the corn ethanol pathway have been investigated, the N_2O emissions from corn production, the energy use in corn ethanol plants, and the ethanol co-products. For all three issues a range of values from the recent literature (2010 to 2015) has been developed and any recommendations of changes in the default values for the models have been presented. Trends in the parameters are also noted.

The scope of work requested that the N_2O emission information should be presented in a manner that is consistent with the IPCC methodology. However the literature search did identify a number of papers that suggest the emissions are not a linear function of the nitrogen applied.

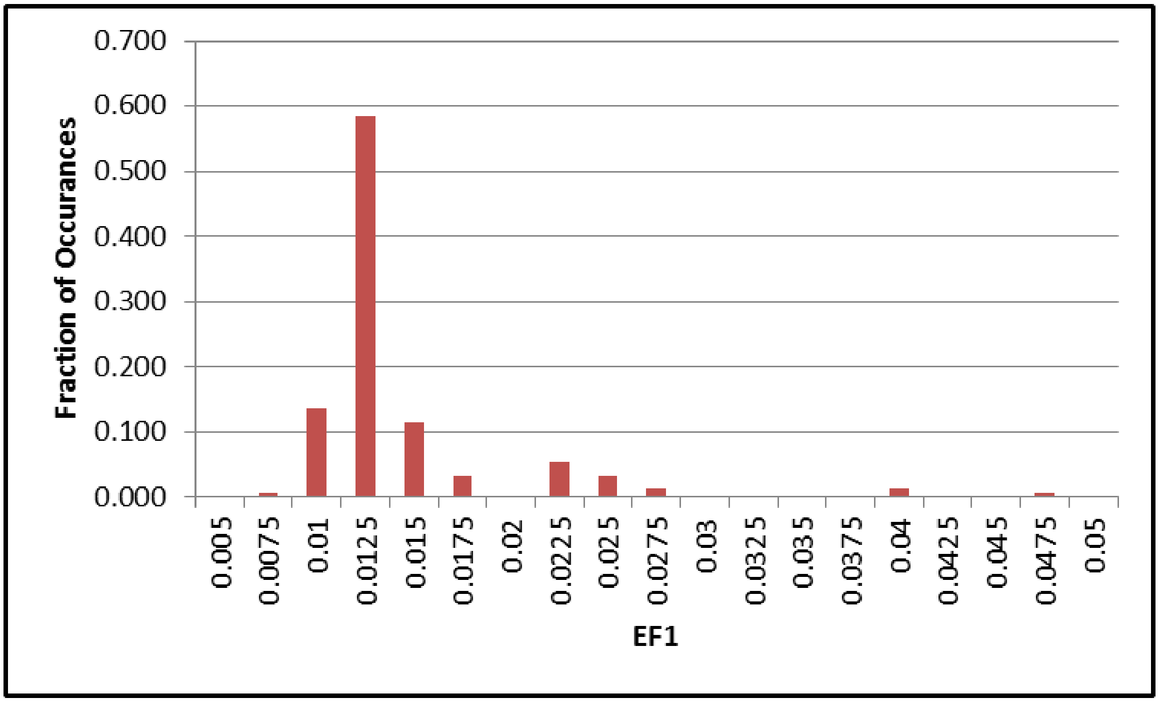
GREET and GHGenius take a similar approach to calculating the N_2O emissions and generally follow the approach recommended by the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The N_2O calculations in GREET are slightly less transparent in that the emission factors are embedded in equations in the model and changes in the emission factors require the user to change the equations rather than just changing a cell value as is the case in GHGenius. BioGrace is less transparent in the N_2O calculations unless the user chooses to use the IPCC 2006 methodology. This methodology is not used for the EU RED default values.

In the IPCC methodology the direct emission factor (EF_1) accounts for 75 to 80% of the N_2O emissions and is thus the most significant parameter. The indirect emissions due to leaching are 15 to 20% and the indirect emissions due to volatilization are 5 to 10%.

EF_1 can be influenced by a number of soil and climatic conditions. For IPCC Tier 2 and Tier 3 approaches the precipitation is the factor with the most influence on EF_1. Thus EF_1 is regionally specific and the models should use values that are reflective of the region being modelled.

The GNOC model is a public model that produces a value for EF_1 for a specific location considering soil conditions and climatic conditions. This model was used to look at N_2O emissions for US corn production by agricultural district. The production weighted average for EF1 was 0.0119, the range was 0.0072 and the max was 0.0474. The distribution of the values is shown in the following figure. Note that the range would be different if the analysis was done at the state level instead of at the agricultural district level.

Figure 1-12 Distribution of GNOC EF_1 for US Corn



GNOC uses the IPCC Tier 1 emission factor for volatilization and either zero or the IPCC Tier 1 emission factors for leaching. The total N_2O emissions calculated by GREET and GNOC are almost identical. However GREET N_2O emissions are lower than would be calculated using the emission factors developed from the EPA NIR and the USDA GHG Inventory reports.

The default for EF_1 for crop residues in GREET could be increased to the same factor as used for synthetic fertilizer (0.0125) and GREET could consider including a factor to account for corn production on histosols. No changes to GHGenius are recommended.

The thermal energy use for all of the corn ethanol dry mills for the year 2014 was found and production data for about half of them was used to generate energy use per gallon information. The energy use default values in GREET and GHGenius are appropriate and no changes are required.

While the model default values are very close to the 2014 average values, there is a range of energy use for individual plants. Thermal energy requirements ranged from 14,088 to 33,500 BTU (LHV)/gal.

The type of energy used in the corn ethanol plants has changed over time and in 2014, 98.3% of the energy used for thermal applications was natural gas. The coal use was only 1.1% and some of the plants that used coal switched to natural gas during 2014. The coal use in dry mill plants is probably close to zero in 2016. The default values in GREET and GHGenius should be changed to at least match the 2014 data.

There is a trend for ethanol plant to use less energy over time.

European ethanol plants do not produce as much electricity as the BioGrace model suggests. There is very limited data on natural gas use in European ethanol plants but the values in BioGrace are grossly exaggerated and do not reflect the actual operation of the plants with respect to gas used and electricity produced.

Co-products can be dealt with in LCA models several different ways. The ISO recommended approach would be the displacement approach. This is the way that corn ethanol co-products were assessed in the RFS2 program and in the CARB LCFS program. It is not the approach use in BioGrace, where energy allocation is used and the co-product credit is a function of the emissions of producing corn and ethanol and the co-product yield.

GREET and GHGenius use the displacement approach as the default approach for corn ethanol. The GREET calculations for the emissions displaced require information on the species (beef, dairy, swine, and poultry) that the co-products are fed to and the feed displaced (corn, soymeal, and urea) by the co-products for each species. There is also a methane credit for distillers grains fed to beef. This information is combined with the quantity of distillers' grain produced per gallon of ethanol.

There is no regular accounting of DDG consumption by species but there have been estimates made by various researchers. In the GREET calculations the one factor that has the most influence on the final co-product credit is the fraction fed to beef. This is because of the extra credit for avoided methane emissions when the DDG is fed to beef. The GREET default vault value is 40.6%; two values found in the literature were 45 and 54%. GREET should also investigate the potential or a methane reduction for dairy cattle. Both of these changes would increase the co-product credit for corn ethanol.

Counteracting this, the GREET value for the quantity of DDG produced is too high. The value in the model was established when ethanol yields were lower and DDG production was higher. As ethanol yields increase, DDG production drops at approximately twice the rate. In GHGenius the quantity of distillers' grains produced is a function of the ethanol yield, GREET should consider a similar approach.

There is a clear trend for reduced DDG production per gallon of ethanol produced. There is also a trend for increased extraction' of corn oil from the distillers' grain.

3. PETROLEUM FUELS

Task 2 of the work looked at five other fuel production pathways, petroleum fuels are the first of the five pathways. For each of the five pathways the scope of the work included a literature review of recent literature (2010 to 2015) to identify ranges of the key parameters that had been identified in Project E102, to determine if there were other parameters that were important in the lifecycle and to scan the literature to assess future trends. The literature that is used to support the default values in the models was to be included in the literature survey.

Gasoline and diesel fuel are important fuels for the lifecycle analysis of alternative fuels because the fuels are used in many of the alternative fuel production processes and because they are the fuels that new fuels are compared to. Four aspects of the petroleum fuel lifecycles are investigated below, the energy use and fugitive emissions for both the crude oil production stage and the refining stages of the lifecycles.

3.1 CRUDE OIL PRODUCTION ENERGY USE

The emissions from energy use during crude oil production are a major contributor to the lifecycle emissions of crude oil up to the refinery gate. The subject is discussed below.

3.1.1 Existing Model Values

The values that are used in the models are discussed below. BioGrace does not include this pathway so the approach used in the JEC WTW V4a reports is discussed instead.

3.1.1.1 GREET

There has been some development of the GREET model in this area over the years but other aspects of this stage in GREET haven't changes since GREET was first released 20 years ago.

Table 1-32 GREET Crude Oil Energy Use

Parameter	GREET 2014	GREET 2015	GREET 2016
Volume Fraction			
Conventional	0.906	0.793	0.715
Oil Sands	0.094	0.104	0.115
Shale Oil	0.0	0.107	0.17
Energy Efficiency			
Conventional	0.98	0.98	0.98
Oil Sands	0.74-0.93	0.74-0.93	0.74-0.93
Shale Oil		0.985-0.988	0.985-0.988

The total energy consumption for the weighted average crude oil production in GREET 2016 is 5.8% of the crude oil delivered. Crude oil transportation increases that to 8.3%.

GREET has added new types of crude oil in recent years and changed the fraction of each type of crude oil, but the energy use for conventional crude oil has not changed since GREET 1.5 and that value was based on existing studies published between 1991 and 1995.

The oil sands additions and the shale oil addition in 2015 were based on detailed studies undertaken by Adam Brandt and his team at Stanford (2015) and by the University of California at Davis (2015). The oil sands work utilized data supplied by the Alberta Energy Regulator and the shale oil work used the OPGEE model and data from the State of North Dakota and IHS data sets.

It is the energy use for conventional oil in GREET that relies on very old information.

The GHG emissions for crude oil production are those related to energy use coupled with the fugitive emissions discussed later. The GREET results are shown in the following table.

Table 1-33 GREET Crude Oil GHG Emissions

Parameter	GREET 2014	GREET 2015	GREET 2016
	g CO_2eq/mm BTU (LHV)		
Energy Related	5,198	6,060	6,638
Fugitive Emissions	3,255	1,606	3,436
Total Emissions	9,173	7,666	10,074

The GREET 2016 value is 9.5 g CO_2eq/MJ (LHV).

3.1.1.2 GHGenius

GHGenius has crude oil energy use for different types of crude oil (condensate, conventional, heavy, bitumen and synthetic oil) and for twenty-three regions around the world. For Canadian production the data for bitumen and synthetic oil production is from the Alberta Energy Regulator, the same source as is used in GREET. There was some data available from the Government of Canada on the energy use for conventional oil. The crude oil supply to the United States is from US DOE EIA data and varies with the year and region in GHGenius.

For oil supply outside of Canada the OPGEE model has been used to estimate the energy use and then that energy use has been used in GHGenius. The IOGP data has been used to scale energy use over time in the model.

The energy use for crude oil consumed in the United States in 2014 is shown in the following table. The energy consumed/energy delivered is a measure of efficiency and the 0.090 is comparable to the 5.8% value in GREET 2016.

Table 1-34 GHGenius Crude Oil Production Energy Use

Fuel	Kj/tonne of oil	Energy consumed/Energy Delivered
Crude oil	23,600	0.001
Diesel fuel	225,645	0.005
Residual fuel	67,774	0.002
Natural gas	2,935,231	0.066
Coal	0	0.000
Electricity	541,237	0.012
Gasoline	75,618	0.002
Coke	42,084	0.001
Still Gas	100,893	0.002
Total (TJ and kJ/tonne-oil)	4,012,084	0.090

The GHG emissions for the US from GHGenius are shown in the following table. They are higher than the GREET values.

Table 1-35 GHGenius Crude Oil Emissions for US

Parameter	GHGenius	GREET Units
	g CO_2eq/GJ (LHV)	g CO_2eq/mm BTU (LHV)
Energy Related	7,657	8,078
Fugitive Emissions	4,952	5,224
Total Emissions	12,609	13,302

3.1.1.3 JEC WTW

The JEC WTW work increased the energy consumed during crude oil production in version 4 from 2.5% to 6.5%. The earlier value was based on a personal communication in 2002 with Shell Oil. The later version is based on data from the International Association of Oil & Gas Producers (IOGP) and it includes the actual energy expended (0.027 MJ/MJ crude) plus the energy lost in flaring (0.037 MJ/MJ crude) and venting (0.001 MJ/MJ crude). The IOGP data is regionalized and the JEC work uses a weighted average of the crude oil regions that supply Europe.

The GHG emissions for crude oil production in Europe are 4.7 g CO_2eq/MJ (LHV).

The IOGP data is for the combined production of oil and natural gas but it is the only reported source of aggregated primary data that is publicly available.

3.1.2 Literature Review

The top results from the literature search are shown in Appendix 2. Search terns included "energy consumption" "crude oil production" “EROEI” and “EROI”. Papers that included algae, ethanol and biodiesel were excluded to try and narrow the returns. The papers were mostly very general and lacked specific energy consumption data.

Several reports with interesting information were identified in other searches.

3.1.2.1 Cooney et al 2016. Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models

The National Energy Technology Laboratory produced a well-to-wheels (WTW) life cycle greenhouse gas analysis of petroleum-based fuels consumed in the U.S. in 2005, known as the NETL 2005 Petroleum Baseline. This study uses a set of engineering-based, open-source models combined with publicly available data to calculate baseline results for 2014.

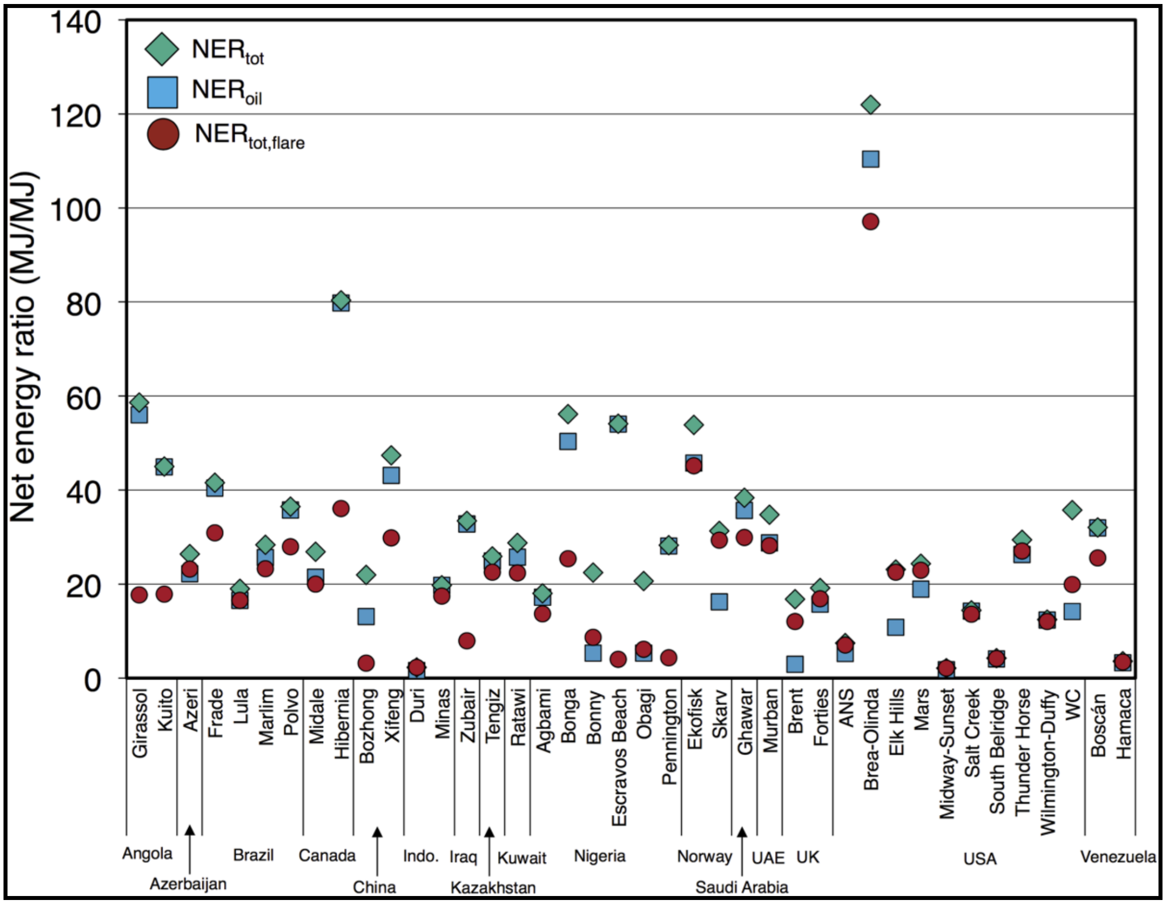
The OPGEE model was used to estimate the GHG emissions for the crude oils refined in the US and the Prelim model was used to estimate the refining emissions. The crude oil import data was obtained from the EIA Company Level import data as that has information on the API gravity and the sulphur content of the crude oil. A number of assumptions are required to be made to align the country level data available to the field level data required for OPGEE.

The OPGEE crude oil results, for the crude oil mix used in the US in 2014, were reported to be 10.6 g CO_2eq/MJ (LHV) for the production plus 0.7 g/MJ for the transportation for a total of 11.3 g CO_2eq/MJ (LHV). For the crude oil slate used in 2015 the GHG emissions were 13.7 g CO_2eq/MJ (LHV). Both values are higher than the GREET 2016 result of 9.5 g CO_2eq/MJ (LHV).

3.1.2.2 Brandt et al. 2014. Energy Return on Investment (EROI) for Forty Global Oilfields Using a Detailed Engineering-Based Model of Oil Production

The EROI is a metric that is essentially the inverse of the efficiency metric used in GREET. The 98% efficiency for conventional oil in GREET is equivalent to an EROI of 50. Thus studies that look at EROI can be used to estimate the efficiency input in GREET. This paper used OPGEE to look at 40 global oil fields, utilizing detailed data for each field from hundreds of technical and scientific data sources. OPGEE actually reports a net energy return, units of energy produced per unit of energy consumed. The fields had NER ranging from 2 to 100 MJ of crude/MJ of energy consumed. The results are shown in the following figure.

Figure 1-13 Total net energy ratio NER_{tot} and oil-specific net energy ratio NER_{oil} for studied global oil fields



There is a wide range of results but the values were also presented in groups as shown in the following table.

Table 1-36 Results by Group

Field Type	Mean NER_{tot}	Std Dev
All fields	31.2	22.3
High water-oil ratio	16.3	8
Deep	30.2	16.5
Ultra-deep	24.3	5.2
Old	25.2	16.6
Heavy oil	20.8	17.6
Ultra heavy oil	12.5	16.9
Thermal EOR	3	1.2

The mean value of 31.2 is equivalent to an efficiency in GREET of 96.8% but there is significant variation between the types of fields and within the types of fields. Thermal EOR fields would have an equivalent GREET efficiency of 66.7%.

3.1.2.3 Clearstone Engineering Ltd. 2014. Volume 1- Overview of the GHG Emissions Inventory.

This report was prepared for Environment Canada to assist with the development of the Canadian National Inventory Report. The emissions inventory was developed using an IPCC Tier 3 bottom-up assessment methodology beginning at the individual facility and process unit level and aggregating the results to ultimately provide emission estimates by facility and geographic area. Emission contributions due to both fuel-use and non-fuel-use sources (i.e., fugitive sources) have been evaluated. The data was developed for 2011. The results of the inventory are summarized in the following table.

Table 1-37 Crude Oil GHG Emissions

	Unit	GHG emissions, kg CO_2eq/unit	GHG Emissions, g CO_2eq/MJ (LHV)
Well Drilling	Per well	125,290	-
Well Servicing	Per well	10,180	-
Well Testing	Per well	17,810	-
Light/Medium Crude Oil Production	Cubic metre	203.71	4.8
Heavy Crude Oil Cold Production	Cubic metre	448.75	11.2
Heavy Crude Oil Thermal Production	Cubic metre	596.20	14.9

This data set is one of the very few bottom up accounting of GHG emissions for oil and gas production activities in the world. It is likely that the EPA has some similar data that they have been gathering through their GHG emission reporting program.

3.1.2.4 Rahman et al 2014. Greenhouse gas emissions from recovery of various North American conventional crudes

The overall objective of this research was to estimate the GHG emissions in recovery of five different conventional crudes from North America through the development of data-intensive, bottom up engineering models and to perform a comparative assessment of the GHG emissions. This study focused on all the crude recovery subunit operations and quantifies GHG emissions from drilling wells, crude extraction, venting, flaring, and fugitives, and crude oil processing for five well-known North American crudes. The five crudes evaluated in this study are: Alaska North Slope, California's Kern County heavy oil, Mars, Maya, and Bow River heavy oil. Some of the findings are summarized in the following table.

Table 1-38 Assumptions and Results

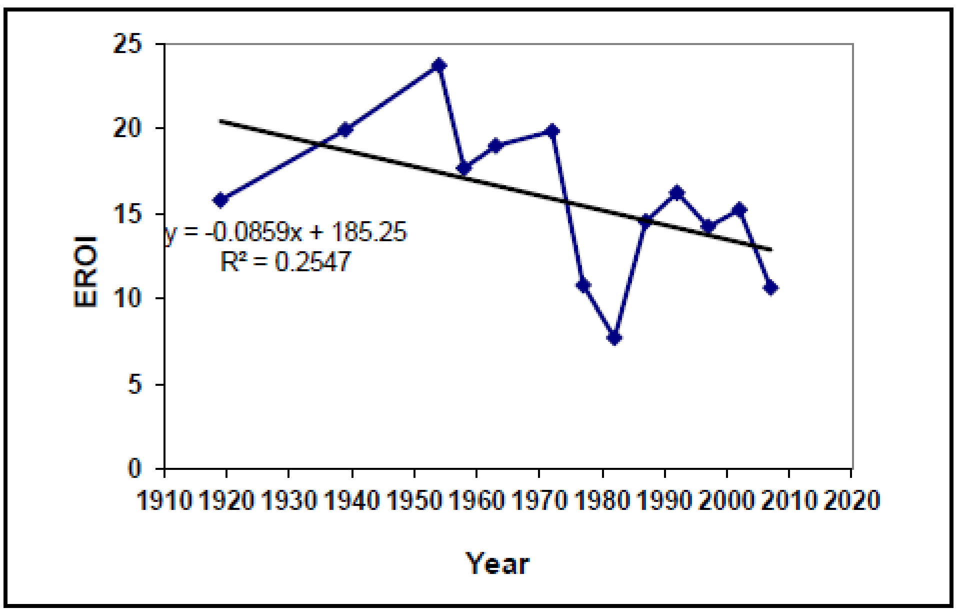
Crude	Extraction Efficiency	Flaring	Venting	Fugitive	GHG Emissions
	%	m^3/m^3			g CO_2/MJ
Alaska N Slope	96.8	3.82	0.68	2.13	5.73
Kern	65	0.74	0.74	0.11	23.85
Mars	98.2	1.33	0.78	0.21	3.94
Maya	98.6	13.46	0.95	0.06	4.20
Bow River Heavy	98.2	9.63	1.99	0.32	5.54

This work did not use OPGEE but did take a similar engineering model approach to calculating the GHG emissions.

3.1.2.5 Guilford et al. 2011. A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production

The data in this report ends in 2007 but it does provide a long-term view of the EROI for US oil and gas production. The data was taken from the US Census Bureau and considered the energy required for finding and producing oil. The results are shown in the following figure.

Figure 1-14 Long Term EROI for US Production



The EROI for production of the oil and gas industry was about 20:1 from 1919 to 1972, declined to about 8:1 in 1982 when peak drilling occurred, recovered to about 17:1 from

1986 to 2002, and declined sharply to about 11:1 in the mid-to-late 2000s. An EROI of 10 would indicate that the GREET efficiency should by 90%.

3.1.2.6 ICCT 2014. Upstream Emissions of Fossil Fuel Feedstocks for Transport Fuels Consumed in the EU

This report and the next report by Exergia focused on crude oils supplied to EU refineries and is comparable to the JEC results and not to GREET or GHGenius 4.03a. The study used the OPGEE model. ICCT were able to obtain adequate data to perform an initial analysis of over 300 oil fields from a variety of sources.

The 265 oil fields assessed for the EU Baseline have been associated with crude blends being supplied into Europe (covering 93% of European oil consumption) – ICCT estimate that the volume weighted average CI of the oil used in Europe is 10.0 g CO_2e/MJ (LHV). The range for the different crude oil streams ranged from 3.2 to 23.3 g CO_2e/MJ (LHV).

3.1.2.7 Exergia 2015. Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas

Exergia undertook a similar study as the ICCT but also included the refinery emissions and tried to accurately track the oil shipments to specific refining regions in Europe. They also paid attention to gas flaring data and this developed an independent data set for running in OPGEE. The average CI for crude oils delivered to Europe was calculated to be 9.7 g CO_2eq/MJ (LHV), very similar to the ICCT value although there were significant differences in some specific oilfields. The values ranged from 4.73 to 26.19 g CO_2eq/MJ (LHV).

3.1.3 Data Sources

There are very few data sources for the energy or carbon intensity for crude oil production.

3.1.3.1 International Association of Oil and Gas Producers

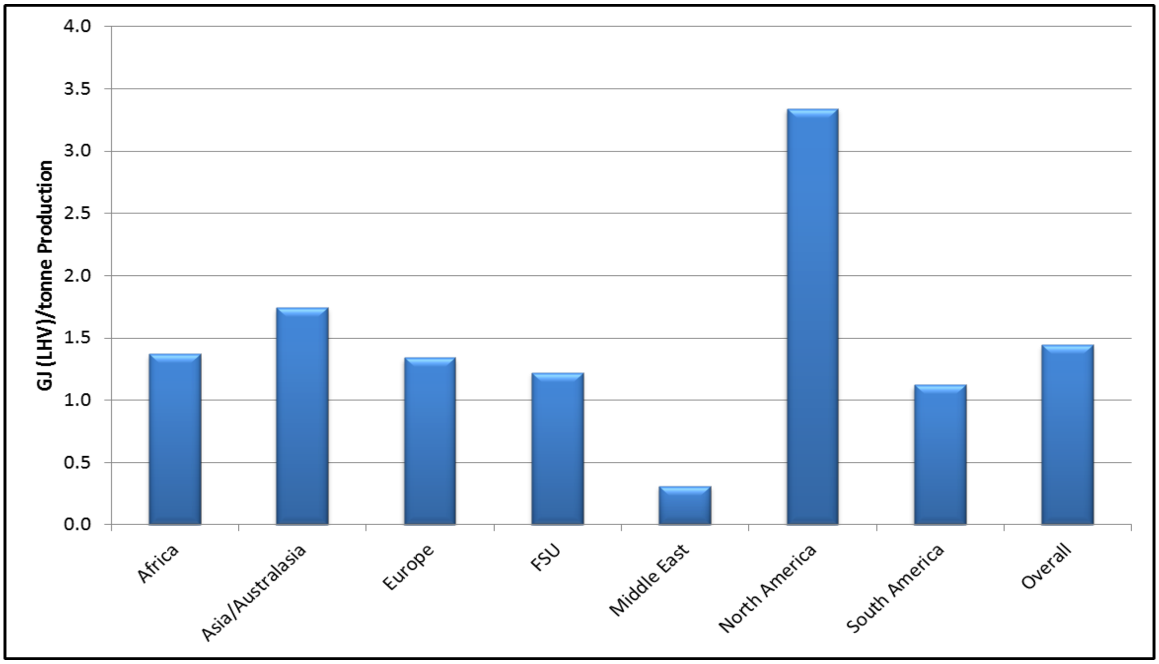
The only comprehensive data set is that developed by the International Association of Oil and Gas Producers (IOGP). They have collected environmental data from its member companies every year since 1999. The objective of this programme has been to allow member companies to compare their performance with other companies in the sector leading, it is hoped, to improved and more efficient performance. The programme also contributes to the industry's wish to be more transparent about its operations.

In 2015, data was submitted by 38 of IOGP's 56 member operating companies covering operations in 75 countries worldwide. This total includes 38 of the 43 companies that contributed data in 2014. The data is for combined oil and gas production and represented oil and gas wellhead production of 2,124 million tonnes (15.8 billion BOE), about 28% of 2015 global production sales, with the absolute and relative production values virtually unchanged compared with 2014. Regional coverage is uneven, ranging from 88% of known production in Europe to 10% in the Former Soviet Union (FSU).

In 2015, IOGP reporting companies consumed on average 1.4 gigajoules of energy for every tonne of hydrocarbon produced; a 3% reduction compared with the 2014 average. This is equivalent to 96.6% efficiency in the GREET model.

There are significant regional differences, as shown in the following figure of 2015 results. The energy intensity in North America is much higher than the rest of the world and that could be because some oil sands production is included.

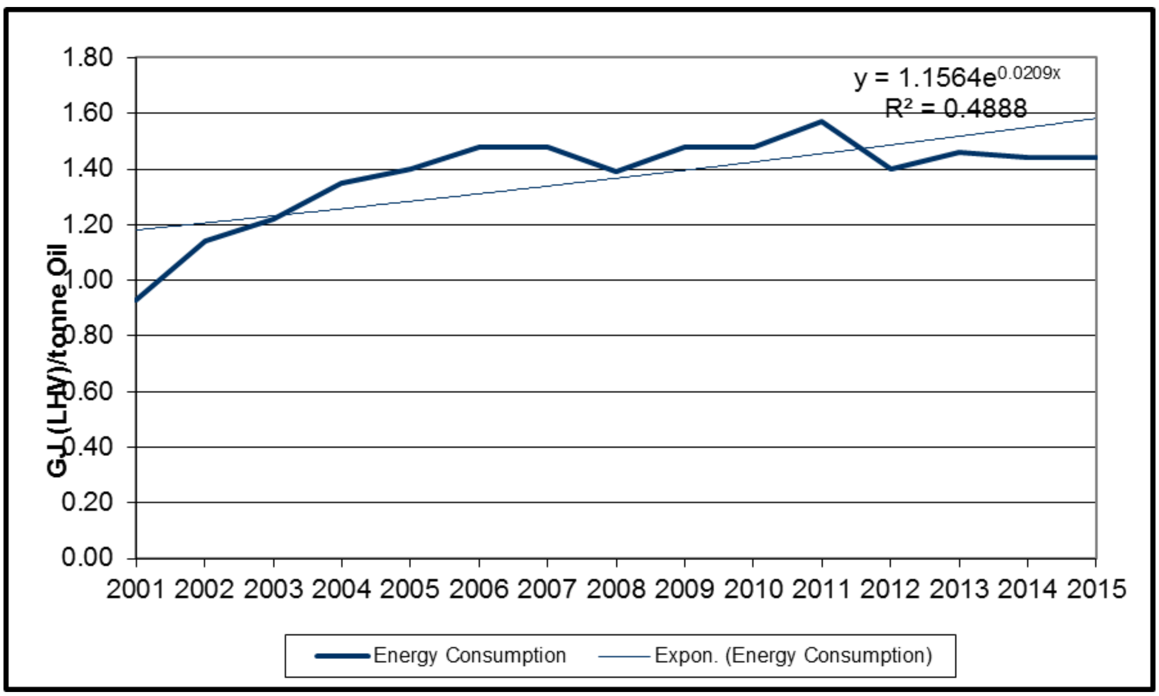
Figure 1-15 Regional Energy Use



3.1.4 Trends

The IOGP energy data has been reported since 2001. The global trend for energy consumption per tonne of oil equivalent is shown in the following figure.

Figure 1-16 IOGP Energy Use Trend



The long-term trend is upward but the energy use has been relatively static for several years. It is likely that the global average is higher than is shown here, as IOGP members tend to be the large international companies who operate larger, more modern fields.

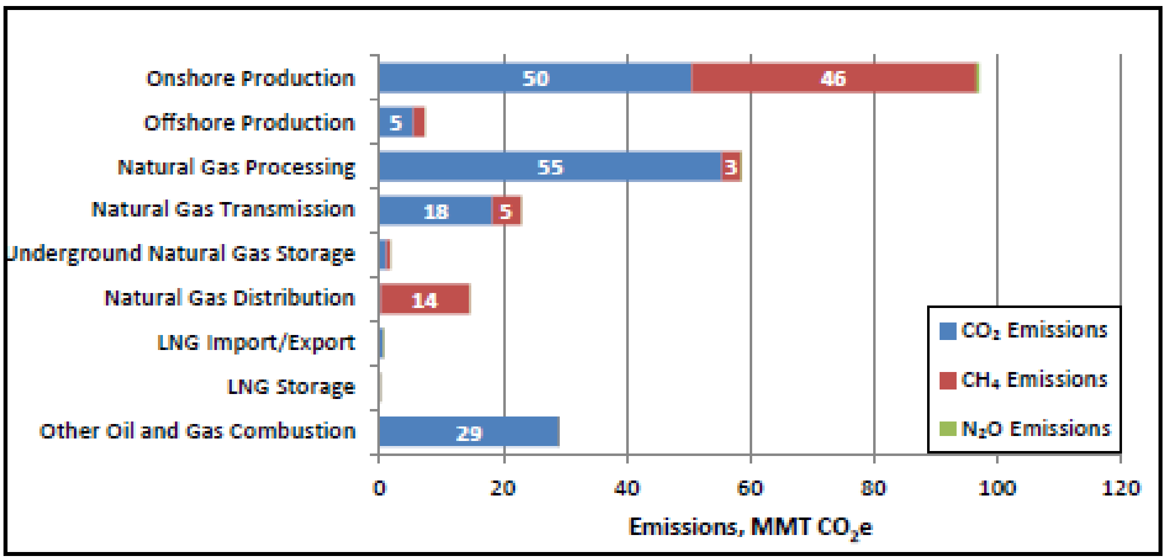
3.1.4.1 EPA FLIGHT

Facility level GHG emission data exists for on and offshore petroleum and gas producers. The EPA Flight database, which was used for ethanol plant energy use, includes 696 reporting petroleum and natural gas producing facilities in 2014 that reported 108 million tonnes of GHG emissions. Production of oil and gas is not reported in the exportable data for these facilities making it difficult to develop emission factors. However, when one drills down into the available online data, some facilities do report oil and gas production volumes through some of the equipment, and it may therefore be possible to develop some emission factors from this data.

The following link can be used to access the data. EPA Flight Data - Petroleum and Natural Gas Systems. Individual reporting facilities are shown on the map and by clicking on the icon, the summary of the emissions from the facility are shown in a new page. That new page has a link to the detailed emission data and sometimes oil and gas production data.

The EPA does produce a sector profile based on the reported emission data but the sector profile does not contain any throughput data making it impossible to use the profile to develop emission factors. The sector profile emissions summary for 2015 is shown in the following figure.

Figure 1-17 2015 Petroleum Sector Reported Emissions



3.1.5 Crude Oil Production Energy Use Findings

The three models have very different levels of details in terms of how the GHG emissions associated with energy use for crude oil production are determined. GREET has been expanding this area in recent models with progressively more detail in the 2014, 2015, and 2016 versions. However 70% of the crude oil production still uses an original estimate of energy use from the 1990s literature. This value could be improved though the use of OPGEE values or even the IOGP combined value for oil and gas production.

Primary data or even aggregated primary data is very scarce on a global basis. There is the IOGP data, which has a 15-year time series for 35 to 40% of the world's production but it combines oil and gas production and doesn't have the level of specificity that the models generally require.

It may be possible to extract some data from the EPA FLIGHT database but it must be extracted manually and the detail on what is reported at each facility is likely going to vary.

With the lack of availability of primary data, the OPGEE model is gaining in popularity as a tool to estimate the GHG emissions from oil production around the world. However, OPGEE is an engineering model and for many production fields the full data set required for the model is not available and default values are used. This will have a negative impact on the certainty of the results produced by the model. The full LCA models can be tuned to produce similar results to the OPGEE model.

3.2 CRUDE OIL PRODUCTION FUGITIVE EMISSIONS

Fugitive methane emissions can be a significant contributor to the GHG emissions associated with some types of crude oil production systems. The subject is discussed below.

3.2.1 Existing Model Values

The values that are used in the models are discussed below.

3.2.1.1 GREET

GREET inputs methane emissions for crude oil production as an input value. Starting with GREET 2014, the US EPA National Inventory Report has been used to estimate methane emissions from crude oil production. The GREET 2013 value was only 8.3 g methane per million BTU. The value was updated in GREET 2015 and 2016 as the EPA enhanced their emission factors and equipment inventory. GREET assumes that the US oil production is similar to production in other regions and the US value is applied to all conventional oil production.

Table 1-39 GREET Crude Oil Methane Emissions

Parameter	GREET 2014	GREET 2015	GREET 2016
	g CH_4/mm BTU (LHV)		
Conventional	108	41	155
Mined Bitumen	112	112	112
Mined SCO	139	139	139
In Situ Bitumen	157	157	157
In Situ SCO	0	0	0
Bakken shale	65	65	65
Eagle Ford shale	64	64	64

With the US average being used for conventional oil and the oil shale values being lower, there may be a small underestimation of methane from US crude oil production.

3.2.1.2 GHGenius

GHGenius estimates methane emissions from venting, fugitive sources and incomplete combustion of flared gas separately for each producing region in the model.

A variety of estimates of vented methane in crude oil production were identified in the latest revision of the data. There is a wide range in the emissions, from less than 0.5 to more than 20 kg methane/tonne of oil. The data from Canada and the US, which are similar, are the most rigorous estimates, based on detailed equipment inventories and emission factors.

It seemed unreasonable to assume that other countries would have lower venting rates than Canada and the US where the industry has been subject to emission control standards for many years. Therefore, we will use a constant value of 5 kg methane/tonne of oil produced for venting emissions, except that Canada continues to be calculated separately for different types of crude oil due to the availability of better data.

For fugitive emissions, again a variety of sources of information were found, there is the bottom up estimates of the US EPA, OPGEE calculations for major fields, and the IOGP annual data. The range is smaller than it was for venting emissions, from about 0.1 to 2.5 kg methane/tonne of oil. Based on the data, GHGenius uses the value of 1.25 kg methane/tonne of oil (about the mid-point of the range) for all regions, with the exception of bitumen and synthetic production in Canada, as these already had detailed fugitive emission estimates.

Flaring of associated gas is practiced at many crude oil production sites around the world. GHGenius used NOAA data for 2010 and uses a flared efficiency of 95% to calculate the emissions from flared gas.

The following table shows the combined methane emissions for various sources of crude oil in GHGenius. The US average supply number is not really comparable to the GREET value since GREET is based on US production only and GHGenius is based on all crude oil supplied to the United States.

Table 1-40 GHGenius Methane Emissions

Crude Oil Source	Methane	
	g CH_4/GJ (LHV)	g CH_4/mm BTU (LHV)
Canada conventional oil	64.5	68.0
Canada conv heavy	151.6	159.9
Canada bitumen	69.8	73.6
Canada synthetic oil	139.3	147.0
US average supply	185.6	195.8

3.2.1.3 JEC WTW

The methane emissions in the JEC version 4a work are 0.67 g CO_2eq/MJ for crude oil production. This is 28 g methane per mm BTU. This includes venting, flaring and fugitive emissions. The data source is the International Association of Oil and Gas Producers. The data is supplemented with flaring data from NOAA. The value is quite low compared to North America Data.

3.2.2 Literature Review

Two sets of search terms “energy consumption” with “crude oil Production” and EROEI and “crude oil production” were used for the literature review. The top papers are found in Appendix 2, sections 10.4 and 10.5. Very few of the papers deal with just crude oil production and none presented primary or aggregated primary data that could be used in the models. Several of the papers used aerial methods to estimate the methane emissions.

3.2.2.1 Schneising et al 2014. Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations

This paper demonstrated that positive methane anomalies associated with the oil and gas industries can be detected from space and that corresponding regional emissions can be constrained using satellite observations. The paper found very high methane rates with methane emissions from oil production equalling 10% by energy of the oil produced.

3.2.2.2 Peischl et al 2016. Quantifying atmospheric methane emissions from oil and natural gas production in the Bakken shale region of North Dakota

This paper presents in situ airborne measurements of methane (CH_4) and ethane (C_2H_6) taken aboard a NOAA DHC-6 Twin Otter research aircraft in May 2014 over the Williston Basin in northwestern North Dakota, a region of rapidly growing oil and natural gas production. The Williston Basin is best known for the Bakken shale formation, from which a significant increase in oil and gas extraction has occurred since 2009. They derived a CH_4 emission rate from this region using airborne data by calculating the CH_4 enhancement flux through the planetary boundary layer downwind of the region. They calculated an energy loss rate of $1.6 \pm 0.5\%$, a factor of approximately 6 lower than that reported by Schneising et al. They concluded that the exceptionally high atmospheric loss rate of CH_4 reported by Schneising et al. [2014] for 2009 to 2011 is inconsistent with our airborne data from May 2014.

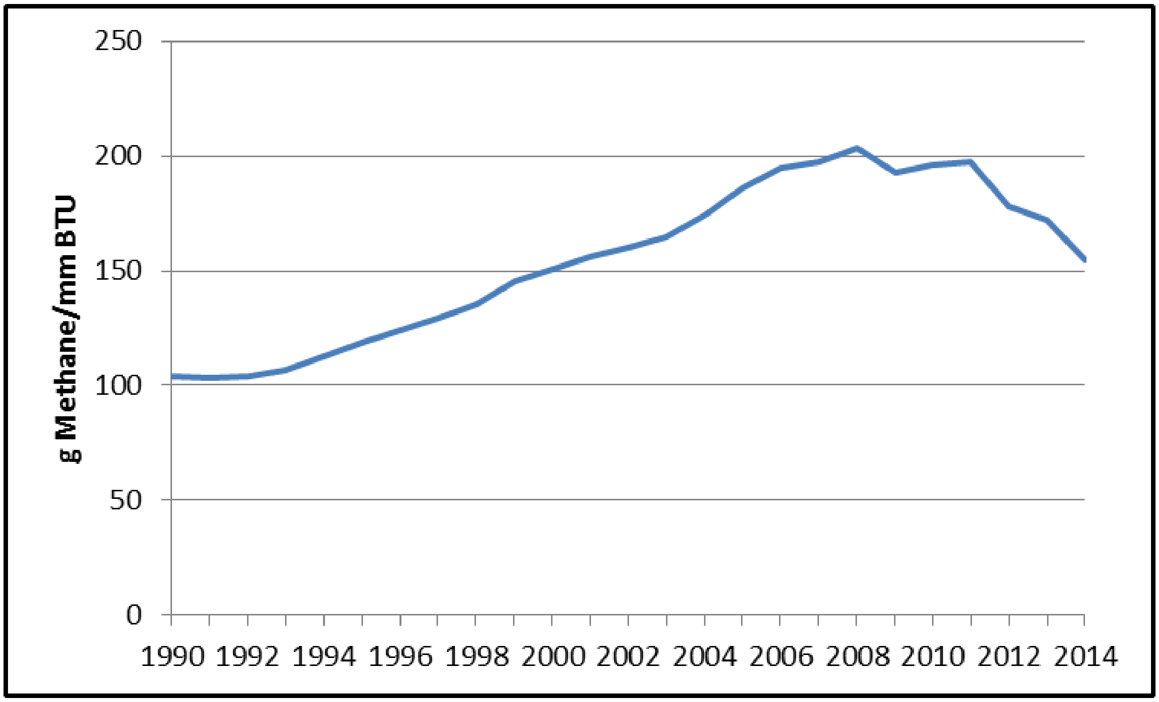
A loss rate of 1.6% is equivalent to 360 g CH_4/mm BTU, a much higher rate than is used in GREET for Bakken oil production.

3.2.3 Data Sources

The US National GHG Inventory report includes estimates for fugitive emissions of methane and carbon dioxide from petroleum production, transportation and refining systems. This information can be combined with activity data from the US DOE on crude oil production rates and oil refining rates to generate the emission factors that are used in the models.

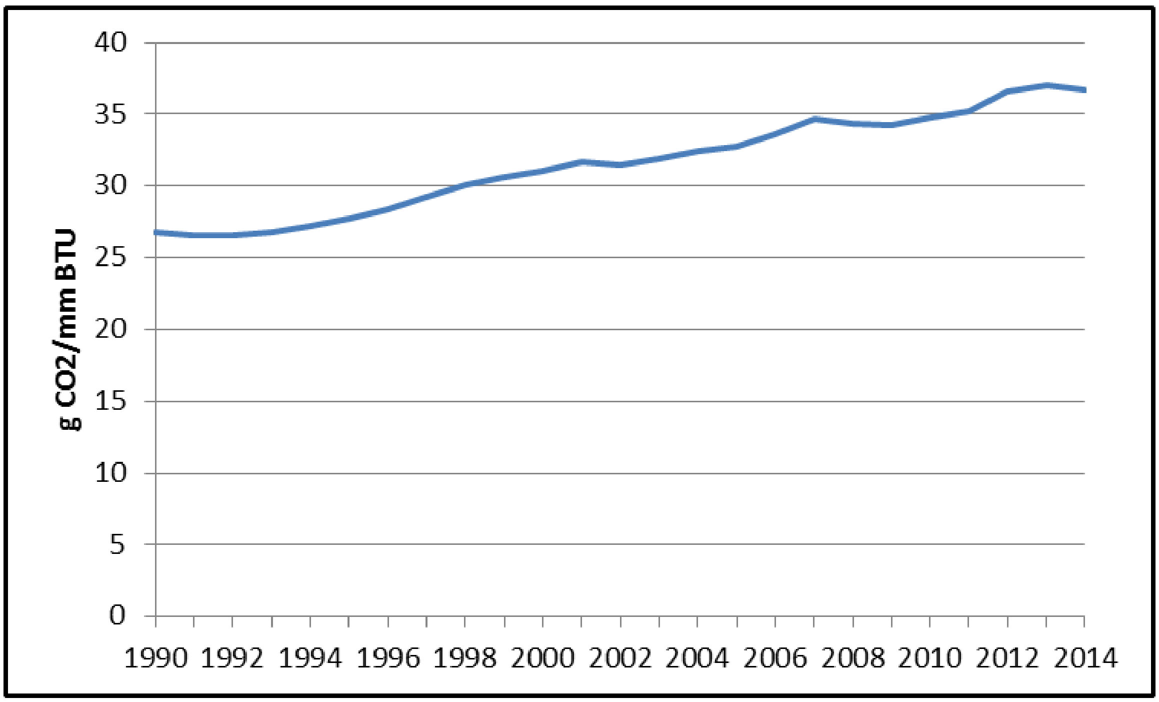
The following figure shows the methane emission for crude oil production per million BTU of crude oil production. This data set is aggregated over all crude oil production systems.

Figure 1-18 Methane and CO_2 Emissions for US Crude Oil Production



The non-combustion CO_2 emissions are much lower than the methane emissions and are shown in the following figure.

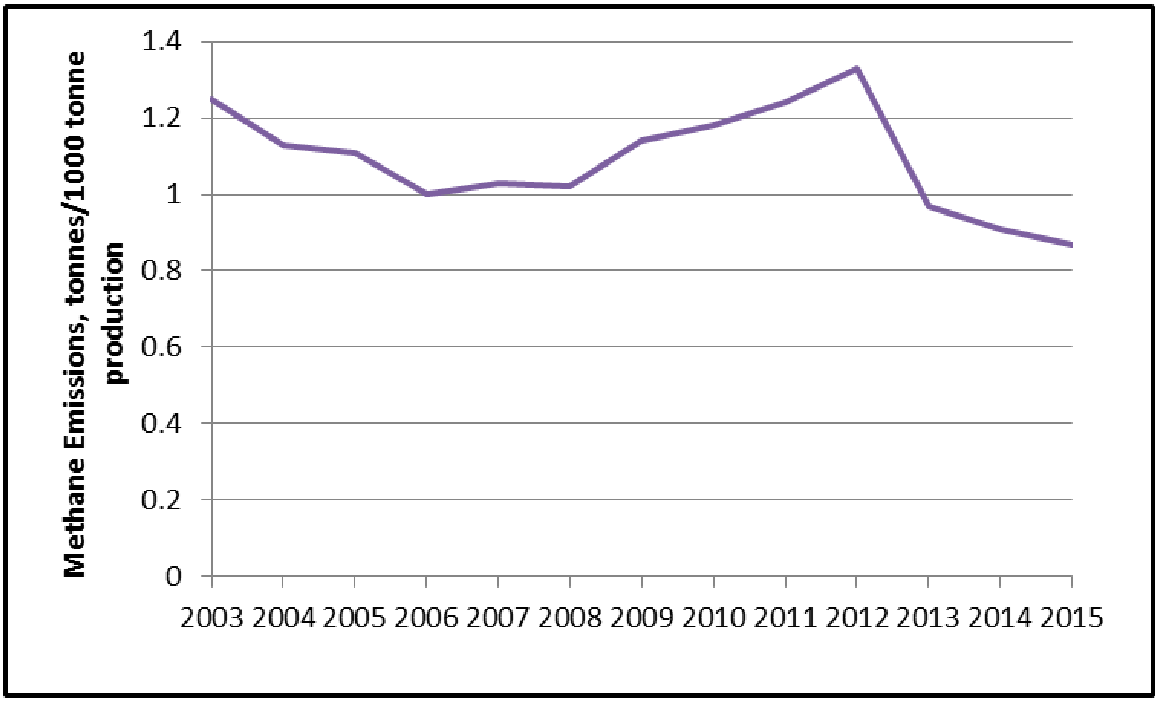
Figure 1-19 Non Combustion CO_2 Emissions US Crude Oil Production



3.2.4 International Association of Oil and Gas Producers

Methane emissions are reported by the IOGP. The same caveats apply to the energy data — the methane is for the combined production of oil and gas and the coverage varies by region.

Figure 1-20 IOGP Methane Emissions



A value of 0.9 tonne methane per 1000 tonnes is equivalent to 23 grams of methane per mm BTU. The value for North America was 61 g CH_4/mm BTU. These values are significantly lower than the values from the US National Inventory report.

3.2.5 Trends

The US EPA data indicates that methane emissions increased until about 2008, stabilized through to 2011 and have been dropping since then. While GHGenius has some capacity to reduce these emissions over time, in GREET 2016, the emissions are a fixed value and have to be manually adjusted. Consideration of changing this to a lookup function for historical data or for future estimates should be made.

3.2.6 Crude Oil Fugitive Emission Findings

There remains significant uncertainty with respect to methane emissions from crude oil production. The best data sources are the IOGP and the national inventory reports of UNFCCC Annex 1 countries. There is a significant variation in the reported values from these two sources.

Top down estimations of methane emissions are generally much higher than the bottom up approaches that are used in inventory systems and in the models.

With such a wide variation it is impossible to suggest a better range of values for use in the models.

3.3 OIL REFINING ENERGY USE

The emissions from the refining of the crude oil are typically on the same order of magnitude as the emissions from producing the crude oil. They are therefore important parameters. Refining energy use will vary with the type of crude oil being refined and by the refinery configuration.

3.3.1 Existing Model Values

There is a range of approaches used in the three models and they are described in the following sections.

3.3.1.1 GREET

The refining energy approach in GREET was updated in 2014. Two papers were written and published in the peer reviewed literature (Forman et al, 2014 and Elgowainy et al, 2014). The second paper has the details of the derivation of the inputs for GREET.

The goals of the GREET update were to correlate the variations in overall efficiency of U.S. refineries with variations in crude quality, refinery complexity, and product slate; and to develop estimates of average and range, as well as distribution functions for refining process energy and GHG emission intensities and process fuel shares for each refined product. These additions to the GREET model will enable accurate assessment of the energy and carbon intensities of various petroleum fuels on a life-cycle basis, which is the method used by legislators and government agencies in the United States and abroad.

The approach taken was to use results from a linear programming (LP) model to conduct in-depth analysis of 43 large U.S. refineries, each with a capacity greater than 100,000 bbl/day. Although the 43 refineries represent only 31% of the current 139 operating refineries in the United States, they represent 70% of the total U.S. refining capacity and span a wide range of crude sources/quality, product slates, and refinery complexity in PADD regions I, II, III, and V. PADD IV has the smallest refining capacity among all PADD regions (less than 4% of total U.S. refining capacity) and was excluded from this study.

Process level allocation was then applied to allocate energy use and therefore GHG emissions to specific refined petroleum products. The average crude oil characteristics have changed in GREET between the 2014 and 2016 models, so the energy use is also changed based on the algorithms developed from the LP data. GREET can use the energy efficiency set by the crude oil quality or by values from a time series. The energy use per product, based on the crude oil quality, is shown in the following table.

Table 1-41 GREET Refining Energy Use

	GREET 2014	GREET 2015	GREET 2016
API gravity of Average Crude to Refineries	29.6	30.6	31.2
S Content of Average Crude to Refineries (wt. %)	1.7	1.8	1.8
Refinery Heavy Product Yield (mmBTU of mmBTU of total refinery products)	11.0%	11.0%	11.0%
Refinery Complexity Index	10.8	10.8	10.8
Gasoline Efficiency, %	88.4	88.5	88.7
Diesel Efficiency, %	90.7	90.8	90.9

3.3.1.2 GHGenius

GHGenius also adjusts the refining energy based on the API gravity and sulphur content of the crude oil. It uses the data on own use of energy from the US DOE EIA to determine the base energy use and then any future change in crude oil quality has an adjustment applied to the historical energy use based on the change in crude relative to the last year that has refinery energy use. The GHGenius energy use for the US and the US regions is shown in the following table. The information is for 2011, the last year of actual data in version 4.03a.

Table 1-42 GHGenius Refinery Energy Use

	US East	US Central	US West	US
API gravity	33.1	30.9	28.9	31.4
S content (wt. %)	0.71	1.48	1.35	1.47
Total Energy Use, joules/joule	0.067	0.099	0.114	0.10
Gasoline, joules/joule	0.071	0.128	0.118	0.12

The gasoline efficiency in GHGenius is very close to that of GREET. In GHGenius gasoline and diesel have the same efficiency or energy use, while in GREET the diesel efficiency is about 2% higher than the gasoline efficiency.

3.3.1.3 JEC WTW

The refining emissions in the JEC WTW do take a different approach than the other models in that they use the marginal energy use to calculate the emissions. The other two models use the average emission approach. The energy use and GHG emissions from version 4a of the model are shown in the following table.

Table 1-43 JEC Refining Energy Use and Emissions

Fuel	Energy	Emissions
	MJ/MJ product	g CO_2eq/MJ
Gasoline	0.08	7.0
Diesel	0.10	8.6

The energy use and emissions are from a CONCAWE internal model.

3.3.2 Literature Review

The literature review used the terms “oil refining” and “energy consumption”. The top papers returned are listed in Appendix 2, section10.6.

3.3.2.1 Hirshfeld et al 2012. Analysis of Energy Use and CO_2 Emissions in the U.S. Refining Sector, With Projections for 2025

This analysis used linear programming modeling of the U.S. refining sector to estimate total annual energy consumption and CO_2 emissions in 2025 for four projected U.S. crude oil slates. The baseline is similar to the current U.S. crude slate; the other three contain larger proportions of higher density, higher sulfur crudes than the current or any previous U.S. crude slates. The latter cases reflect aggressive assumptions regarding the volumes of Canadian crudes in the U.S. crude slate in 2025.

The analysis projects U.S. refinery energy use 3.7%−6.3% (≈ 0.13−0.22 quads/year) higher and refinery CO_2 emissions 5.4%−9.3% (≈ 0.014−0.024 gigatons/year) higher in the study cases than in the baseline.

3.3.2.2 Exergia 2015. Study on Actual GHG Data for Diesel, Petrol, Kerosene and Natural Gas

This study used the Primes model of the energy sector in Europe to calculate the GHG emissions of European refineries. The average EU CO_2 coefficients for petrol, diesel and kerosene are 8.2, 7.6 and 4.7 g CO_2eq/MJ of product respectively. There was considerable variation in the results from country to country. The average results were only slightly higher than the JEC results.

3.3.3 Data Sources

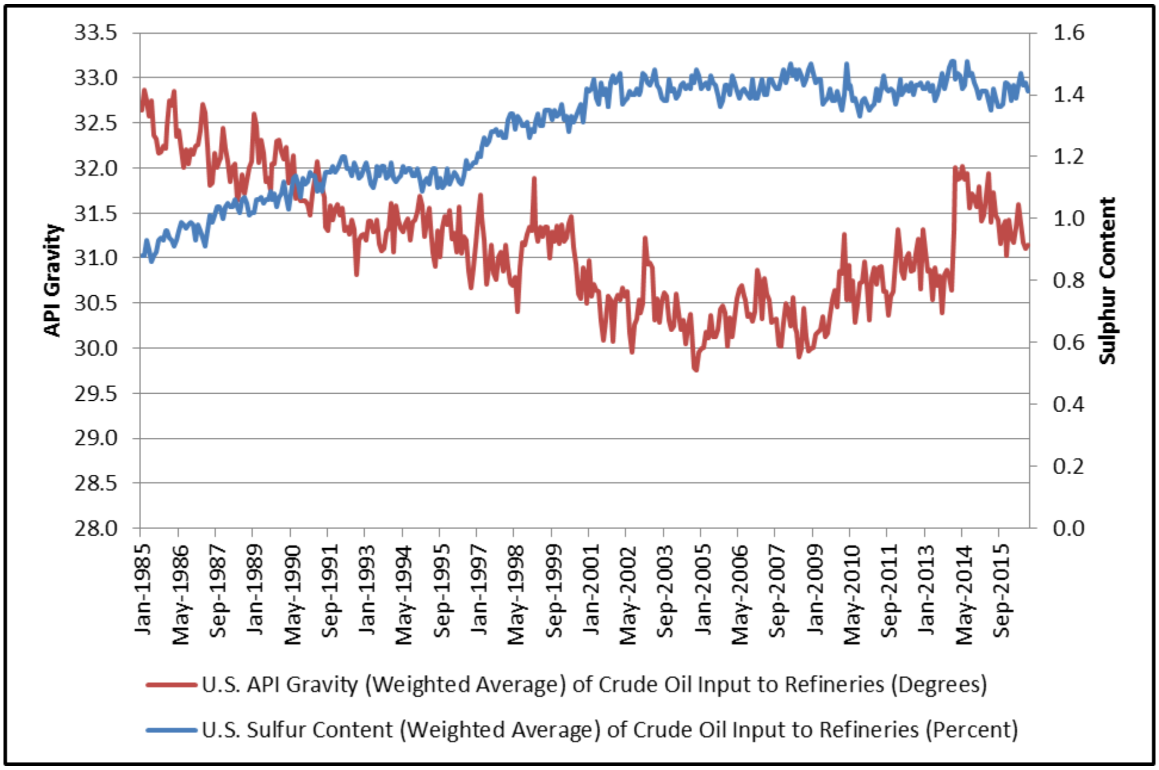
Energy use in US refineries is reported by the US Energy Information Administration. This is found at the page entitled Fuel Consumed at Refineries (http://www.eia.gov/dnav/pet/pet_pnp_capfuel_dcu_nus_a.htm). The data is available for the period 1985 to 2015. The data is available by PADD and for the US as a whole. A separate data series from 2008 is available on natural gas consumption for hydrogen production.

This data source is used in GHGenius and was previously used for GREET before GREET changed to using an LP model output.

3.3.4 Trends

Refinery energy use is a function of many variables. GREET and GHGenius now adjust the refining energy based on the crude oil properties. There has been a long-term trend to crude oils with higher density and sulphur contents, which require extra energy, but this trend has been reversed the past several years.

Figure 1-21 Crude Oil Input Quality



The energy can also be impacted by the specifications that the refineries must meet and these specifications are becoming more stringent leading to an increase in energy use and thus higher emissions.

3.3.5 Oil Refining Energy Use Findings

GREET and GHGenius use different approaches and underlying data for the energy use and GHG emissions at oil refineries. GHGenius uses publicly available data whereas GREET now uses the output from a proprietary LP model. However, the results are quite close.

Both models now respond to different crude quality input to the refineries.

3.4 Oil Refining Fugitive Emissions

Oil refineries will produce gaseous products as well as liquid products. The gaseous products are susceptible to leakage and thus there is the potential for fugitive emissions from the refineries. This is discussed in the following section.

3.4.1 Existing Model Values

The existing model values for fugitive emissions are presented below.

3.4.1.1 GREET

GREET includes CO_2 from the steam methane reformer (461 g CO_2/mm BTU for gasoline) as the only source of non-combustion emissions in the refining of gasoline and diesel fuel.

3.4.1.2 GHGenius

GHGenius has a small value for methane emissions and some non-combustion CO_2 emissions. The values in the model are old and not well supported. The CO_2 emissions are 974 g/GJ (HHV) (1100 g/mm BTU). The methane emissions are 1.8 g/GJ (HHV) (2.0 g/mm BTU LHV).

3.4.1.3 JEC WTW

The JEC WTW version 4a has no methane or N_2O emissions from the refinery. The assumption being that there are no fugitive emissions from the refinery.

3.4.2 Literature Review

The literature search used the terms “oil refining” and “fugitive emissions”. The results are in section 11.7 of Appendix 2. None of the most relevant papers returned by the search had any useful information for modelling.

3.4.2.1 Robinson et al 2011. Infrared differential absorption Lidar (DIAL) measurements of hydrocarbon emissions

This paper describes the use of an infrared (IR) differential absorption Lidar (DIAL) system to measure VOC emissions at a petrochemical site and a landfill. The volatile organic compound (VOC) measurements at the petrochemical site it found that the American Petroleum Institute’s methodology of the time for calculating the emitted flux underestimated by a factor of 2.4. No speciation was reported for the VOC emissions.

3.4.2.2 Chambers et al 2008. Direct Measurement of Fugitive Emissions of Hydrocarbons from a Refinery

This earlier paper also used the DIAL approach to measure emissions, including methane, from an oil refinery. Refinery fugitive emissions as measured with DIAL during this demonstration study were 1,240 kg/hr of C_{2+} hydrocarbons, 300 kg/hr of methane, and 5 kg/hr of benzene. The annual methane emissions would be 2.5 kt for a single refinery. The EPA reports only 23.5 kt of methane from fugitive and combustion emissions for all US refineries.

3.4.2.3 Hoyt et al 2015. Measured and estimated benzene and volatile organic carbon (VOC) emissions at a major U.S. refinery/chemical plant: Comparison and prioritization

This paper did not address methane but looked at benzene and VOCs. The authors reported that the results of this study indicate estimated emissions were never higher and were commonly lower than the measured emissions. At one source location, VOC emissions were found to be largely representative of those measured (i.e., the catalytic reformer), but more often, emissions were significantly underestimated (e.g., up to 448 times greater than estimated at a floating roof tank). The sources with both the largest relative error between the estimate and the measurement and the largest magnitude of emissions in this study were a wastewater treatment process, an aromatics concentration unit and benzene extraction unit process area, and two sets of tanks.

3.4.3 Data Sources

There were two data sources identified with some data on fugitive emissions at refineries. They are discussed below.

3.4.3.1 EPA Flight Data

All refineries must report their GHG emissions to the EPA annually. The 2015 data set has 144 reporting facilities and 176 million tonnes of GHG emissions. The emissions are generally calculated from emission factors and facility activity rates. There is a lot of data in the database but, like the information for petroleum production, it is not easily extracted, as the ability to export data is limited to the total GHG emissions.

3.4.3.2 EPA National Inventory Report

The National Inventory Report has data on methane emissions and non-combustion CO_2 emissions in petroleum refineries. The emission factors used for methane are shown in the following table. These are developed from the annual GHG reports supplied by the refiners.

Table 1-44 EPA NIR Methane Emission factors

Source	MT CH_4/Mbbl	g CH_4/mm BTU
Vented Emissions		
Uncontrolled Blowdowns	0.000971	0.17
Asphalt Blowing	0.000049	0.01
Process Vents	0.000215	0.04
CEMS	0.000006	0.00
Total vented	0.001241	0.21
Fugitive Emissions		
Equipment Leaks	0.000457	0.08
Storage Tanks	0.000237	0.04
Loading Operations	0.000002	0.00
Total Fugitive	0.000696	0.12

The total value is 0.33 g methane per million BTU.

The non-combustion CO_2 emissions in the refining sector are from asphalt blowing and process vents. The Emission factors used by the EPA are shown in the following table.

Table 1-45 CO_2 Emission Factors

Source	MT CO_2/Mbbl	g CO_2/mm BTU
Asphalt Blowing	0.020	3.4
Process vents	0.009	1.6
Total	0.029	5.0

3.4.4 Trends

The only long-term data sets are those from the EPA NIR and those do not indicate any trend for methane or non-combustion CO_2 emissions.

3.4.5 Oil Refining Fugitive Emission Findings

Most of the information on vented and fugitive methane emissions from refineries is based on emission factors. The few actual measurements of methane from refineries are much higher than the emission factor based approach. The impact on the lifecycle GHG emissions of petroleum fuels is relatively small.

3.5 Additional Parameters

No additional parameters were identified as part of this work.

3.6 Petroleum Fuels Summary

The majority of the emissions from the production of refined petroleum products come from either production of the crude oil or the refining of the crude oil into finished products. For both stage energy use and fugitive emissions contribute to the production emissions.

The three models have very different levels of details in terms of how the GHG emissions associated with energy use for crude oil production are determined. GREET has been expanding this area in recent models with progressively more detail in the 2014, 2015, and 2016 versions. However 70% of the crude oil production still uses an original estimate of energy use from the 1990s literature. This value could be improved though the use of OPGEE values or even the IOGP combined value for oil and gas production.

Primary data or even aggregated primary data is very scarce on a global basis. There is the IOGP data, which has a 15-year time series for 35 to 40% of the world's production but it combines oil and gas production and doesn't have the level of specificity that the models generally require.

It may be possible to extract some data from the EPA FLIGHT database but it must be extracted manually and the detail on what is reported at each facility is likely going to vary.

With the lack of availability of primary data, the OPGEE model is gaining in popularity as a tool to estimate the GHG emissions from oil production around the world. However, OPGEE is an engineering model and for many production fields the full data set required for the model is not available and default values are used. This will have a negative impact on the certainty of the results produced by the model. The full LCA models can be tuned to produce similar results to the OPGEE model.

Results from the OPGEE model indicate that there is a huge range in the energy required to produce crude oil ranging from less than 1% of the energy in the produced oil to more than 30% of the energy in the produced oil, with an average of 3.2%. The data from the IOGP has an average energy use for oil and gas production of 3% as well. However, since oil refineries are generally larger than individual oil fields aggregated data is probably a better measure of the range of energy use. The range of energy use for crude oil production is likely in the range of 2 to 10% of the energy in the crude for any given refinery.

There remains significant uncertainty with respect to methane emissions from crude oil production. The best data sources are the IOGP (~23 g CH_4/MM BTU) and the national inventory reports of UNFCCC Annex 1 countries (US is 150 g CH_4/MM BTU). There is a significant variation in the reported values from these two sources.

Top down estimations of methane emissions are generally much higher than the bottom up approaches that are used in inventory systems and in the models. With such a wide variation it is impossible to suggest a better range of values for use in the models.

There are generally good data sets on energy use in refineries at the national level and sometimes at the sub national levels. Refinery energy use is a function of many parameters and GHGenius and GREET are capable of adjusting energy use based on crude oil density and sulphur. Allocated energy use in the GREET model is between 10 and 12% of the energy in the finished products for diesel and gasoline. Unallocated energy use in GHGenius is between 6.7% and 11.4% of the energy produced.

There will be a range of values between refineries but again due to the fungible nature of the products information on individual refineries is not particularly valuable.

Most of the information on vented and fugitive methane emissions from refineries is based on emission factors. The few actual measurements of methane from refineries are much higher than the emission factor based approach. The impact on the lifecycle GHG emissions of petroleum fuels is relatively small.

The available data shows that energy used for producing crude has increased in the past two decades but has been relatively stable for several years. Fugitive methane emissions from crude oil production have a downward trend over the past decade.

There are no apparent trends in refinery energy use or methane emissions apparent from the long term data sets available.

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.

Natural gas is also an important pathway because the gas is often used in the production of other transportation fuels such as gasoline and diesel, ethanol, and biodiesel and renewable diesel.

This review is focussed on three key parameters, fugitive emissions from the complete supply chain, the energy used for CNG compression, and the efficiency of the engines when operated on CNG.

4.1 FUGITIVE EMISSIONS

Fugitive emissions from the natural gas supply chain have been a topic of great interest over the past few years. There has been a substantial amount of work undertaken in this area, much of it organized by the Environmental Defence Fund (EDF) and supported by a broad range of industry participants. The area is important because of the relatively high GWP of methane and thus even small quantities of methane can have significant impact on the GHG emissions of the supply chain.

4.1.1 Existing Model Values

The existing fugitive emission values in the models are discussed below.

4.1.1.1 GREET

The fugitive emissions in the natural gas supply chain were updated in GREET 2015 (Burnham et al, 2015) and again in GREET 2016 (Burnham, 2016). The values in both cases were derived from the EPA NIR that was published in April of each year. The GREET team stated that "We will continue to monitor and evaluate emerging research in this area and update GREET accordingly." The 2016 NIR released in April 2016 has significant changes to the fugitive emissions and the rates in the 2015 and 2016 models are shown in the following table for conventional gas.

Table 1-46 GREET Fugitive Emissions – Conventional Gas

Sector	GREET 2015	GREET 2016
	g CH_4/mmBTU (LHV)	
Production	62.3	144.4
Processing	26.7	26.2
Transmission	84.5	74.6
Distribution	88.9	28.0
Distribution (station pathway)	69.1	17.7
Total	262.4	286.9
Total Station Pathway	242.5	276.6

The production number for shale gas is higher than it is for conventional gas but the rest of the values are the same.

GREET assigns less than average distribution emissions to a CNG station and does not include any fugitive emissions for the CNG station itself.

4.1.1.2 GHGenius

GHGenius uses the EPA National GHG Inventory for the methane fugitive emissions. Version 4.03a of the model was released in March 2014 and it used the inventory report that was published in April 2013. The current development version of GHGenius used the data from the April 2016 report. Both values for the US natural gas system are summarized in the following table. GHGenius has separate values for the gas supply chain in Canada.

Table 1-47 GHGenius Methane Emission Factors

	GHGenius 4.03a	GHGenius 5.0
	g Methane/MM BTU (LHV)	
Production	232.8	176
Processing	36.6	37
Transmission	68.5	39
Distribution	67.2	25
CNG Station	71.8	70
Total	476.9	347

One of the largest differences between GREET and GHGenius is in the gas transmission stage. The EPA reports some methane emissions from combustion as part of the fugitive emissions. In GHGenius the high emissions from the use of reciprocal engines are calculated as part of the combustion engines and not as fugitive emissions.

4.1.1.3 BioGrace

BioGrace does not have a natural gas pathway. In the previous work, the emissions for natural gas from the JEC Well to Wheels work were evaluated. The fugitive methane emissions for two European supply systems are shown below based on version 4a of the JEC work.

Table 1-48 JEC V4a Methane Emissions

	EU Mix, 2500 Km transmission	Russian gas, 7000 km by transmission
	g Methane/MM BTU (LHV)	
Production and Processing	93.9	104.7
Transmission	85.8	197.4
Distribution	0.6	0.7
CNG station	7.8	7.8
Total	188.2	310.6

4.1.1.4 Model Summary

The emission factors used in the three models are shown in the following table.

Table 1-49 Methane Emission Factor Comparison

	GREET 2016	GHGenius 4.03a	GHGenius 5.0	JEC V 4a
	g Methane/MM BTU (LHV)			
Production	144.4	232.8	176	104.7
Processing	26.2	36.6	37	Inc.
Transmission	74.6	68.5	39	197.4
Distribution	28.0	67.2	25	0.7
CNG Station	0	71.8	70	7.8
Total	273.2	476.9	347	310.6

The JEC numbers can't be directly compared to the GREET and GHGenius values since the locations are different. One note is that GHGenius and the JEC have methane emissions for CNG stations and GREET does not. GREET also reduces the distribution emissions for CNG stations based on the assumption that the stations are located on the higher pressure portion of the distribution network and avoid the emission losses on the low pressure part of the network.

There have been significant changes in the EPA estimates from year to year as they incorporate data from actual operations and revise their equipment inventory counts and the emission factors for specific types of equipment. The latest inventory increased the production emissions, had little change on the processing emissions, and reduced the transmission and distribution emissions.

4.1.2 Literature Review

There has been a large number of research papers published in past several years that have looked at fugitive emissions from the natural gas supply chain. Most of these were funded and organized by the Environmental Defense Fund. The studies examined all areas that make up the oil and gas supply chain: production; gathering lines and processing facilities; long-distance pipelines, storage, and local distribution; as well as some end users using natural gas, commercial trucks and refueling stations.

There are also a few other papers that have been used by the EPA in the development of the NIR. These and the EDF papers are discussed below.

4.1.2.1 Environmental Defense Fund Papers

To date there have been 26 papers published as part of the EDF program. There are still several other studies that were part of the program that have not yet been published. The dates, titles, and short summary of each paper are presented below.

1. **December 2013:** UT Production study: This work reports direct measurements of methane emissions at 190 onshore natural gas sites in the United States (150 production sites, 27 well completion flowbacks, 9 well unloadings, and 4 workovers). Overall, if emission factors from this work for completion flowbacks, equipment leaks, and pneumatic pumps and controllers are assumed to be representative of national populations and are used to estimate national emissions, total annual emissions from these source categories are calculated to be 957 Gg of methane (with sampling and measurement uncertainties estimated at ±200 Gg). The estimate for comparable source categories in the EPA national inventory is ~1,200 Gg. Additional

measurements of unloadings and workovers are needed to produce national emission estimates for these source categories. The 957 Gg in emissions for completion flowbacks, pneumatics, and equipment leaks, coupled with EPA national inventory estimates for other categories, leads to an estimated 2,300 Gg of methane emission s from natural gas production (0.42% of gross gas production). http://www.pnas.org/lookup/doi/10.1073/pnas.1304880110

2. **May 2014**: NOAA DJ Basin Flyover: Emissions of methane (CH_4) from oil and natural gas (O&G) operations in the most densely drilled area of the Denver-Julesburg Basin in Weld County located in northeastern Colorado are estimated for 2 days in May 2012 using aircraft-based CH_4 observations and planetary boundary layer height and ground-based wind profile measurements. Total top-down CH_4 emission estimates are 25.8 ± 8.4 and 26.2 ± 10.7 t CH_4/h for the 29 and 31 May flights, respectively. Using inventory data, we estimate the total emissions of CH_4 from non-O&G gas-related sources at 7.1 ± 1.7 and 6.3 ± 1.0 t CH4/h for these 2 days. The difference in emissions is attributed to O&G sources in the study region, and their total emission is on average 19.3 ± 6.9 t/h, close to 3 times higher than an hourly emission estimate based on Environmental Protection Agency's Greenhouse Gas Reporting Program data for 2012. http://onlinelibrary.wiley.com/doi/10.1002/2013JD021272/pdf
3. **November 2014:** HARC/EPA Fence-line study: http://pubs.acs.org/doi/abs/10.1021/es503070q
4. **December 2014** UT Pneumatics Study: http://pubs.acs.org/doi/abs/10.1021/es5040156
5. **December 2014** UT Liquid Unloadings Study: http://pubs.acs.org/doi/abs/10.1021/es504016r
6. **January 2015:** Harvard Boston Urban Methane Study: http://www.pnas.org/content/early/2015/01/21/1416261112
7. **February 2015:** CSU Transmission and Storage study: Measurement paper: http://pubs.acs.org/doi/abs/10.1021/es5060258
8. **February 2015:** CSU Gathering and Processing study: Measurement paper: http://pubs.acs.org/doi/abs/10.1021/es5052809
9. **March 2015:** WSU Local Distribution study: http://pubs.acs.org/doi/abs/10.1021/es505116p
10. **May 2015:** CSU Gathering and Processing study, Methods paper: http://www.atmos-meas-tech.net/8/2017/2015/amt-8-2017-2015.html

July 2015: Barnett Coordinated Campaign (12 papers)

11. Overview: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02305
12. NOAA led Top-down study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00217
13. Bottom-up inventory - EDF: http://pubs.acs.org/doi/abs/10.1021/es506359c
14. Functional super-emitter study - EDF: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00133
15. Michigan airborne study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00219
16. WVU compressor study: http://pubs.acs.org/doi/abs/10.1021/es506163m
17. Princeton near-field study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00705
18. Purdue aircraft study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00410

19. Aerodyne mobile study: http://pubs.acs.org/doi/abs/10.1021/es506352j
20. U of Houston mobile study: http://pubs.acs.org/doi/abs/10.1021/es5063055
21. Picarro mobile flux study: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00099
22. Cincinnati tracer apportionment: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b00057
23. **July 2015**: CSU Transmission and Storage study National results paper: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b01669
24. **August 2015:** CSU Gathering and Processing study CSU Gathering and Processing study National results paper: http://pubs.acs.org/doi/abs/10.1021/acs.est.5b02275
25. **April 2016.** Aerial Surveys of Elevated Hydrocarbon Emissions from Oil and Gas Production Sites. http://pubs.acs.org/doi/abs/10.1021/acs.est.6b00705
26. **August 2016.** Direct and Indirect Measurements and Modeling of Methane Emissions in Indianapolis, Indiana. http://pubs.acs.org/doi/abs/10.1021/acs.est.6b01198
27. **January 2017**. Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector. http://dx.doi.org/10.1021/acs.est.5b06059

4.1.2.2 EPA 2016 NIR Papers

In the 2016 EPA NIR, a number of papers were cited as sources of new data or new emission factors. These included:

1. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas and Petroleum Production Emissions. https://www.epa.gov/sites/production/files/2016-08/documents/final_revision_to_production_segment_emissions_2016-04-14.pdf

   Most of the changes to the production emissions were a result of a better inventory of equipment used in the production process. Pneumatic controllers were segregated into three types: low bleed, high bleed, and intermittent bleed. New emission factors were developed for each type.

   The EPA asked for input on several issues for use in future emission inventories including other sources of emission factors and how to include super emitters in the inventory. Super emitters could increase the emissions from the sector in future years.

2. Inventory of U.S. GHG Emissions and Sinks 1990-2014: Revision to Gathering and Boosting Station Emissions. https://www.epa.gov/sites/production/files/2016-08/documents/final_revision_gb_station_emissions_2016-04-14.pdf

   Changes to the emissions for gas gathering and boosting stations (part of the gas production emissions) were based on two of the EDF studies (papers 8 and 24 in the previous list). These fugitive emissions increased significantly as a result of the new data.

   Activity data for this sector is an issue but the EPA expects better data will be available from the 2017 GHG reporting program. Revisions could be expected after that data is available.

3. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Transmission and Storage Emissions.

https://www.epa.gov/sites/production/files/2016-08/documents/final_revision_ng_trans_storage_emissions_2016-04-14.pdf

The EPA has new activity data available from their GHG reporting program and new emission measurements were available from the EDF papers number 7 and 23 listed above. There was a significant reduction in these emissions.

As with the other sectors, the EPA is asking for feedback in a number of areas related to activity data and emission factors.

4. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2014: Revisions to Natural Gas Distribution Emissions. https://www.epa.gov/sites/production/files/2016-08/documents/final_revision_ng_distribution_emissions_2016-04-14.pdf

   New emission data sources included the EDF paper number 9 and a study by Clearstone Engineering. A large reduction in the emission factor for metering and pressure reduction stations reduced these emissions.

   The EPA is looking for feedback on a number of issues, some of which would likely reduce emissions and others, including emissions after the customer meter that would likely increase emissions.

4.1.3 Data Sources

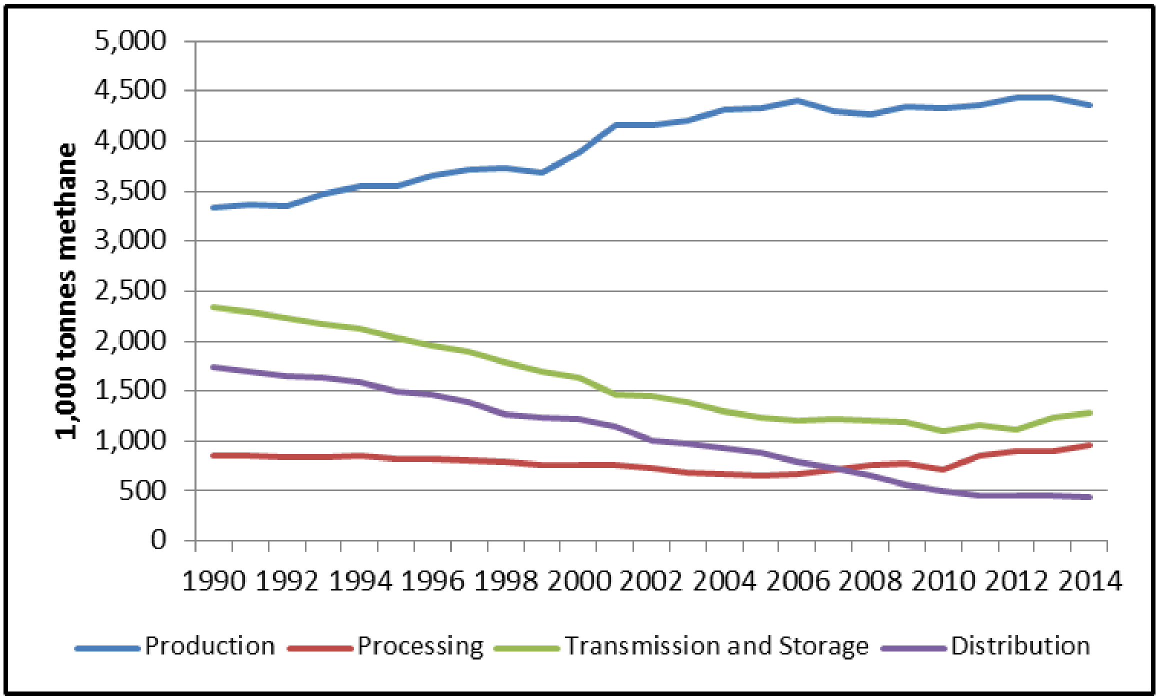
The primary data source for GREET and GHGenius is the US EPA NIR. GREET 2016 includes the changes in the NIR released in April 2016. The development version of GHGenius (5.0) also includes these changes.

4.1.4 Trends

The methodology used in all National Inventory Reports is such that when changes are made from one year to the next, the whole data series from 1990 must be updated with the new methodology. This makes it very easy to look at the trends.

The total emissions of methane from 1990 to 2014 are shown in the following figure.

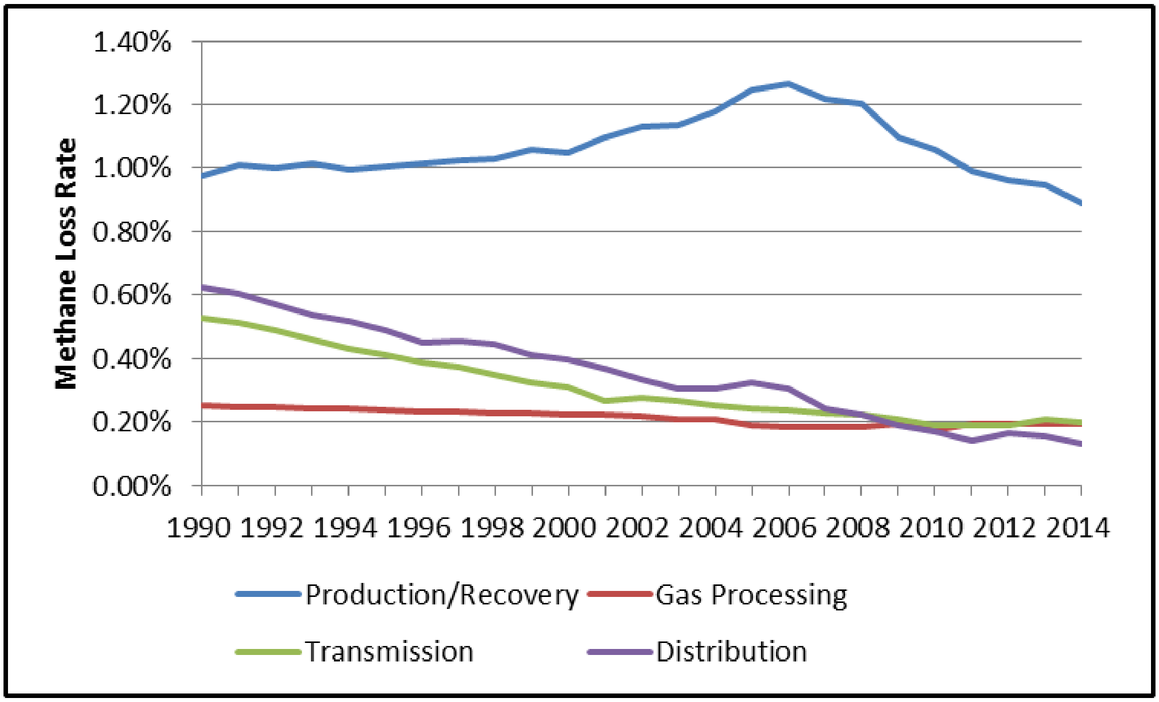
Figure 1-22 US Methane Emissions Natural Gas Sector



Source: US EPA NIR 1990-2014

For modelling purposes it is better to have the emissions per unit of gas. The challenge is that the EPA does not report the volume of gas that goes through the various stages of the gas supply system. GREET and GHGenius make slightly different assumptions about that volume. In GHGenius, dry gas production is used for the production stage. This volume plus imports (total supply) is used for the gas processing stage. For gas transmission the total supply less lease and plant fuel is used. For gas distribution the transmission volume less pipeline fuel and gas used in electricity generators is used. The emission data is shown as a % of the gas for that stage in the following figure.

Figure 1-23 US Fugitive Emission Factor Trends



Source: Calculation from NIR and US DOE Data

For gas transmission and storage, the EPA includes methane emissions from the exhaust of the engines driving the compressors as part of the methane emissions. Since these emissions should be calculated separately in the models from the fuel use in the engines, these emissions have been removed from the values shown in the above figure.

Fugitive emissions per unit of gas production have been declining for gas transmission and distribution as operating companies focus on methane reductions. The fugitive emissions have been relatively stable for the gas processing stage. The emissions for gas production increased through to about 2006 and have been declining since then.

Looking forward there are two issues that impact the gas production emissions. The first is that the emissions in the latest inventory do not include the impact of "super emitters". These are sources that have very high emissions, often resulting from equipment malfunctions. They are very difficult to predict and the EPA has asked for input from the industry and public on how these sources might be included in the inventory. Inclusion of these sources will increase the production methane emissions. The other factor is that the governments of Canada and the US have set targets to reduce fugitive emissions from the oil and gas sector by 40 to 45% from 2012 levels by 2025.

4.1.5 Fugitive Emission Findings

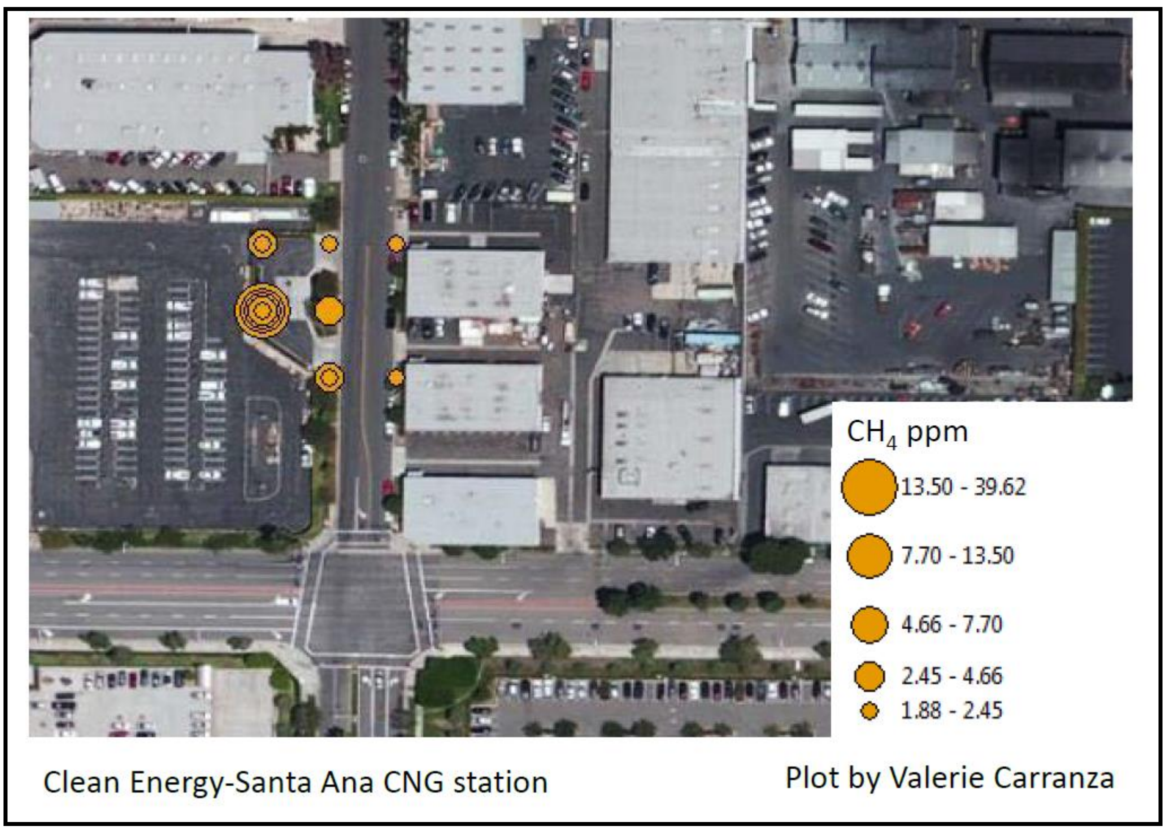
The methane fugitive emissions for the natural gas supply chain still have some uncertainty in spite of the significant amount of work undertaken in recent years to get a better understanding of the issue. GREET 2016 has moved to using the NIR data released in 2016 although there are some differences between the values in the model and those reported here.

One of the larger differences is in the transmission sector. Methane slip from reciprocating engines is included in the EPA fugitive emissions. There is the possibility that these emissions are included in both the combustion and leakage emissions in GREET 2016.

GREET doesn't include fugitive emissions from the CNG stations. The only study that has quantified these emissions is a 2009 GTI report (Field Measurement Program to Improve Uncertainties for Key Greenhouse Gas Emission Factors for Distribution Sources). This report measured a wide range of emissions at 10 different sites. The average emission rate was 7,315 pounds of methane per year per compressor. The emissions per unit of CNG compressed and dispensed were not reported, but the emissions are likely in the range of 0.3 to 0.4% of throughput. These emissions were measured in a Pump to Wheel study finally published in Jan 2017 (Clark et al). The emissions were measured at eight stations employing a variety of designs; the average loss rate was 0.09%. This included the emissions from the nozzle, the compressor, and other sources. There was a significant variation reported in the emissions from each part of the system, but the overall range for the eight stations was not reported.

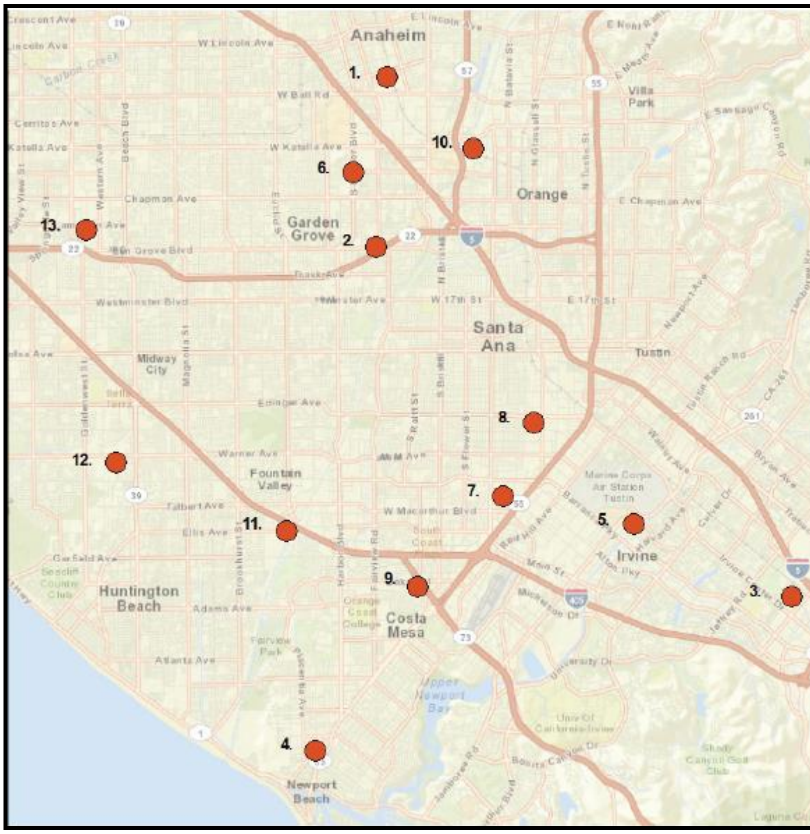
More recent work on identifying emission sources (but not emission rates) was reported by Hopkins (2016) who reported on the results for the South Coast Air Quality District in California. The emissions at a CNG station are shown in the following figure.

Figure 1-24 CNG Station Methane Emissions



Hopkins et al (2016) reported methane emissions at 12 of 13 stations monitored in the Los Angeles area. Like the earlier work by GTI a wide range of emissions were found at different stations, as shown below.

Figure 1-25 Methane Emissions at Los Angeles CNG Stations



Site	Maximum observed excess CH_4 (ppb)
1	1290
2	470
3	2620
4	1690
5	12290
6	3930
7	37800
8	830
9	700
10	8520
11	2850
12	610
13	170

This is clearly a source of fugitive emissions that is not included in GREET but it is included in GHGenius. More data on the percent loss is required to accurately model this emission source.

4.2 CNG Energy Use

The energy use for CNG compression was identified as a variable with some uncertainty in the previous work. CNG compressors can use gas or electric drive (electric is most common) and the inlet pressure to the compressor is variable and has a larger influence on the energy consumption than the final filling pressure.

4.2.1 Existing Model Values

The CNG pathway exists in GREET and GHGenius but not in BioGrace. The values used in the JEC work version 4a are reported here instead of BioGrace values.

4.2.1.1 GREET

The GREET model assumptions have been constant for the 2013 to 2016 models. The user can choose how much of the energy is supplied by natural gas and how much by electricity, with the default value being 100% electric drive. The efficiencies are calculated using input data on the compression sheet.

Table 1-50 GREET CNG Compressor Efficiency Calculation

	NG Compressor at Refueling Station
Inlet Pressure [psia]	50
Outlet Pressure [psia]	4,800
Inlet Temperature [ºF]	70
Compression Ratio per Stage	2.1
Number of Compression Stages	7
Compressor Adiabatic Efficiency	65.0%
Theoretical Energy [kWh/kg]	0.17
Shaft Energy [kWh/kg]	0.26
Electric Motor Efficiency	92.0%
NG Engine Efficiency	35.0%
Electric Energy [kWh/kg]	0.29
NG Energy [kWh/kg]	0.75
Compression Efficiency (Electric)	97.9%
Compression Efficiency (NG Engine)	94.6%

The 97.9% efficiency is equivalent to an electric energy consumption of 0.29 kWh/kg of NG delivered (LHV). 4800 PSI outlet pressure is high for a public compressor station but it does not have a large impact on the energy consumption. If the GREET values were changed to 65 psia inlet and 3600 psia outlet, the energy requirement would drop to 0.26 kWh/kg.

4.2.1.2 GHGenius

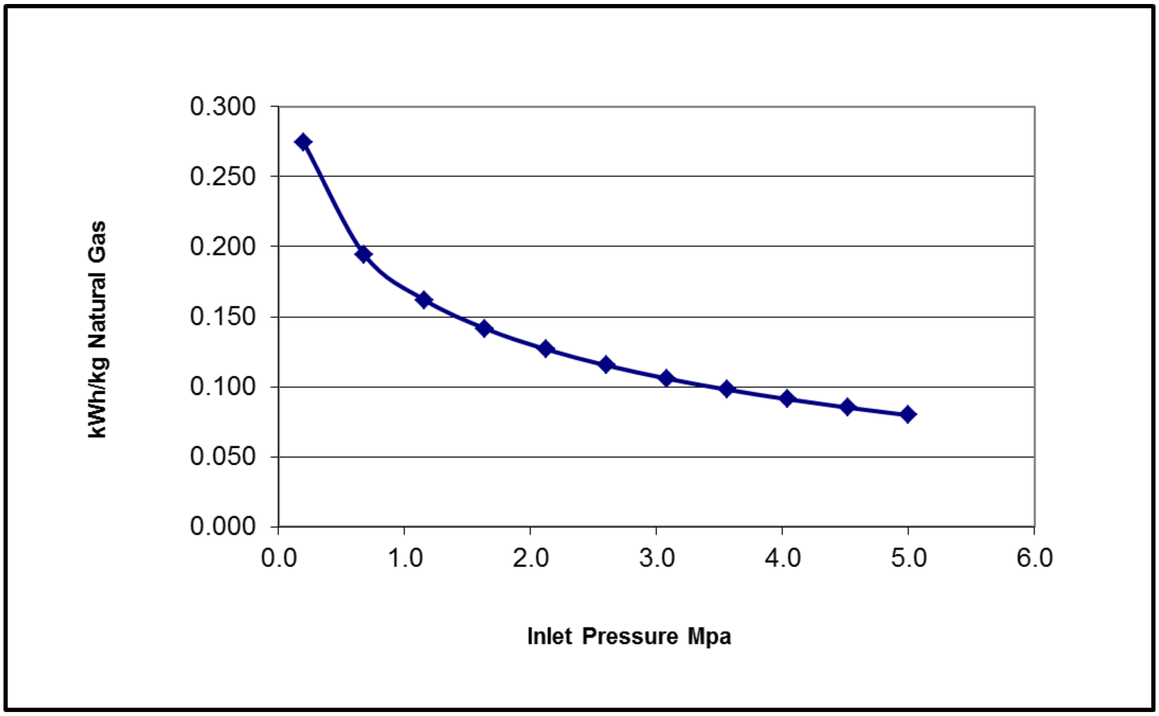
GHGenius has user input values for the inlet and outlet pressure only. The model calculates the energy requirements from those two values. The values and the calculated energy consumption are shown in the table below.

Table 1-51 GHGenius CNG Compressor Energy

	Model Units	GREET Units
Inlet Pressure	0.448 MPa	65 psia
Outlet Pressure	24.821 MPA	3,600 psia
Energy use, kWh/kg (LHV)	0.25	0.25

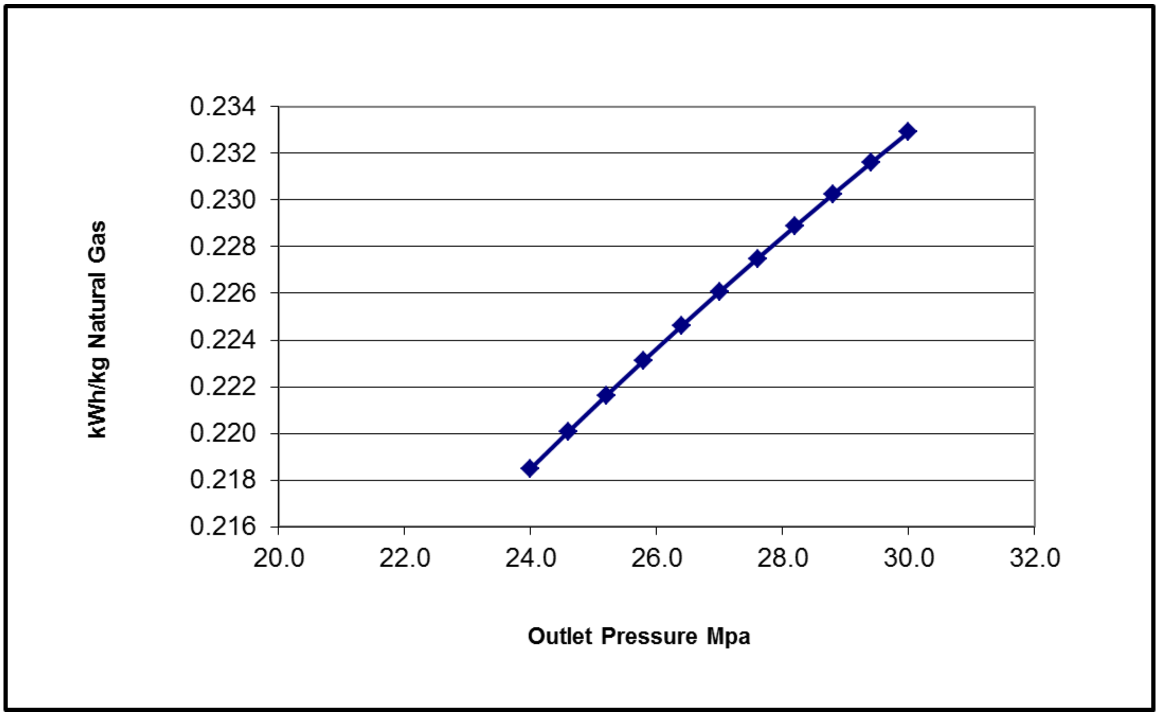
The following figure shows the sensitivity of the energy consumption to the inlet pressure in GHGenius.

Figure 1-26 Energy Use Sensitivity to Inlet Pressure



The same sensitivity to the outlet pressure is shown in the following figure. The impact is much smaller.

Figure 1-27 Energy Use Sensitivity to Outlet Pressure



4.2.1.3 JEC WTW V4a

The JEC WTW V4a study used a value of 0.0220 joules/joule (LHV) (0.29 kWh/kg) for electricity for gas compression. The values is based on an inlet pressure of 0.4 MPa (58 psia) and an outlet pressure of 25 MPa (3,625 psia). The energy figures represent 4-stage isentropic compression with 75% compressor efficiency and 90% electric driver efficiency.

4.2.2 Literature Review

A number of specific search terms were used to try to identify papers in the peer reviewed literature, such as "CNG Compressor" kWh/kg, "NGV Compressor" kWh/kg, "CNG Compressor" "inlet pressure" with very few papers (<10 papers for each term) being returned. Of the papers that were identified, only one reported a value for energy consumption.

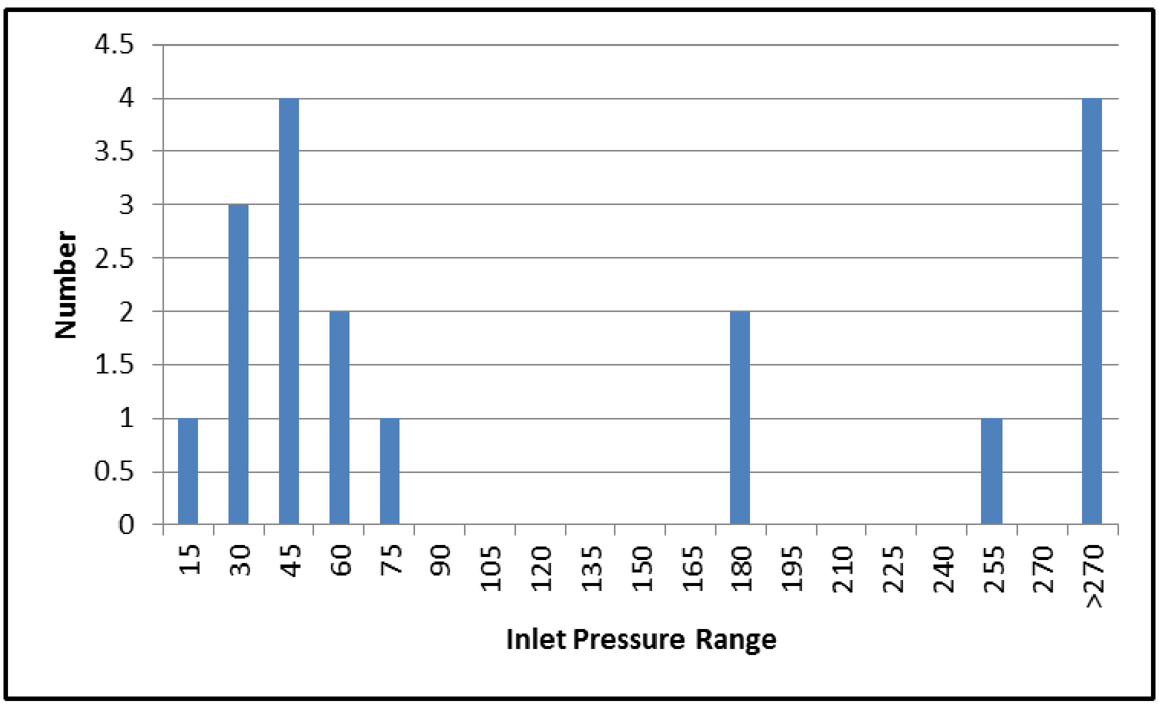
4.2.2.1 Lee et al. 2011. Eco-efficiency of H_2 and fuel cell buses

This paper reported on CNG and hydrogen fueling systems. The reported energy consumption for CNG compression was 0.57 kWh/kg of CNG and a 2007 reference was provided. The source was a Korean natural gas provider.

4.2.2.2 CRC Project No. PC-2-12

This CRC project was undertaken by Southwest Research Institute. The report mostly focussed on gas quality at 23 CNG stations but they did report the compressor inlet pressure at 18 of 23 stations that were visited and sampled. The average inlet pressure was 136 psig (150 psia), three times higher than the values in the models but the average was impacted by several high-pressure stations. A histogram of the inlet pressure is shown below.

Figure 1-28 CNG Station Inlet Pressure



4.2.3 Data Sources

Only one public document was found that dealt with the issue of compression energy for CNG. CARB released a discussion paper (2016) on natural gas as a transportation fuel and reported that all CNG pathways reviewed by CARB in 2016 had compressor efficiencies greater than 96%. In the CA GREET 2.0 model this can be achieved as long as the inlet pressure is above 1 psia. The power requirements at 96% efficiency are 0.54 kWh/kg.

4.2.4 Trends

There is insufficient data available to develop any trends in the inlet pressure or compression energy requirements for CNG stations.

4.2.5 CNG Energy Use Findings

The three models use a similar approach to determining the compression energy requirements and all have similar inputs and results.

There is very limited data available to support the values in the models. The one report that was identified that had compiled the inlet pressure conditions for 18 CNG stations had an average value 3 times higher than what is used in the models. However, most of the stations did have values that were similar to the model inputs, and the average was skewed by a few stations that had inlet pressures up to eight times the average value.

Some of the papers that described CNG stations in general terms, without having useful data for the models, did note that electricity is required for more than just the compressor. There are lights, fans and other smaller electrical loads associated with the compressors, so using a conservative value for the inlet pressure may offset these other loads that are not included in the models.

4.3 ENGINE EFFICIENCY

Natural gas engines can have lower combustion efficiency than gasoline or diesel engines and thus the emission reductions in the upstream fuel cycle may be offset by higher energy use for miles driven. The relative energy efficiency between the natural gas engine and the liquid petroleum fuel is an important factor for an emissions comparison. This issue can be complicated by the fact that the gas engines have different shapes for the power, torque and brake specific fuel consumption curves and thus the relative performance can be influenced by the duty cycles of the engine and vehicle.

4.3.1 Existing Model Values

GREET and GHGenius have light and heavy-duty natural gas engines but BioGrace does not have vehicles or natural gas. The JEC work considered only light duty vehicles.

4.3.1.1 GREET

Heavy-duty vehicles were added to the GREET model in 2014. The fuel economy ratios used for heavy-duty and light-duty vehicles is shown in the following tables.

Table 1-52 GREET 2014 Fuel Economy Ratios for HD Natural Gas Vehicles

HDV Subcategory	MY 1990–2005	MY 2010–2020
Combination long-haul or short-haul trucks	0.80	0.90
Heavy heavy-duty vocational vehicles	0.80	0.90
Refuse trucks	0.75	0.85
Medium and light heavy-duty vocational vehicles	0.75	0.85
Heavy-duty pickup trucks and vans	0.75	0.85
Medium heavy-duty vocational vehicles	0.95	0.95
Heavy-duty pickup trucks and vans	0.95	0.95
Transit buses	0.75	0.85
Intercity buses	0.80	0.90
School buses	0.75	0.85

The light-duty fuel economy ratios change over time in GREET. The model year is five years earlier than the year that the model is run for.

Table 1-53 GREET 2014 Fuel Economy Ratios for LD Natural Gas Vehicles

	Dedicated CNG	Bi-fuel CNG
1990	95.0%	90.0%
1995	95.0%	90.0%
2000	95.0%	90.0%
2005	95.0%	91.0%
2010	103.0%	92.5%
2015	103.0%	94.0%
2020	105.0%	95.0%

In GREET 2014 the dedicated light-duty natural gas vehicles are more efficient than the gasoline vehicle and the heavy-duty are less efficient than the diesel vehicles. In both vehicle classes there is no difference between CNG and LNG in GREET. The same ratios are used in GREET 2015 and 2016.

4.3.1.2 GHGenius

The GHGenius fuel economy rations are shown in the following table. These ratios used the higher heating value of the fuels and are thus slightly different than the LHV ratios used in GREET; both values are shown in the table. The values in GHGenius do change over time because the change is very gradual and isn't apparent in a five year period. The HD LNG engine technology in GHGenius assumes a high-pressure direct injection system with diesel pilot ignition.

Table 1-54 GHGenius Fuel Economy Ratios

	HD CNG	HD LNG	LD CNG
2015 (HHV)	0.86	1.01	0.98
2015 (LHV Equivalent)	0.84	0.98	0.95
2020 (HHV)	0.86	1.01	0.98
2020 (LHV Equivalent)	0.84	0.98	0.95

4.3.1.3 JEC WTW V4a

The JEC work only considers light duty vehicles. Port and direct injection dedicated fuel engines are considered and values for 2010 and 2020 are provided. The values used in their modelling are shown in the following table.

Table 1-55 JEC CNG Fuel Economy Ratios

	2010	2020
Port Injection	0.91	0.98
Direct Injection	0.96	0.98

4.3.2 Literature Used for Models

The information in the literature on the engine efficiency of natural gas engines and vehicles that was used for the models is summarized in the following sections.

4.3.2.1 GREET Sources

The heavy-duty natural gas engines and vehicles were added to GREET with the 2014 release so the data used is relatively recent.

Three papers are cited in the GREET documentation of the HD module report (2014). Two of the papers are in the public domain and the other is not.

4.3.2.1.1 Yoon et al 2013.

The paper by Yoon et al (2013) examined CNG transit buses tested on a laboratory chassis dynamometer and considered criteria air contaminants and GHG emissions. 2007 and 2000 engine model years were tested. No diesel buses were tested for comparison.

4.3.2.1.1.1 Gao et al 2012.

The Gao (2012) paper compared the fuel economy of natural gas and diesel class 8 trucks using the Autonomie computer program. The relative fuel economy for the natural gas version ranged from 0.875 to 0.952 depending on the load and the driving cycle. The results are reported as diesel gallons equivalent.

4.3.2.1.1.2 Carder et al 2014.

The Carder et al (2014) report was prepared for the South Coast Air Quality Management District but it is not in the public domain. The report does appear to have real world data on diesel and natural gas vehicles unlike the other two references.

4.3.2.2 GHGenius Sources

The relative fuel economy in GHGenius for the light-duty vehicles was developed from data at fueleconomy.gov by comparing equivalent light-duty natural gas and gasoline vehicles. The data and the rate of change were established in 2003 when there were a number of original equipment manufacturers offering these vehicles. The OEM NG vehicle was the Honda Civic, which was last produced in 2015.

The HD CNG relative fuel use was developed from certification data of the CumminsWestport Engines. The HD LNG data is from a number of tests of the Westport HPDI engine.

4.3.2.3 JEC Sources

The fuel use of the latest JEC work is based on simulations from the AVL Cruise software. The software simulated the NEDC drive cycle.

4.3.3 Recent Literature

The search of the literature since 2010 focussed on real world experience since the models generally rely on test simulations or standard drive cycles. Much of the recent literature uses GREET or GHGenius to model the lifecycle emissions from natural gas vehicles and is thus not particularly applicable to model development. Several papers were found that have real world experience.

4.3.3.1 Quirus et al 2016. Real-World Emissions from Modern Heavy-Duty Diesel, Natural Gas, and Hybrid Diesel Trucks Operating Along Major California Freight Corridors.

Emissions were measured from seven heavy-duty on-road vehicles that were operated along six common route types used for freight transport in California. There was one 2013 model year CNG vehicle in the test fleet, there were 5 diesel engine vehicles and one diesel hybrid. Four of the diesel engines had more horsepower than the CNG engine and one was similar. There were five different diving cycles used.

The results by driving cycle compare the CNG truck to an average of 4 diesel trucks with similar technologies. The individual truck comparisons were done on the average of all of the driving cycles. The CNG truck and the diesel truck with similar power are compared in the following table.

Table 1-56 Real World CNG vs Diesel Truck

	CNG	Diesel	CNG/Diesel
	g/mile		
CO_2	1,913	2,116	0.90
CO	9.77	1.5	6.5
NOx	0.33	1.37	0.24
THC	2.74	0.03	91
PM	0.004	0.006	0.67
Ratio NO/NOx	0.96	0.65	-

The GREET model with a fuel economy ratio of 0.90 for CNG has a CO_2 emissions ratio of 0.87, very close to the average over all of the drive cycles. GHGenius has a CO_2 emission ratio of 0.85. This one test would suggest that the fuel economy ratio in GREET is a little too high and in GHGenius it is a little too low.

The following table compares the CNG with an average of 4 trucks for different driving cycles. This table shows the importance of the driving cycle on the relative performance of the two fuels.

Table 1-57 Real World Driving Cycles CNG vs. Diesel CO_2

	CNG	Diesel	CNG/Diesel
	g/mile		
Hill Climb	2,108	1,936	1.09
Interstate	1,379	1,469	0.94
Regional	1,495	1,680	0.89
Local	2,214	2,473	0.90
Near-Dock	2,369	2,702	0.88

4.3.3.2 Thiruvengadam et al 2016. Unregulated, Greenhouse Gas and Ammonia Emissions from Current Technology Heavy-Duty Vehicles

This study did chassis dynamometer testing of diesel and natural gas vehicles. Goods movement and refuse trucks were tested on both fuels. Vehicles were tested on the chassis dynamometer using driving cycles that are representative of real-world driving patterns for the respective vehicle vocations. The results are summarized in the following table. The relative fuel economy is not quite as good as that reported in the previous report for the goods moving vehicles but the CNG performance in the refuse truck is very good. The diesel refuse trucks consume significant amounts of fuel to maintain the high temperatures required in the SCR emission control systems.

Table 1-58 GHG Emission Comparison

	CNG	Diesel	CNG/Diesel
		g/mile	
Goods movement			
CO_2	2,250	2,420	0.93
CH_4	1.7	0.0	-
N_2O	0.001	0.006	0.17
GHG	2,297	2,440	0.94
Refuse			
CO_2	2,370	3,250	0.73
CH_4	6.4	0.0	-
N_2O	0.003	0.0	-
GHG	2,540	3,250	0.78

This study also tested a HPDI natural gas engine in comparison to a diesel goods moving vehicle. Those results are shown in the following table. The GHG emissions are only slightly better than the spark ignited engine shown in the previous table.

Table 1-59 GHG Emission Comparison HPDI NG Engine

	CNG	Diesel	CNG/Diesel
		g/mile	
Goods movement			
CO_2	2,150	2,420	0.89
CH_4	2.6	0.0	-
N_2O	0.008	0.006	1.3
GHG	2,242	2,440	0.92

4.3.3.3 Sandu et al 2014. Real-World Activity and Fuel Use of Diesel and CNG Refuse Trucks

This study included 18 diesel and 6 CNG trucks with model years from 2003 to 2012. There were three configurations, roll-off (diesel only), front loader, and side loader. The results are summarized in the following table. Only one of the diesel trucks had a SCR system, which could explain the difference to the results in the previous study.

Table 1-60 Diesel vs. CNG Refuse Trucks

	CNG	Diesel	CNG/Diesel
	mpg		
Front Load	2.3	2.6	0.88
Side Load	1.5	2.9	0.52

4.3.3.4 ampCNG. 2015. The per-mile Costs of Operating Compressed Natural Gas Trucks

This study reported on the experience of one fleet with 16 million miles of experience with CNG. The engine was Cummins ISX 12G in class 8 trucks that haul milk from the farm to the processor. The reported average fuel economy was 6.31 miles per diesel gallon equivalent. The reported average fuel use for the diesel fleet in similar service is 6.1 mpg. In this case the CNG trucks had reported better fuel economy than the diesel trucks.

4.3.3.5 Wang et al 2011. On-road pollutant emission and fuel consumption characteristics of buses in Beijing

On-road emission and fuel consumption levels for Euro III and IV buses fueled on diesel and compressed natural gas (CNG) were compared and emission and fuel consumption characteristics of buses were analyzed based on approximately 28,700 groups of instantaneous data obtained in Beijing using a portable emissions measurement system (PEMS). The results are summarized in the following table.

Table 1-61 Euro IV Diesel vs CNG Buses

	Diesel	CNG
Engine displacement, litres	6.7	5.9
After treatment	SCR	Oxidation catalyst
CO_2, g/km	815	1130
CO, g/km	1.4	8.4
NOx, g/km	11.0	3.1
HC, g/km	0.04	0.6
PM, g/km	0.6	0.1
Fuel consumption, g/km	260	420

The relative efficiency performance of the CNG buses was quite low compared to other reports at about 72%. The lower NOx and PM emissions are typical of other reports. Euro IV engine technology does not represent the current state of the art so the data is not particularly useful for the models.

4.3.3.6 Zhang et al 2014. Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing

Seventy-five heavy-duty public transit buses, including different fuel systems (conventional diesel, natural gas and diesel hybrid), were tested on-road in Beijing using portable emission measurement systems. Natural gas buses had comparable CO_2 emission factors but higher fuel consumption relative to diesel buses. The on-road emission measurements were carried out during 2008–2012. The CNG buses were only certified to Euro III, whereas the diesel buses ranged from Euro II to Euro V standards. The energy use of the diesel buses did not vary significantly between certification levels. The results are summarized in the following table.

Table 1-62 Performance of Beijing Buses

Parameter	Diesel (Euro III)	CNG
Energy use, MJ/km	11.5	16.1
CO_2, g/km	800	932

The relative engine efficiency was 71% for the CNG buses, similar to the previous paper and necessarily representative of current technology.

4.3.3.7 Olodsson et al 2014. Enhanced Emission Performance and Fuel Efficiency for HD Methane Engines.

Tests of state-of-the-art technology for methane fuelled heavy duty vehicles were carried out in Sweden, Finland and Canada as part of an IEA Advanced Motor Fuel implementing agreement. Measurements were carried out on chassis dynamometers in laboratories under well-specified conditions, as well as on the road in real-life operation by the use of Portable Emission Measurement System (PEMS). On-road testing reflected the normal use of a vehicle, such as influence of ambient temperature, topography, vehicle/engine load and driving patterns. Vehicles tested included spark ignited (SI) dedicated gas engines and vehicles equipped with compression ignited engines (CI) using a combination of methane gas and diesel, at various mixing ratios, as the fuel. The SI CNG engines employed both lean burn technology and the more recent approach in North America of stoichiometric combustion with a three-way catalyst.

The report also contains emission results in the VTT database. Data for two and three axle buses are available. The 2 axle buses average results are shown below.

Table 1-63 Euro EEC Diesel vs CNG 2 Axle Buses

	Diesel	CNG
Number of tests	23	8
CO_2, g/km	1167	1196
CO, g/km	1.07	2.78
NOx, g/km	6.38	3.17
HC, g/km	0.04	1.28
PM, g/km	0.08	0.01
Fuel consumption, g/km	369	471
Energy use, MJ/km	15.9	23.2

The relative engine efficiency from this data is 68.5%.

The data from the three axle buses is shown in the following table. The CNG buses had 150,000 to 650,000 km of use whereas the diesel buses had between 5000 and 95,000 km, so the busses may not be exactly comparable.

Table 1-64 Euro EEC Diesel vs CNG Buses 3 Axle Buses

	Diesel	CNG
Number of tests	6	6
CO_2, g/km	1461	1319
CO, g/km	1.41	10.96
NOx, g/km	5.50	6.37
HC, g/km	0.04	1.69
PM, g/km	0.077	0.010
Fuel consumption, g/km	462	519
Energy use, MJ/km	19.9	25.5

The relative engine efficiency for this set of buses is 78%.

4.3.3.8 Ouellette et al 2016. Progress in the development of natural gas high pressure direct injection for Euro VI heavy-duty trucks

Injecting natural gas directly in the combustion chamber at the end of the compression stroke, High Pressure Direct Injection (HPDI) of Natural Gas, ignited with pilot diesel fuel, preserves the fundamental characteristics of diesel combustion such as high efficiency and high specific torque. High combustion efficiency coupled with the lower carbon content of natural gas results in the potential for significant reductions in greenhouse gases.

Westport previously developed a first generation HPDI fuel system for a Cummins 15L HD engine. The first generation fuel system was installed by Westport on purchased Cummins 15L ISX engines and matched to the corresponding diesel engine after treatment. Westport certified the engines to EPA and CARB 2010, relying on the base engine cooled EGR and the standard SCR and DPF unit, and to ADR 80-03 relying on cooled EGR and a DPF. 1300 trucks were put into service in North America and Australia between 2007 and 2013, providing much insight about the technology’s strengths and weaknesses.

Westport has set out to develop a second generation fuel system to enable integration on state of the art HD diesel engines and demonstrate performance, efficiency and Euro VI emissions compliance. This second generation system has been tested on transient test beds but not yet in real world driving conditions. The reported results are shown in the following table.

Table 1-65 Second Generation HPDI Test Results

Parameter	Results
Road duty cycle bsfc relative to diesel. HPDI includes hydraulic pump parasitic.	1.01 – 1.03
Tailpipe GHG over various transient cycles, relative to diesel	0.80 – 0.82
Road duty cycle Gas Energy Ratio (GER)	0.94 – 0.95
World Harmonized Test Cycle GER	0.91 – 0.93

The performance of the engines is very close diesel and would have an engine efficiency of 97% if the test results translate to real world results.

4.3.4 Data Sources

Public data sources on the performance of light and heavy-duty natural gas engines and vehicles are limited.

4.3.4.1 Light Duty Vehicles

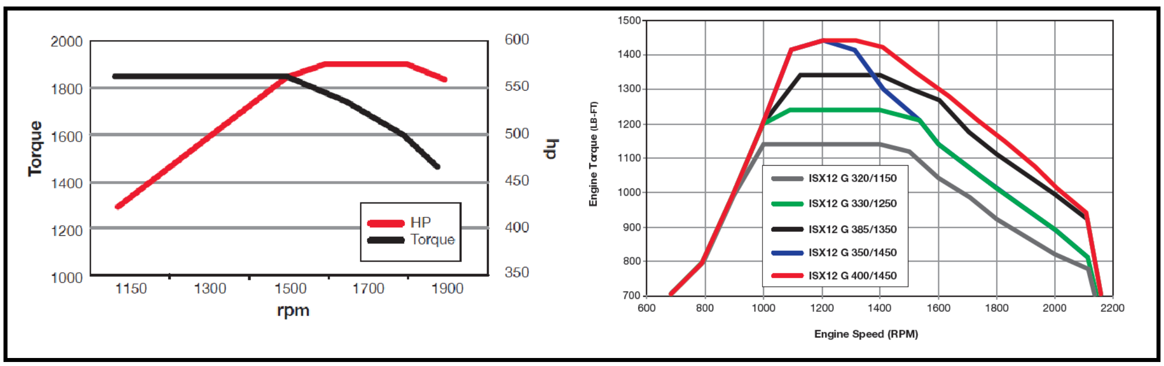
The published furl economy results from EPA certification tests are available for all light-duty vehicles (www.fueleconomy.gov). When there were light-duty OEM natural gas vehicles this was a valuable source of information, as matching vehicles with gasoline and natural gas could be compared. The last OEM NG vehicle manufactured was the 2015 Honda Civic.

This vehicle had a fuel economy rate of 31 mpg on natural gas compared to 32 mpg for the gasoline version. This is a 97% relative efficiency for the natural gas engine. This is higher than s currently in GREET and about the same as in GHGenius.

4.3.4.2 Heavy Duty Vehicles

Certification data is available for heavy-duty natural gas engines and that can be compared to an equivalent diesel engine. The challenge is that the literature suggests that the duty cycle of the vehicle can have a large impact on the relative performance, primarily due to the very different torque and bsfc curves of the two types of engines. This is shown in the following figure with the diesel engine on the left and the natural gas engine on the right.

Figure 1-29 Torque Curves



4.3.5 Trends

There is very little data available to assess any trends in the relative performance of natural gas engines. More recent test data for natural gas engines has better performance than older test data. GREET and GHGenius also show better performance of newer engines.

The Sandu and Thiruvengadam papers show different performance characteristics depending on the truck service. This characteristic complicates modeling, as the difference in performance from one duty cycle to another is very large. All that can really be concluded at this time is that generalizations for NG engine performance is a challenge and that more real world performance data would be a welcomed addition for the modellers.

4.3.6 Engine Efficiency Findings

The most recent real world data from the United States has very similar relative energy use as is currently in the models for normal driving cycles. There does appear to be some driving cycles, such as refuse trucks, where the CNG engines perform better than the diesel engines. These duty cycles are characterized by a lot of start and stop driving cycles and new diesel engines have difficulty maintaining temperatures for the emission control systems. Urban buses may have a similar problem but no recent information was found on the real world performance of these vehicles.

4.4 Additional Parameters

One additional parameter for the natural gas cycle where data is scarce is on the energy use in gas production and processing. The total and the type of energy used in GREET have only changed a small amount since GREET 1.5. In GHGenius the natural gas use in gas production is taken from the Annual Energy Outlook but that now only reports the combined natural gas use in production and processing whereas it used to provide separate values for gas production and gas processing. This is combined with information on the types of energy used from the 2002 Census. Later Census reports do not provide the same level of detail as the earlier publications. The total energy consumption in gas production and processing is quite similar in GREET and GHGenius but better quality data would benefit both models.

4.5 Natural Gas Summary

This review is focused on three key parameters, fugitive emissions from the complete supply chain, the energy used for CNG compression, and the efficiency of the engines when operated on CNG.

There has been a large amount of work undertaken in recent years and reported in the literature on methane emissions throughout the natural gas supply chain. Most of the work has found a wide range in the results with the average being skewed by a relatively few “super emitters”. The models use average values for the supply chain and given the fungible nature of the supply chain this is the appropriate approach for modeling. GREET and GHGenius both rely on the US NIR emission data for natural gas fugitive emissions.

For natural gas compression there is very little information on fugitive emissions for this stage of the lifecycle. There are several papers that identify the emissions but not the unit throughputs. Only one 2017 paper has quantified the emissions per unit of fuel. The average loss rate was 0.09% and while the range was provided for each component for all of the stations monitored, the overall range was not provided.

The three models use a similar approach to determining the compression energy requirements and all have similar inputs and results. However, there is very limited data available to support the values in the models. The one report that was identified that had compiled the inlet pressure conditions for 18 CNG stations had an average value 3 times higher than what is used in the models. However, most of the stations did have values that were similar to the model inputs, and the average was skewed by a few stations that had inlet pressures up to eight times the average value.

GREET and GHGenius both use the relative energy use between natural gas and liquid fuel engines to determine the combustion emissions. The most recent real world data from the United States for natural gas vehicles has very similar relative energy use as is currently in the models for normal driving cycles. There does appear to be some driving cycles, such as refuse trucks, where the CNG engines perform better than the diesel engines. These duty cycles are characterized by a lot of start and stop driving cycles and new diesel engines have difficulty maintaining temperatures for the emission control systems. Urban buses may have a similar problem but no recent information was found on the real world performance of these vehicles. The range of relative energy use is therefore dependent on the vehicle applications and within applications there is insufficient information available to determine representative ranges.

Of the three areas investigated, the only trend that is apparent is the reduction in fugitive methane emissions from the natural gas supply chain. There is a long term trend to reduced losses from the transmission and distribution portions of the supply chain. The methane losses from the gas production stage appear to have peaked about 10 years ago and have declined in the past decade.

5. SOYBEANS

Soybeans are the major oilseed crop in the United States, even though they are grown mostly for the protein content and not the oil. Three areas of uncertainty and variability were identified in the previous work: N_2O emissions, farm energy use, and the energy use for oilseed crushing and biodiesel/renewable diesel production. These issues are discussed below.

5.1 N_2O EMISSIONS

The methodology of calculating N_2O emissions from agricultural soils is described in section 1 of the report related to corn production. The N_2O emissions are calculated using the quantity of nitrogen applied and the various N_2O emission factors. Since corn and soybeans are generally grown in rotation, the N_2O emission factors that are developed for corn should apply to soybeans. The larger issue for soybeans is actually determining the quantity of nitrogen applied.

5.1.1 Existing Model Values

The existing model values are discussed below.

5.1.1.1 GREET

The N_2O emissions for soybean production were significantly changed in GREET 2015. The factors that make up the emission calculations for both GREET 2014 and GREET 2015 are shown in the following table. GREET 2016 has the same values as GREET 2015.

Table 1-66 GREET Soybean N_2O Emissions

Emission factors	GREET 2014	GREET 2015
EF_1 Syn fert	0.010	0.010
EF_1 crop residue	0.010	0.010
EF_4	0.01	0.01
EF_5	0.0075	0.0075
$Frac_{gasf}$	0.10	0.10
$Frac_{leach}$	0.30	0.30
N_2O emissions: N in N_2O as % of N in N fertilizer	1.225	1.325
N_2O emissions: N in N_2O as % of N in Biomass	1.225	1.225
N_2O emissions from N fixation: grams N_2O	-	7.3
Syn N, g/bushel	49.9	49.9
Residue N, g/bushel	200.7	557

In the memo that was released with the GREET 2015 release (Cai et al, 2015) the following summary was provided.

> *Here, we updated the nitrogen content in soybean residues according to a review of 159 measurements, which represented an average nitrogen content of 1.21% in the residues, resulting in about 557 grams nitrogen in residues per bushel of soybean grain (Salvagiotti et al., 2008), in comparison to about 200 grams nitrogen in residues per bushel of soybean grain that was previously estimated in GREET. In addition, we adopted the Intergovernmental Panel on Climate Change (IPCC) Tier 2 emission*

factor of 1.225% for N_2O emissions from crop residues (IPCC, 2006) for soybean residues. With this update, the total N_2O emissions from nitrogen fertilizer and soybean residues estimated in GREET are about 1.14 kg N_2O/ha.

5.1.1.2 GHGenius

The GHGenius model inputs for soybean production in the United States are shown in the following table.

Table 1-67 GHGenius Soybean N_2O Emissions

Emission factors	GHGenius 4.03a	GREET units
EF_1 Syn fert	0.0125	0.0125
EF_1 crop residue	0.0125	0.0125
EF_4	0.01	0.01
EF_5	0.0075	0.0075
$Frac_{gasf}$	0.10	0.10
$Frac_{leach}$	0.30	0.30
N_2O emissions: N in N_2O as % of N in N fertilizer	1.575	1.575
N_2O emissions: N in N_2O as % of N in Biomass	1.475	1.475
Syn N,	1,921 g/tonne	50 g/bushel
Above ground N content, %	0.60	0.6
Below ground N content, %	4.1	4.1
Residue N	36,193 g/tonne	984 g/bushel

The GHGenius soybean N_2O emissions were developed to provide the same emissions as the USDA reported in their 2011 report U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2008. The N_2O emissions for US soybeans are 1.86 kg N_2O/ha.

5.1.1.3 BioGrace

The N_2O emissions in the BioGrace model are a fixed value of 2.23 kg/ha. This value is higher than in GREET and in GHGenius. The BioGrace values are reportedly calculated in accordance with the IPCC 2006 Guidelines.

5.1.2 Literature Review

N_2O emissions in GREET and GHGenius are calculated using the IPCC methodology. The drivers of the emissions are the emission factors and the nitrogen applied. Given that corn and soybeans are grown in the same regions, the information presented in the corn ethanol section on N_2O emission factors is also applicable to soybean production. The real variable is therefore the nitrogen content of the soybean residues.

There are a number of documents that are described below that were identified from the review of values used in the models. In addition to the search terms soybean, "nitrogen content", and "below ground residue" were used and the top results are shown in the appendix.

5.1.2.1 IPCC 2006 Guidance

The IPCC 2006 Guidance document reports that the soybean above and below ground residue nitrogen content is 0.8% but the reference is from 1925. There is more recent data, which suggests that this value is much too low.

5.1.2.2 Cai et al. Updated N_2O Emissions for Soybean Fields

The GREET memo on the 2015 soybean update included a review of the recent literature. Some of the key papers identified in this memo are briefly summarized below.

> *Yang and Cai (2006) conducted a soybean pot experiment by growing soybeans in 15 experimental pots. They reported that the N_2O emissions increased strikingly in the late growth period (i.e., the grain-filling stage), accounting for about 94% of the total N_2O emissions of biologically fixed nitrogen from the entire soybean crop growth cycle. They suggested that the emissions were mostly from senescence and the decomposition of roots and nodules containing the nitrogen fixed by soybean plant legumes.*
>
> *The number of nodules decreased significantly from full pod to full maturity, which indicates the senescence of nodules (Shah, 2014). A recent study by Inaba et al. (2012) that citied the Yang and Cai (2006) study found that N_2O emissions from degraded soybean nodules in late growth phase depends on denitrification by Bradyrhizobium japonicum in the rhizosphere. The 15N tracer experiment in Inaba et al. (2012) indicated that the N_2O emissions come from nitrogen fixed in the nodules. Besides, they found that both soil microbes and nodule degradation are required for the emissions of N_2O from the soybean rhizosphere.*

The GREET memo had a table that summarized the data that was reviewed and that table is shown below.

Table 1-68 A comparison of N_2O emission flux measurements from soybean fields in literature and the estimation in GRET 2015

Studies	Background emissions in measurement?	Location	N_2O flux, kg/ha	Notes
Parkin and Kaspar, (2006)	Yes	Central Iowa	2.7, 2.2, and 2.3	Under chisel plow, no-till, and no-till cover crop, respectively
Venterea et al. (2010)	Yes	Minnesota	0.7 − 1.2	
Wagner- Riddle et al. (1997)	Yes	Ontario, Canada	2.21	No fertilizer application; with manure application in previous fallow
Wagner- Riddle et al. (2007)	Yes	Ontario, Canada	0.49 and 1.07	For fields with conventional tillage practices in separate years
Rochette et al. (2004)	Yes	Quebec, Canada	0.72–4.84	No fertilizer application
Rochette et al. (2008)	Yes	Eastern Canada	0.42–1.52	No fertilizer application; measurement was from soils under moldboard plow
BioGrace (The European Union, 2015)	Yes	European Union	2.23	
This analysis	No		1.85	This includes emissions from nitrogen fertilizers, soybean residues, and nitrogen fixation.

5.1.2.3 USDA. 2016. U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2013

The USDA GHG Inventory Report 1990-2013 combines corn and soybean into row crops and presents the results for row crops. The GHG emissions for row crops are reported as 2.30 kg N_2O/ha, which is the combined value for corn and soybeans. Since there is much less uncertainty for the nitrogen content of corn residue it is possible to calculate the N_2O emissions for corn per hectare. Using the N_2O emission factors identified for corn earlier, the N_2O emissions are calculated to be 4.34 kg N_20/ha. This would suggest that the soybean emissions would be lower than this to achieve the average of 2.3 kg N_2O/ha.

The USDA report states that the soybean residue nitrogen content is 2.3% and they cite a 1985 report by Barnard and Kristoferson. The USDA assumes that the residue to crop ratio for soybeans is 2.1. This produces 126 lb of residue per bushel of soybeans and with a nitrogen content of 2.3%, this calculation suggests 1,315 g N per bushel, a higher value than used in GREET and GHGenius.

5.1.2.4 Rahman, M., Sampa, M. 2012. Combined Effects of Bradyrihizobial Strains, Municipal Solid Waste Compost and Fertilizers on Nodulation, N Content and Uptake of Soybean.

Rahman and Sampa (2012) found that the soybean stover had N contents of 0.94 to 2.29% and N contents in the roots of 0.5 to 1.1%. They also reported the N content of soybean modules separately as 0.82 to 2.91%. Unfortunately they did not report the mass of N accounted for by the nodules.

5.1.2.5 JRC. 2016. Definition of input data to assess GHG default emissions from biofuels in EU legislation

The JRC issued a limited distribution report in August 2016. This report describes the assumptions made by the JRC when compiling the updated data set used to calculate default and typical GHG emissions for the different liquid pathways. The JRC uses an above ground N content of 0.8% and a below ground N content of 8.7%. They cite Chudziak and Bauen (2013) as the source. The citation says that the paper has been submitted for publication but no such publication has been found.

The 8.7% is a calculated value and it assumes that the N_2O emissions measured in 7 unfertilized sites is 1.26 kg N/ha and that that is 1% of the total N in the residue. However, they used a relatively low value for the underground biomass and assume that there are no background N_2O emissions from the previous crop nor from mineralization of N from soil carbon loss.

5.1.3 Data Sources

The two potential data sources are the annual US EPA national GHG Emission inventory and the USDA GHG inventory for agriculture and forestry that is done every five years. Unfortunately neither report has information specifically for soybeans.

5.1.4 Trends

There is no data available to establish any trends for the variables that impact soybean N_2O emissions.

5.1.5 Soybean N_2O Findings

GREET 2015 is a significant upgrade over previous versions for the soybean production emissions. It has a much more reasonable estimate of the nitrogen content of the underground residue.

There remains considerable uncertainty over the nitrogen content of the soybeans residues. Many of the papers in the literature continue to use the IPCC default value, which contains a value from a 1925 reference. All of the authors who have looked at the issue consider this to be too low. One of the challenges is that some of the nodules decompose in the growing year and so any analysis that is done at the end of the year will miss that N in a measurement of residue nitrogen content.

5.2 FARMING ENERGY

Soybean farming energy had been identified because there were some significant variations between some state level surveys and the national average values that were generally used in the models. More recent, detailed national data has become available that addresses the differences in the data.

5.2.1 Existing Model Values

The existing model values and the data sources are discussed below.

5.2.1.1 GREET

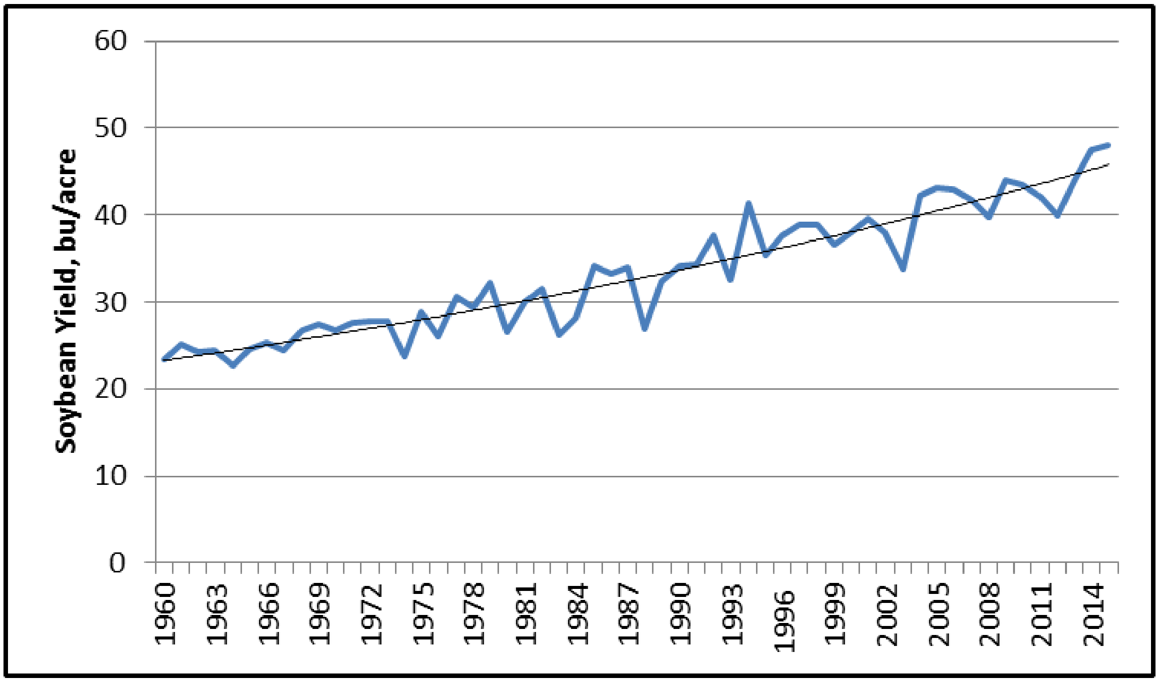
The soybean energy use values in GREET 2014 and 2016 are shown in the following table.

Table 1-69 GREET 2014 and 2016 Soybean Farming Energy

Fuel	2014 Value	2016
Total	16,718 BTU/bu	19,443 BTU/bu
Diesel	63.9%	70.4%
Gasoline	22.2%	15.7%
Natural Gas	8.1%	5.1%
LPG	2.5%	3.9%
Electricity	3.3%	4.8%

The soybean energy values have increased in GREET 2016 (19,443 BTU/bu) and are based on the 2012 USDA ARMS survey data. The previous values were based on the 2006 ARMS survey. The one issue with the 2012 data was that soybean yields in 2012 were 10% below the trend yield. Energy use is mostly a function of area and not the yield, so using data from a single year can distort the values.

Figure 1-30 Soybean Yield



5.2.1.2 GHGenius

GHGenius 4.03a employs USDA ARMs data (2006) converted to a value per tonne and then employs an annual improvement factor of 0.75% to adjust the values to the target year for modelling. For 2014, the model values are shown below in the GHGenius and GREET units. The values are very close to the GREET 2014 and 2015 values.

Table 1-70 GHGenius Soybean Energy Values

Parameter	GHGenius Values	
	Per tonne	BTU (LHV) Per bushel
Diesel	12.57 litres	11,600
Gasoline	3.97 litres	3,200
Natural Gas	1205 litres	863
LPG	1.34 litres	818
Electricity	6.34 kWh	156
Total	726,378 MJ (HHV)	16,647

GHGenius 5.0 will use a slightly different approach. It will include the 2012 USDA data on energy use per hectare and the data is used along with previous surveys in 1990, 2002, 2006 to generate separate rates of change for each of the energy sources. In addition, the soybean yield data is used to generate yield curves and rates of change. The energy use per tonne of production is generated from each of the time series. The result is a much faster rate of change per tonne of production than has been used in the past due to the trend to lower energy use and higher yields.

5.2.1.3 BioGrace

The BioGrace pathway for soybean biodiesel envisioned producing the soybeans in Brazil. The farming energy is a single value for diesel fuel of 2,100 MJ/ha (4.33 gal/acre). The soybean yield is 2.38 tonnes/ha resulting in energy use of 22,700 BTU/bushel, higher than GHGenius or GREET.

The source of the farm energy is a 1999 German Federal Environmental Agency report entitled "Germany: Current assessment of the use of rapeseed oil / RME compared to Denmark". Soybean data is actually not presented in this report.

5.2.2 Literature Review

Combinations of search terms were employed to identify direct farm energy use for soybean production. Appendix 4 has a summary of the terms and results. Very little information was identified.

5.2.2.1 Ramedani et al 2011. An investigation on energy consumption and sensitivity analysis of soybean production farms

The aims of this study were to determine the energy consumption and evaluation of inputs sensitivity for soybean production in Kordkuy county of Iran. The data used in this study was obtained from 32 farmers using a face-to-face questionnaire base of random sampling method. The direct energy inputs are summarized in the following table. Average soybean yield was about 2,285 kg ha^{-1} in the studied region. The production was irrigated and the energy use was very high.

Table 1-71 Soybean Energy Inputs - Iran

Parameter	Value
Diesel fuel	200.6 l/ha
Electricity	111.3 kWh/ha

5.2.2.2 Fore et al 2011. Net energy balance of small-scale on-farm biodiesel production from canola and soybean.

This study estimated the net energy ratio (NER), net energy balance (NEB), and net energy yield (NEY) of small-scale on-farm production of canola and soybean biodiesel in the upper Midwest. Direct energy use in crop production included diesel fuel for field operations consisting of fertilizing, chisel plowing, planting, spraying, swathing, harvesting, and grain transport to processing. Fuel consumption for field operations was based on data from a Farm Machinery Cost Estimation Spreadsheet from the University of Minnesota. The direct diesel energy use was determined to be 41.3 litres/ha (4.4 gal/acre).

5.2.2.3 Raucci et al 2015. Greenhouse gas assessment of Brazilian soybean production: a case study of Mato Grosso State

The aim of this study was to evaluate the main sources of GHG in soybean production in the State of Mato Grosso, Brazil. The analysis considered the Life Cycle Assessment (LCA) from cradle to farm gate. They evaluated 55 farms in the crop years of 2007/08, 2008/09 and 2009/10, accounting for 180,000 ha of soybean cultivation area and totalling 114 individual situations.

Most of soybean areas in Brazil are cultivated under the no-tillage system, with a second-season production known as Safrinha. With this farming strategy growers can take advantage of a long tropical growing season to produce two crops in a single year. The findings are summarized in the following table.

Table 1-72 Soybean Energy Use Brazil

crop year	Average Diesel	Diesel Range	Electricity	Electricity Range
		Litres/ha		kWh/ha
2007/08	30	15.7-45.8	18	1.8-104.0
2008/09	36	22.2-58.0	23	3.9-72.4
2009/10	27	20.0-41.9	28	3.4-136.6
Average	31		23	

The 3-year average values were 3.31 gal/acre of diesel fuel and 9.3 kWh/acre.

5.2.2.4 Minnesota Soybean Research & Promotion Council. 2013. Direct Fuel Use in Minnesota Soybean Production 2012

The study was conducted with ten southern Minnesota farmers with a history of good financial and production management records. The participants were surveyed from two different fuel usage approaches. The first approach in February-April, 2013 determined their total use of each type of fuel during 2012 and was intended to measure fuel “disappearance” or apparent usage by comparing beginning inventories and purchased fuel with ending inventories. The participants separated livestock fuel, off-farm business fuel, and personal fuel use where applicable. The second approach surveyed fuel use by field operation by crop to separate direct soybean fuel from total farm fuel. This process was aided by selecting participants with limited livestock, limited off-farm business, and limited production of crops other than corn & soybeans.

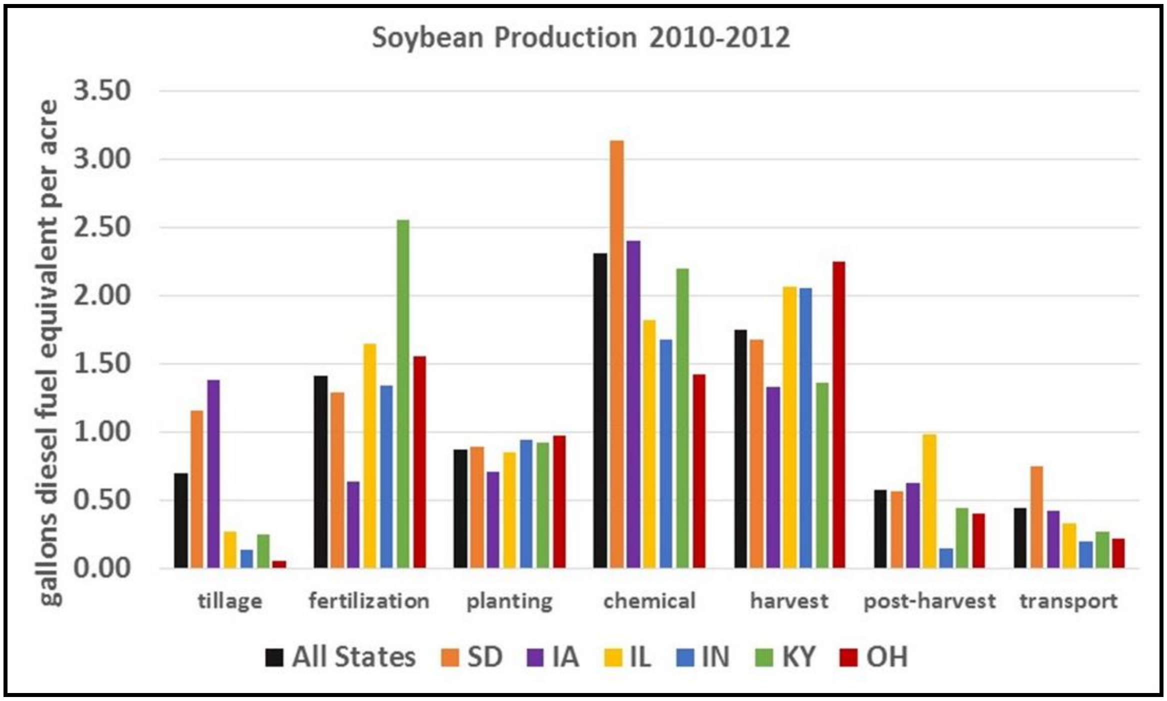
The key finding is that southern Minnesota soybean producers used 3.627 gallons of fuel per acre in 2012 to produce soybeans calculated by methodology 1, commonly used in Minnesota. Using an alternative crop production cycle definition (methodology 2); these Minnesota soybean producers used 4.500 gallons of fuel per acre to produce soybeans in 2012. The corn results were the opposite, lower with method one than method two.

5.2.2.5 Iowa Soybeans Association. 2015. Seeing STAARS: Six State Life Cycle Analysis for Corn and Soy Production

STAARS is a national, farmer-led initiative to improve farm profitability, energy efficiency, and environmental performance, while collecting, analyzing and reporting data documenting current on-farm resource management and sustainability. Nearly 500 soybean growers and their Technical Service Providers (TSPs)/Certified Crop Advisors (CCAs) are engaged in this three-year project. Linkages with land grant universities, state and federal agricultural agencies, and local watershed stakeholders add another layer of participation, helping reduce overlap and optimize outcomes for all involved.

The results are shown in the following figure. The fertilization and chemicals bars are the energy embedded in those products. The direct farm energy is the sum of tillage, planting and harvesting. These total about 3 gal/acre in these six states.

Figure 1-31 STAARS Results for Soybeans



5.2.3 Data Sources

There is one public data source available for soybean production energy use. The most recent data is discussed below.

5.2.3.1 USDA 2012

The USDA ARMS data for energy use includes all direct uses of energy. The data is available by special request and it is broken down to the state level. State level information on tillage practices and irrigation is not available at the state level for 2012 but it is available for 2006. A review of the data shows that energy use is higher in states that irrigate and thus it is obvious that this data includes irrigation energy. Similarly the energy use does vary with the number of tillage passes and thus is representative of actual operations in the US rather than an assumption about machinery use. Soybeans are rarely dried as harvesting is very difficult if the moisture content is above 15%. Any drying energy will be included in the total farm energy use.

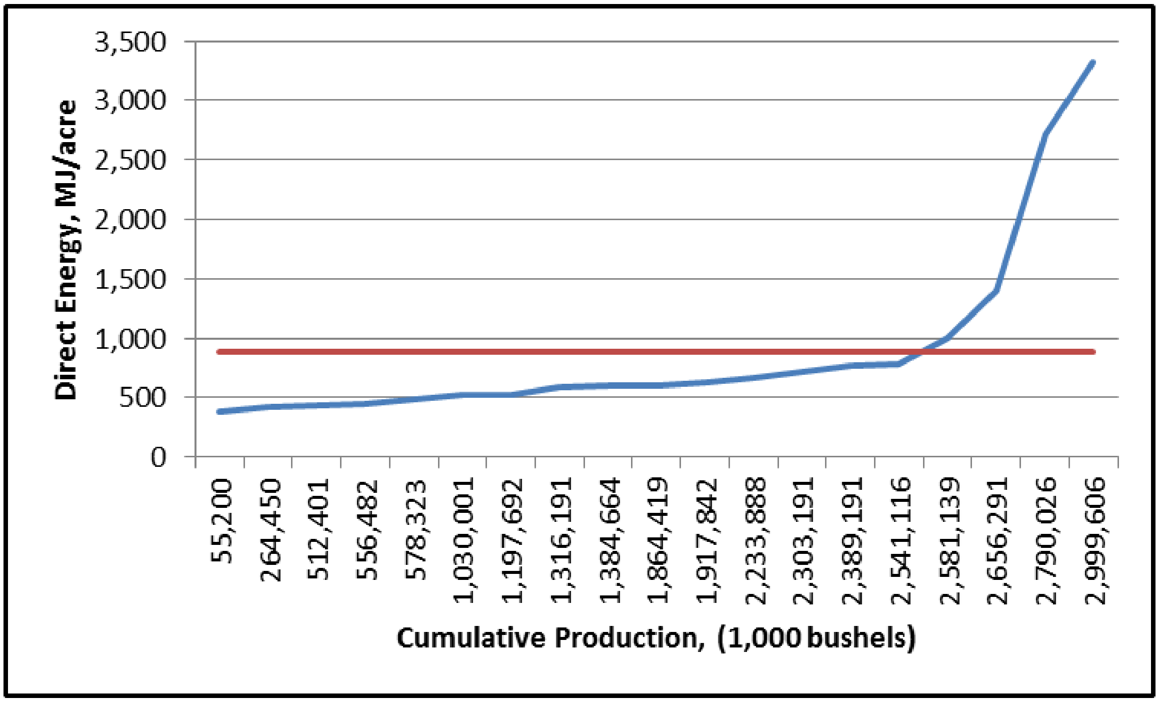
The energy use data from the 2012 ARMS data is shown in the following table. Note that Arkansas, Mississippi, and Nebraska are all high irrigation states.

Table 1-73 Direct Energy Use

	Diesel used	Gasoline used	LP gas used	Natural gas used	Electricity used	Total Energy
	gallons/ acre	gallons/ acre	gallons/ acre	1,000 cu ft/acre	KW hours/ acre	MJ (HHV)/ acre
U.S.	4.26	1.09	0.36	0.04	10.95	884
Arkansas	15.93	1.46	0.04	0	53.22	2,715
Illinois	3.07	1.04	0.02	0	3.56	601
Indiana	1.84	1.20	0.01	0	0.78	431
Iowa	2.68	0.97	0	0	0.17	520
Kansas	2.15	0.94	1.82	0.05	14.54	721
Kentucky	1.55	1.14	0	0	0.60	379
Louisiana	5.24	1.20	0.69	0	2.21	999
Michigan	4.16	1.17	0	0	3.49	775
Minnesota	3.50	1.01	0	0	4.64	661
Mississippi	8.00	1.30	0.26	0	11.64	1,407
Missouri	4.29	1.00	0.15	0	2.45	785
Nebraska	13.14	1.15	3.38	0.61	70.54	3,317
North Carolina	2.61	1.76	0.01	0	2.97	625
North Dakota	2.67	1.04	0	0	0.16	528
Ohio	1.88	1.07	0.01	0	0.74	419
South Dakota	2.69	0.91	0	0	20.62	587
Tennessee	1.87	1.29	0	0	0.15	444
Virginia	2.07	1.32	0.04	0	0.73	483
Wisconsin	3.12	1.05	0	0	1.39	599

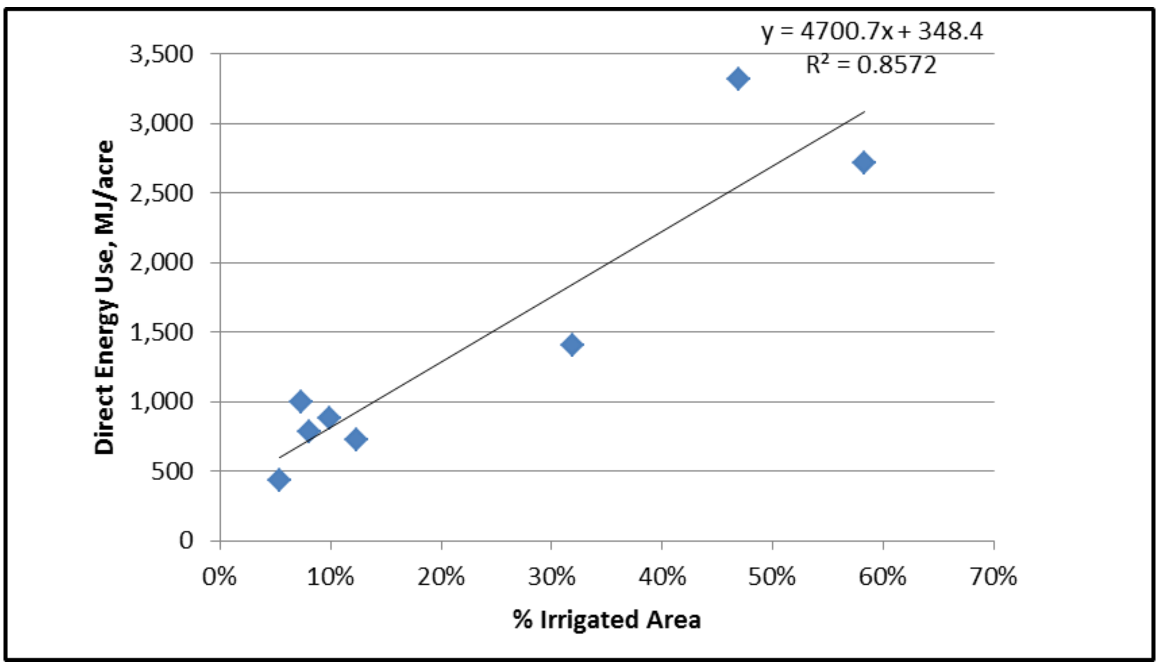
The distribution of the direct energy use is shown in the following figure. The US average is shown in the red line. Only about 15% of the production has above average energy use and they are all states with irrigation.

Figure 1-32 Energy Use Distribution



The first figure shows the energy use vs. the % of the area in a state that is irrigated. There is a fairly strong correlation and the states with high rates of irrigated land have energy use five times higher than non-irrigated states.

Figure 1-33 Energy Use vs. Irrigated Area



The following table reports the energy use for states with irrigated soybean production, without irrigated production, and the national average. The National average values are used in GREET 2016 and in GHGenius.

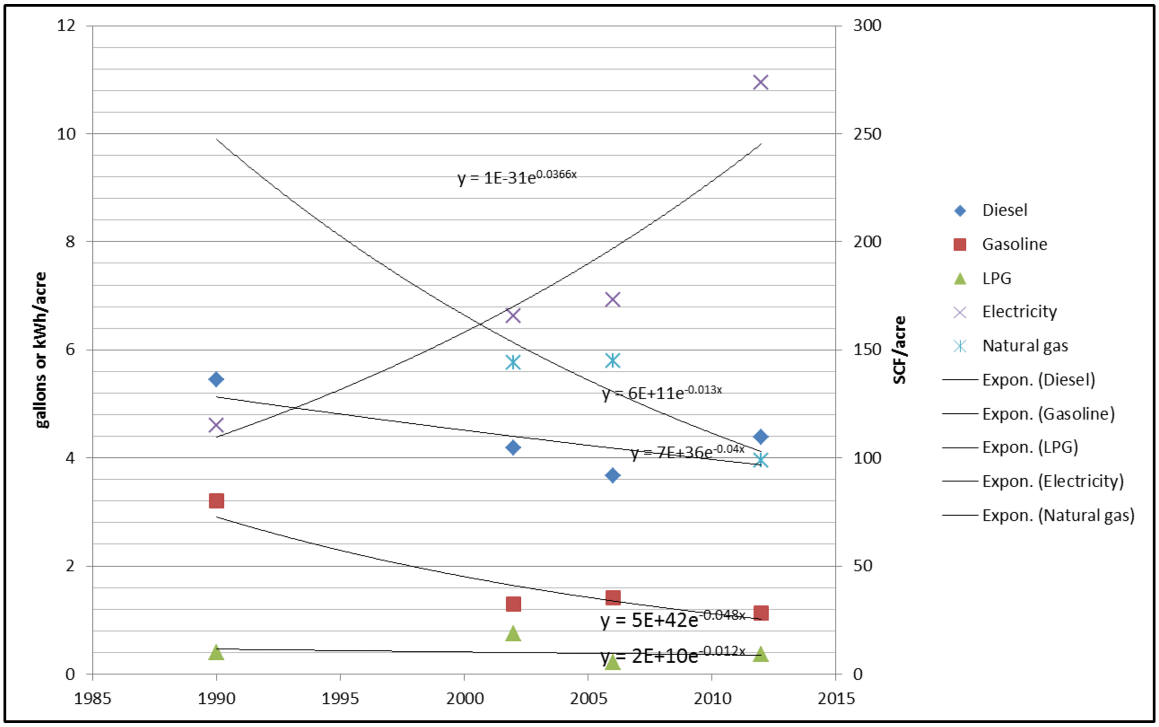
Table 1-74 Energy Use With and Without Irrigation

		With Irrigation	Without Irrigation	National average
Diesel	gallons/acre	7.01	2.83	4.26
Gasoline	gallons/acre	1.15	1.05	1.09
LPG	gallons/acre	1.00	0.01	0.36
Natural gas	1,000 cu ft/acre	0.13	0.00	0.04
Electricity	KW hours/acre	24.53	3.57	10.95
Total	BTU (LHV)/acre	1,323,000	497,000	778,000

5.2.4 Trends

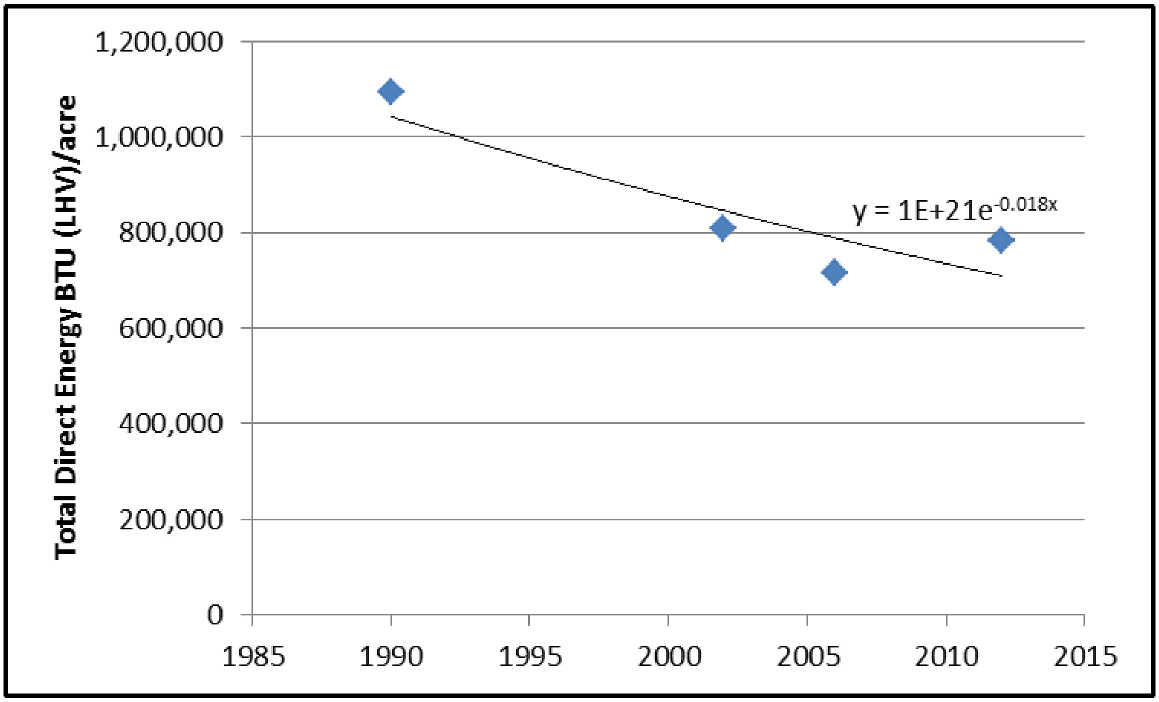
USDA ARMS surveys for soybeans were undertaken in 1990, 2002, 2006, and 2012. The energy use for each of the surveys is shown in the following figure.

Figure 1-34 Soybean Production Energy Use Trends



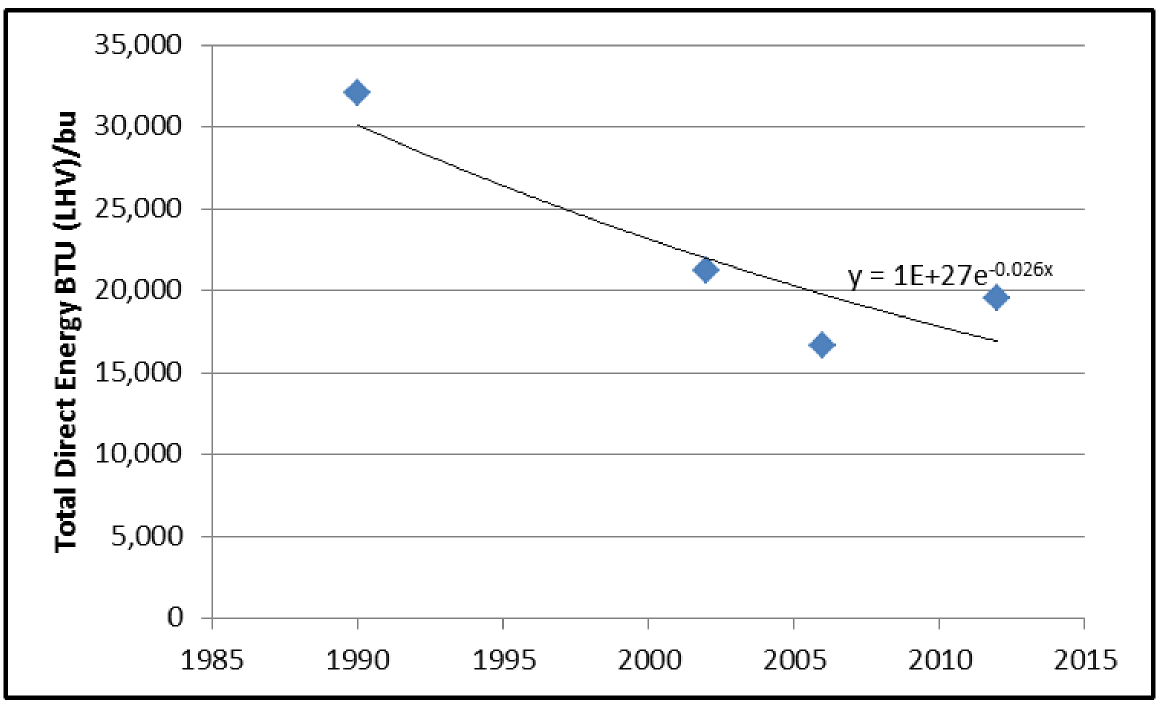
There have been significant reductions in gasoline and natural gas use, slower reductions in diesel and LPG, and an increase in electricity over this time period, all on a per acre basis. The total energy consumption is shown in the following figure.

Figure 1-35 Soybean Production Total Energy Use



For modelling, it is generally the energy use per unit of production that is important rather than energy per acre. This is shown in the following figure. The energy use declines by 2.6% per year and this is conservative since the 2012 yield was significantly below the trend line.

Figure 1-36 Energy Use per Bushel



5.2.5 Farm Energy Use Findings

GREET and GHGenius both use data from the USDA ARMS program. A detailed look at the data shows large variations in energy use from state to state with much of the variation apparently caused by energy used for irrigation. Energy used in soybean production in non-irrigated states is lower than the average and is in line with data from state level surveys. The data used in the BioGrace model is an estimate based on energy used in rapeseed production in the 1990s.

There is a difference between GREET 2016 and GHGenius 5.0 in terms of how the data is used. GREET converts the energy used per acre (from USDA) to energy used per bushel using the 2012 soybean yield and then holds that level from 2012 to 2020. In GHGenius the energy used per acre is used to generate trends in energy use and the long-term USDA yield data is used to project the production per acre. The projected energy use and projected yield are then used to calculate the energy used per bushel in the model.

The GREET approach is subject to distortion by low or high yield years, whereas the GHGenius approach will use trend data to adjust for years that experience unusual growing conditions.

5.3 SOYBEAN CRUSHING ENERGY USE

The energy consumed in the crushing process is a significant part of the biodiesel lifecycle but, in an LCA, a large part of the emissions (depending on the allocation method) are allocated to the meal. The available data is discussed below.

5.3.1 Existing Model Values

The data used in the three models is presented below.

5.3.2 GREET

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, however the values used in GREET are about 35% higher than the original NOPA dataset. GREET uses data that is representative of the production of crude soybean oil. The values are the same in GREET 2014 to 2016.

Table 1-75 GREET Soybean Crushing Energy

	Fraction, %	Energy, BTU/lb soyoil
Residual oil	0.9%	33
Diesel fuel	0.4%	15
Gasoline	0.0%	0
Natural gas	56.1%	2068
Coal	27.6%	1018
Liquefied petroleum gas	0.0%	0
Electricity	12.1%	446
N-hexane (a solvent from crude)	1.6%	59
Biomass	0.9%	33
Landfill Gas	0.4%	15
Total	100.00%	3687

5.3.2.1 GHGenius

The oilseed crushing energy use in GHGenius is based on the NOPA data but converts all thermal energy to natural gas. The model inputs are shown in the following table.

Table 1-76 GHGenius Soybean Crushing

Parameter	Value	
	GHGenius Units	GREET Units, BTU/lb oil
Natural Gas	152 litres/litre oil	2,425
Electricity	0.26 kWh/litre oil	440
Total		2,865

5.3.2.2 BioGrace

The crushing of the beans and refining of the oil takes place in Europe in the scenario modelled in BioGrace. 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 1-77 BioGrace Soybean Crushing

Parameter	Value	
	BioGrace Units	GREET Units, BTU/lb
Natural Gas	1,554 MJ/t soybeans	668
Electricity	84 kWh/t soybeans	130
Hexane	0.98 kg/t soybeans	22
Refining		
Natural Gas	45.1 MJ/t oil	19
Electricity	8.4 kWh/t oil	13
Total		852

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 total energy modelled is much less than the values used in GREET and GHGenius and it is probably not appropriate to use the rapeseed data for soybean crushing.

5.3.3 Literature Review

The literature search for soybean crushing energy did not turn up any new useful information. Most of the papers that discussed the crushing energy were papers that looked at the biodiesel production lifecycle and those papers generally relied on older references.

5.3.4 Data Sources

The most complete data set for soybean crushing is the updated data set provided by the National Oilseed Processers Association (NOPA). This dataset was originally developed in

2008 and was updated with revised electricity data in 2015. The data is shown in the following table.

Table 1-78 NOPA Energy Data Set

	KWh/1000 bushels	kWh/tonne	kWh/lb soy oil
Electricity, kWh/tonne	1,500	56	0.13
Thermal Energy	BTU/1000 Bushel	MJ (HHV)/tonne	BTU (HHV)/lb soybeans
Natural Gas	20,150,000	615	1,758
#2 Fuel Oil	155,000	5	14
#6 Fuel Oil	310,000	9	27
Coal	9,920,000	303	866
Biomass	310,000	9	27
Landfill Gas	155,000	5	14
Total Thermal Energy	31,000,000	947	2,705

There are two issues with this data. The first is that it is not stated if the energy is reported on a higher or lower heating value basis. In North America, energy transactions are always done on a higher heating value basis but some LCA models use lower heating values.

The second issue with the NOPA data is that it does not include six plants that purchase steam rather than generate it themselves. At least some of these plants purchase the steam from adjacent power plants where the steam would have otherwise been condensed. Excluding these plants will increase the industry energy use, as the steam is mostly “waste steam”.

Another data set was published by Fediol, the federation representing the European Vegetable Oil and Protein meal Industry in Europe (Fediol, 2013). A number of Fediol companies provided data on their rapeseed and soybean crushing and refining operations. The Fediol soybean data is shown below. This data set only provided the steam usage and not the energy used to produce the steam. Assuming that the boiler efficiency is 80% and a worst case where the water for the steam must also be heated, then the steam requires 3.37 MJ/kg of steam.

Table 1-79 Fediol Soybean Data

Energy	Value
Electricity, kWh/tonne soybeans	28.8
Steam, kg/tonne soybeans	250
Fuel, MJ/tonne at 80% boiler efficiency	845

The Fediol electricity use is about half of the NOPA value and the thermal energy use is about 10% less than the NOPA values.

5.3.5 Trends

There is insufficient data available to determine if there are any trends to the amount of energy used to crush soybeans.

5.3.6 Soybean Crushing Findings

There is only one set of public data on the energy use for soybean crushing and that is the 2008 NOPA data, which was updated in 2015 with revised power consumption. There does appear to have been an issue with unit conversions or interpretation of the data set as the values in GREET, which were taken from a secondary energy source, do not align with the original NOPA data.

5.4 BIODIESEL PLANT ENERGY USE

Biodiesel plant energy use was a parameter with significant variation in the previous work.

5.4.1 Existing Model Values

The values in the existing modes are discussed below.

5.4.1.1 GREET

The process parameters for biodiesel production in GREET 2014 to 2016 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.

Table 1-80 GREET Biodiesel Production

Parameter	Value
Feedstock	1.04 lb/lb
Natural Gas	372 BTU/lb
Electricity	0.016 kWh/lb
Methanol	785 BTU/lb
Total Energy	1,213 BTU/lb
Hydrochloric acid	19.7 grams/lb
Sodium methoxide	10.5 grams/lb
Sodium Hydroxide	0.4 grams/lb
Phosphoric acid	0.3 grams/lb
Citric acid	0.3 grams/lb

5.4.1.2 GHGenius

GHGenius also used the 2009 NBB survey for energy use at biodiesel plants. GHGenius had access to the raw data and was able to separate the virgin vegetable oil plants from all biodiesel plants and so the values are slightly different than those in GREET. The values for soybean biodiesel are summarized in the following table.

Table 1-81 GHGenius Biodiesel Production

Parameter	Value	
	GHGenius Units	GREET Units
Yield	0.88 kg oil/l biodiesel	0.995 lb/lb
Natural Gas	20.2 litres NG/l	350 BTU/lb
Electricity	0.032 kWh/l	0.016 kWh/lb
Methanol	0.102 l/l	744 BTU/lb
Total Energy		1150 BTU/lb
Citric acid	0.0006 kg/litre	0.3 grams/lb
Hydrochloric acid	0.0116 kg/l	5.9 grams/lb
Sodium Methylate	0.0062 kg/l	3.2 grams/lb
Sodium Hydroxide	0.0004 kg/l	0.2 grams/lb
Phosphoric acid	0.0006 kg/l	0.3 grams/lb
Nitrogen	0.025 kg/litre	12.8 grams/lb

5.4.1.3 BioGrace

The process parameters and the GHG emissions for the components of the biodiesel production stage are shown in the following table. As noted in the previous work, these values are extremely high and were based on a misinterpretation of the data supplied to the JRC.

Table 1-82 Biodiesel Production

Parameter	Value	
	BioGrace Units	GREET Units
Yield	0.92 kg oil/l biodiesel	1.04 lb/lb
Natural Gas	3.69 MJ/l	1,788 BTU/lb
Electricity	0.038 kWh/l	0.020 kWh/lb
Methanol	0.17 l/l	1,304 BTU/lb
Total Energy		3,160 BTU/lb
Hydrochloric acid	0.0249 kg/l	12.8 grams/lb
Sodium Carbonate	0.0031 kg/l	1.6 grams/lb
Sodium Hydroxide	0.0084 kg/l	4.3 grams/lb
Phosphoric acid	0.0021 kg/l	1.1 grams/lb

5.4.2 Literature Review

The search terms “Biodiesel production” and “Energy use” produced only one reference that focused on the energy use within a plant.

5.4.2.1 Kaercher et al 2013. Optimization of biodiesel production for self-consumption: considering its environmental impacts

This study worked to optimize biodiesel production with a production capacity of 40-200 L day^{-}, taking into consideration the necessity of identifying and reducing the impacts of the process so as to construct appropriately scaled equipment.

The study did find different energy requirements for different catalysts and different alcohols but given the small scale and the batch nature of the process the findings are not readily transferrable to commercial scale production.

5.4.3 Data Sources

The National Biodiesel Board has completed a survey of the energy used by their members in 2016. That data for vegetable oils is summarized in the following table. The data is presented in the original survey units and in the GREET units. The list of chemicals used is broader than the chemicals included in the GREET model.

Table 1-83 NBB 2016 Energy Survey

Parameter	Survey Results	GREET Units
Feedstock	7.46 lb/gal	1.02 lb/gal
Natural gas	3.534 SCF/gal	447 BTU/gal
Electricity	0.137 kWh/gal	0.019 kWh/lb
Methanol	0.715 lb/gal	820 BTU/gal
Total Energy		1,331 BTU/lb
Sodium Methylate	0.123 lb/gal	2.25 grams/gal
Sodium Methylate conc.	29.5%	
Sodium Hydroxide	0.006 lb/gal	0.15 grams/gal
Sodium Hydroxide conc.	50%	
Hydrochloric acid	0.054 lb/gal	9.9 grams/gal
Hydrochloric acid conc.	33.7%	
Sulphuric acid	0.001 lb/gal	0.06 grams/gal
Sulphuric acid conc.	93%	
Phosphoric Acid	0.004 lb/gal	0.18 grams/gal
Phosphoric Acid conc.	75%	
Nitrogen	0.016 lb/gal	2.2 grams/gal

The energy use is slightly higher than the previous survey but most of the chemicals are lower. There were more plants participating in this survey than participated in the earlier work.

5.4.4 Trends

There is insufficient data available to establish any trends in the biodiesel energy use. The energy use at biodiesel plants is relatively low and the impact of reduced energy use on GHG emissions will be relatively small.

5.4.5 Biodiesel Plant Energy Findings

New data is available for biodiesel plant energy use. This data indicates slightly higher energy use than what is currently in GREET and GHGenius but much less than is in the BioGrace model.

5.5 Renewable Diesel Production

There are several key parameters that influence the GHG emissions from renewable diesel plants. These are the feedstock used per unit of fuel, the quantity of co-products, the hydrogen consumption, the power and the natural gas used. In addition to producing renewable diesel there will also be some lighter liquid and gaseous products produced. In some plant configurations, these can be used to supply the thermal energy requirements and the hydrogen for the process, reducing the need for fossil fuel inputs.

5.5.1 Existing Model Values

The values for each of the key parameters for the renewable diesel process are discussed below.

5.5.1.1 GREET

The GREET model has a renewable diesel pathway for soybean renewable diesel. The parameter values are shown in the following table. There have been no changes in GREET 2015 and 2016 for these parameters. This pathway was added to GREET in 2008 and the parameters have not changed since then.

Table 1-84 GREET Renewable Diesel Parameters

	GREET 2014
Feedstock, lb oil/lb fuel	1.17
LPG Co-product, lb/lb RD	0.059
Natural gas, BTU/lb	83
Electricity, BTU/lb	95
Hydrogen, BTU/lb	1,673

The renewable diesel process is modelled after the UOP process but the model parameters were from Aspen modelling done by NREL for Argonne National Laboratory (Huo et al, 2008).

5.5.1.2 GHGenius

The GHGenius pathway for renewable diesel can process any of the lipids that are in the GHGenius model. The default values that are in GHGenius 4.03a are shown in the following table.

Table 1-85 GHGenius Renewable Diesel Parameters

	GHGenius 4.03a	
Feedstock	0.94 kg/litre	1.22 lb oil/lb fuel
LPG Co-product	0.047 l/l	0.03 lb/lb RD
Naphtha co-product	0.0 l/l	0.0 lb/lb
Natural gas	6 litres/litre	250 BTU/lb
Electricity	0.08 kWh/litre	355 BTU/lb
Hydrogen	0.030 kg/litre	1,800 BTU/lb
Sodium hydroxide	0.001 kg/litre	0.6 g/lb
Phosphoric acid	0.001 kg/litre	0.6 g/lb

5.5.1.3 BioGrace

BioGrace only has a rapeseed, sunflower, and palm oil renewable diesel pathways but the process inputs are independent of the feedstock. The model parameters are shown in the following table. The process exports electricity and natural gas back to the grids and has no other co-products. The co-product credits are increased by 40% in the model. This follows the standard practice of increasing process energy use by 40% in BioGrace but obviously in this case the co-product energy should have been decreased by 40% to be consistent with the conservative philosophy.

Table 1-86 BioGrace Renewable Diesel Parameters

	BioGrace	
Feedstock	0.967 MJ HVO/MJ oil	1.23 lb oil/lb fuel
Natural gas	-0.012 MJ/MJ RD	-226 BTU/lb
Electricity	-0.0021 MJ/MJ RD	-192 BTU/lb
Hydrogen	0.12 MJ H_2/MJ RD	2,263 BTU/lb

5.5.2 Literature Review

The literature review used the search terms "renewable diesel" and "process conditions" and "renewable diesel" and LCA. The results are shown in Appendix 4. Many of the papers described laboratory experiments or reported the results using the GREET model. None of the papers reported the performance of operating facilities.

5.5.2.1 Miller and Kumar. 2013. Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina.

This work relied on Aspen modelling to develop the inputs for the renewable diesel production. The paper did not report the feedstock requirements but did report the hydrogen, natural gas, and electricity requirements as shown in the following table.

Table 1-87 Renewable Diesel Process Inputs

Parameter	Original Units	GREET Units
Hydrogen	0.02 kg/litre	2,660 BTU/lb
Natural gas	5.35 MJ/litre	2,985 BTU/lb
Electricity	0.08 kg/litre	161 BTU/lb

The natural gas requirements are high compared to the inputs in the LCA models.

5.5.2.2 Shonnard et al. 2010. Camelina-Derived Jet Fuel and Diesel: Sustainable Advanced Biofuels

This paper included a co-author from UOP. The work used SimaPro for the LCA work but the paper did not report any of the parameters for the renewable diesel process. The only data reported in the paper was related to the oilseed production and crushing.

5.5.2.3 Uusitalo et al. 2014. Carbon footprint of renewable diesel from palm oil, jatropha oil and rapeseed oil.

This paper relied on production data from a 2008 master's thesis (Nikander, 2008), however there was input from Neste and the thesis is available on the Neste website.

Table 1-88 Renewable Diesel Parameters

	Uusitalo	
Feedstock	1.21 kg /kg RD	1.21 lb/lb
Natural gas	0.026 MJ/kg RD	32 BTU/lb
Electricity	0.03 kWh/kg RD	102 BTU/lb
Hydrogen	0.036 kg/kg RD	1,850 BU/lb

The paper also reported production of propane (0.072 lb/lb RD) and naphtha (0.024 lb/lb RD). The feedstock and the co-products are both higher than is in the GREET model.

5.5.2.4 Fan et al. 2013. A life cycle assessment of pennycress (Thlaspiarvense L.) -derived jet fuel and diesel.

This paper was also co-authored by a UOP employee but it included some information of the renewable diesel production unit although the information did not come from UOP, but from the GREET model.

5.5.3 Data Sources

There is one source of data on the performance of renewable diesel plants and that is from the Neste CARB applications. Diamond Green Diesel has also applied for a CARB CI score but all of their data was redacted in the public version. REG Geismar has not yet gone through the CARB process.

5.5.3.1 Neste CARB Application

To support their Method 2B applications to CARB under the LCFS program Neste publicly reported performance data from their Singapore plant. The data is reported to be from a representative period. It is summarized in the following table.

Table 1-89 Neste Renewable Diesel Parameters

	Neste Singapore	
Feedstock	1.21 kg /kg RD	1.21 lb/lb
Natural gas	Not reported	-
Electricity	0.106 kWh/kg RD	165 BTU/lb
Hydrogen	0.038 kg/kg RD	1,955 BTU/lb
Naphtha	0.0052 kg/kg RD	104 BTU/lb
LPG	0.060 kg/kg RD	1,197 BTU/lb

5.5.4 Trends

There is insufficient actual data on the production process available to determine and trends in the performance of the operating renewable diesel plants.

5.5.5 Renewable Diesel Production Findings

The process parameters for renewable diesel plants can vary depending on the plant configuration. The processes do produce some biogenic fuel gas and a biogenic gasoline fraction liquid fuel. At the same time the plants have a need for hydrogen and thermal energy. The plants have the opportunity to use their biogenic co-products to displace purchase fossil fuels used to make hydrogen and the thermal energy.

If the LCA uses the displacement approach for dealing with the co-products the utilization of the co-products is not important. However if the co-products are dealt with by mass or energy allocation then the plants that use their biogenic co-products to reduce the purchased natural gas or hydrogen will have lower CI scores.

The model parameters and literature values are summarized in the following table. In this case the literature value is the Neste CARB data since that was the only reported primary data that was identified.

Table 1-90 Renewable Diesel Summary

	GREET	GHGenius	BioGrace	Literature
Feedstock, lb/lb RD	1.17	1.22	1.23	1.21
Hydrogen, BTU/lb RD	1,673	1,800	2,263	1,955
Natural gas, BTU/lb RD	83	250	-226	Not reported
Electricity, BTU/lb RD	95	355	-192	165
Co-products, BTU/lb RD	1,096	700	0	1,300

The hydrogen use has the greatest single parameter impact on the GHG emissions from the plant. The model values have the least variation in this parameter. The GREET values are lower than the one available source of actual plant data.

5.6 Additional Parameters

No additional parameters that have a significant impact on the GHG emissions of soybean biodiesel/renewable diesel were identified as part of this work.

5.7 Soybean Findings

Three areas of uncertainty and variability were identified in the previous work (E-102): N_2O emissions, farm energy use, and the energy use for oilseed crushing and biodiesel/renewable diesel production.

There remains considerable uncertainty over the nitrogen content of the soybeans residues. Many of the papers in the literature continue to use the IPCC default value, which contains a value from a 1925 reference. All of the authors who have looked at the issue consider this to be too low. One of the challenges is that some of the root nodules decompose in the growing year and so any analysis that is done at the end of the year will miss that N in a measurement of residue nitrogen content.

The recent GREET update identified literature which had N_2O emissions ranging from 0.7 to 4.84 kg N_2O/ha. GREET now has a value of 1.84 kg N_2O/ha. Other sources identified in the recent literature are within this range

For farm energy use, GREET and GHGenius both use data from the USDA ARMS program. A detailed look at the data from that program shows large variations in energy use from state to state with much of the variation apparently caused by energy used for irrigation. The energy used ranged from 379 MJ/acre to 3,317 MJ/acre, with an average of 825 MJ/acre. Energy used in soybean production in non-irrigated states is lower than the average and is in line with data from state level surveys.

There is only one set of public data on the energy use for soybean crushing and that is the 2008 NOPA data, which was updated in 2015 with revised power consumption. There does appear to have been an issue with unit conversions or interpretation of the data set as the values in GREET, which were taken from a secondary energy source, do not align with the original NOPA data.

New data is available for biodiesel plant energy use. This data indicates slightly higher energy use than what is currently in GREET and GHGenius but much less than is in the BioGrace model.

For renewable diesel production only one value was identified in the literature that is based on actual plant data. The feedstock, hydrogen, and electricity consumption are all higher than the values used in GREET, but so is the quantity of co-products produced.

In the parameters that were evaluated only the farm energy use has a long term trend. More no till agriculture, more efficient farm equipment and higher yields all lead to less energy use per unit of production. The other parameters, N_2O emissions and plant energy use, either have insufficient data available to identify trends or show no trend from the available data.

6. SUGARCANE ETHANOL

Sugarcane ethanol production is significantly different than corn ethanol production and has different key factors impacting the GHG emissions. Four parameters were identified for investigation: the N_2O emissions for producing sugarcane, the energy consumed in mechanical harvesting, methane emissions from the vinasse application systems, and the quantity of co-products produced (primarily electricity). Each of these is discussed below.

6.1 N_2O EMISSIONS

N_2O emissions arise from the degradation of the applied fertilizer and crop (and processing) residues. Field burning will convert some of the crop residue to N_2O and NOx but most of the N in the crop residue will be in the ash that is either left on the field or carried to adjacent fields by the wind.

6.1.1 Existing Model Values

The existing model values are discussed in the following sections.

6.1.1.1 GREET

The GREET model values from the models are shown in the following table.

	GREET 2013	GREET 2014	GREET 2015	GREET 2016
N in fertilizer	800	800	800	800
Fraction of sugarcane straw left in unburnt fields	0.84	0.84	0.84	0.64
N in Crop Residue, g/tonne	484.4	484.4	484.4	359.5
N in vinasse, g/tonne	205	205	205	205
N in filter cake, g/tonne	36	36	36	36
Total N	1525.4	1525.4	1525.4	1,400
EF_1 Syn fert	0.895%	0.895%	0.895%	0.895%
EF_1 crop residue	0.895%	0.895%	0.895%	0.895%
EF_4	1.000%	1.000%	1.000%	1.000%
EF_5	0.750%	0.750%	0.750%	0.750%
$Frac_{gasf}$	0.1	0.1	0.1	0.1
$Frac_{leach}$	0.3	0.3	0.3	0.3
Total, g N_2O/tonne	33.088	32.733	29.311	29.301

The GREET 2016 model assumes that 15% of the fields are burnt prior to harvesting and that 64% of the straw in the unburned fields remains in the field. Both values impact the total nitrogen in the crop residues and the N_2O emissions. The maximum N left in the field with no burning and no straw removal is 518 g N/tonne of cane but, for this case, the synthetic N is reduced so that there is very little change in the N_2O emissions with different assumptions on straw burning and straw removal.

The GREET values were described in a paper by Wang et al (2012). The N_2O emission factor is based on a single paper (Carmo et al 2012) that measured the rates in two fields. The average value has been used in GREET.

6.1.1.2 GHGenius

The assumptions that are used in GHGenius are summarized below. An emission factor for EF1 of 0.0125 has been chosen, as most of the literature supports a higher emission factor for sugarcane than the IPCC default value. The other emission factors are IPCC values.

Table 1-91 N_2O Emission Factors

Name	Cell	Value
N-N_2O/N-input, direct or "on-site" emissions, EF1	I113	0.0125
N content of residue (fraction of dry mass)	I114	0.0080
Ratio of total biomass weight to weight of crop or product harvested	I115	1.55
Of total residue (incl. roots) available, fraction left in the field	I116	0.95
R, C:N ratio	I118	10
NH_3-N+NOx-N per kg N for synthetic, FRAC $_{gasf}$	I119	0.10
NH_3-N+NOx-N per kg N for manure and organic, FRAC $_{gasm}$	I120	0.20
N_2O-N per kg (NH3-N+NOx-N) emitted, EF4	I121	0.01
Synthetic or manure N lost offsite through drainage or runoff, fraction of N applied,	I122	0.30
N-N_2O/N-fertilizer-offsite	I123	0.0075

The total amount of N applied in GHGenius for unburned fields is higher than in GREET with 1.1 kg of synthetic N applied, 0.49 kg of N from vinasse and filtercake and 1.23 kg of N in the crop residue calculated from the above parameters.

6.1.1.3 BioGrace

The BioGrace value for N_2O is 36.1 g N_2O/tonne of cane. It is a fixed value and has no transparency. This is 3.97% of the synthetic N fertilizer applied but there is also vinasse and filtercake applied in the model. The N content of those materials is not specified.

6.1.2 Literature Review

The literature search used the search terms “sugar cane” and “N_2O emissions” and also the term “meta-analysis” to try to find papers that considered more than one site. The top papers are found in the Appendix.

6.1.2.1 Siqueira Neto et al. 2016. Direct N_2O emission factors for synthetic N-fertilizer and organic residues applied on sugarcane for bioethanol production in Central-Southern Brazil.

This paper quantified N_2O emissions from soil covered with different amounts of sugarcane straw and determined the direct N_2O emission factors of nitrogen fertilizers (applied at the planting furrows and in the topdressing) and the by-products of sugarcane processing (filter cake and vinasse) applied to sugarcane fields.

The results showed that the presence of different amounts of sugarcane straw did not change N_2O emissions relative to bare soil (control). N-fertilizer increased N_2O emissions from the soil, especially when urea was used, both at the planting furrow (plant cane) and during the regrowth process (ratoon cane) in relation to ammonium nitrate.

The N emission rates were all less than 1% for this test.

6.1.2.2 Signor et al 2013. N_2O emissions due to nitrogen fertilizer applications in two regions of sugarcane cultivation in Brazil

This paper evaluated N_2O emissions due to application of increasing doses of ammonium nitrate and urea in two sugarcane fields in the mid-southern region of Brazil: Piracicaba (Sao Paulo state) and Goianesia (Goias state).

Although the proportions of N emitted as N_2O were different in Piracicaba and Goianesia, these values showed the same behaviour of cumulated emissions during the evaluation periods. The proportion of N emitted as N_2O in Goianesia is similar to emission factors proposed by IPCC. The N_2O emissions at the Piracicaba site were up to an order of magnitude higher at high N application rates.

6.1.2.3 Otto et al 2016. Nitrogen Use Efficiency for Sugarcane-Biofuel Production: What Is Next?

The objective of this paper was to review recent developments in N management for sugarcane biofuel production and assess estimates of N use efficiency (NUE) and N losses based on future scenarios, as well as for life-cycle assessments of bioenergy production. They found that approximately 60% of the fertilizer N is recovered by plants and soils throughout the crop cycle, while leaching losses and N_2O emissions may reach as high as 5.6% and 1.84% of the applied N, respectively.

They noted that the increasing shift from burning to non-burning (GCTB) systems in Brazil has led to modifications in the country's N management strategies, with an increase in N rates from 1.0 kg N per Mg of stalk to 1.2 kg N per Mg of stalk being adopted by most growers. This N rate is higher than is used in GREET.

The paper reviewed three other studies (including the one used for GREET) and found that the average N_2O emission rate was 1.84% of N applied.

6.1.2.4 Paredes et al. 2015. Nitrous Oxide and Methane Fluxes Following Ammonium Sulfate and Vinasse Application on Sugar Cane Soil

The authors report that the application of fertilizer N or vinasse induced N_2O emissions of 0.6 and 1.04 to 2.20% of the total N from each source, respectively, which is close to the values reported in other field studies in Brazil.

6.1.2.5 Bordonal et al 2015. Greenhouse gas balance from cultivation and direct land use change of recently established sugarcane (Saccharum officinarum) plantation in south-central Brazil.

These authors used an emission factor of 1.325% for synthetic fertilizer and 1.425% for vinasse. Both values are from the IPCC Tier 1 good practice.

6.1.3 Data Sources

There is very little data on N_2O emissions outside of the peer-reviewed literature. The IEA Bioenergy Task 39 project that is looking at GHG models for sugarcane (Cavalett, 2016) has information on sugarcane production from the Brazilian research centre CTBE. They are using 1.23 kg of synthetic N fertilizer per tonne of cane produced, higher than GREET and GHGenius but consistent with the Otto paper above. They use the IPCC emission factors with two exceptions: the volatilization factor is increased from 10% to 30% and the leaching factor is reduced to 5% from 30%. The total N in the N_2O emissions is 1.46%, higher than GREET and lower than GHGenius.

6.1.4 Trends

There is insufficient data to determine any trends in the N_2O emissions of sugar cane production.

6.1.5 N_2O Emission Findings

The N_2O emissions are a function of the quantity of N applied and the emission factor. There remains very little information available on N_2O emissions for Brazilian sugarcane, especially compared to crops such as corn and soybeans. The information that is available would suggest that the synthetic N fertilizer rates in GREET (0.8 kg) and GHGenius (1.1 kg) are too low and should be increased to about 1.2 kg N/tonne of cane.

The data on N_2O emission factors is limited in the literature. GREET uses a factor that is less than the IPCC Tier 1 default values. Many of the papers did use the Tier 1 default values in their analyses. There were also a few papers that did attempt to measure the N_2O emissions and develop overall emission factors. The range for an overall N_2O emission factor would be from 1.22% (GREET) to 1.84% (Otto et al).

6.2 HARVESTING ENERGY

Sugarcane harvesting in Brazil is transitioning from a manual system to a mechanical system. A profile of the sector in 2012 (Confab) reported that 65% of the cane was mechanically harvested. Public data on the energy use in mechanical harvesting systems has been limited.

6.2.1 Existing Model Values

The existing values in the models are shown below.

6.2.1.1 GREET

The GREET values are shown in the following table. The values have been the same for GREET 2013 to 2016. Prior to 2010, GREET used 41,552 BTU/tonne as the farming energy. There is a separate input for the fraction of the field that is mechanically harvested but it does not impact the fuel use in harvesting or any other parameter in the model. The increase in energy was attributed to mechanical harvesting and GREET assumed that energy consumption per tonne during sugarcane harvesting remains constant between 2010 and 2020, despite the increased mechanical harvesting share (Han et al. 2012).

Table 1-92 GREET Sugarcane Farming Energy

	GREET 2016, BTU/tonne cane
Total Energy	95,000
Diesel fuel	36,385
Gasoline	11,685
Natural gas	20,425
Liquefied petroleum gas	17,860
Electricity	8,550

The 95,000 BTU/tonne is explained as follows (Dunn et al, 2011)

> *Seabra et al. (2011) provide the total volume of diesel fuel consumed in sugarcane production, including fuel consumed during transport to processing facilities, as 29 gal/acre. These authors' analysis assumes a transport distance of 13 miles and a transportation energy efficiency of 131 tonne miles/gal (by truck). For two-way truck travel, the energy consumption is 0.10 gal/tonne. The yield per acre is 14 metric tons. Diesel fuel consumption for feedstock production is then 92,942 Btu/tonne cane. Macedo et al. (2008) provide the fuel consumption for the following agricultural operations in the 2005/2006 growing season: planting the cane, managing the ratoon (the new cane growing from stubble left behind after harvest), harvesting, and operating loaders and tractor haulers. The total diesel fuel these activities consumed was 96,051 Btu/tonne cane. In the new GREET release, we use the average of these two values, or 95,000 Btu/tonne cane.*

It is not clear from the description how the breakdown of the 95,000 BTU/tonne was made to the individual fuels since the source would suggest that most of it is diesel fuel.

6.2.1.2 GHGenius

GHGenius allows users to choose the fractions of the cane that is harvested manually and mechanically. The energy use for the two options is shown in the following table. There is more of a difference in the values in GHGenius than in GREET.

Table 1-93 GHGenius Sugarcane Harvesting

	GHGenius	GREET Units
	Litres/tonne cane	BTU (LHV)/ tonne cane
Manual harvest	0.87	29,600
Mechanical harvest	3.2	109,000

The GHGenius inputs were based on reports from 2008 to 2011 by Seabra, Macedo, and Galdos. These reports did not provide a specific value for 100% mechanical harvest.

6.2.1.3 BioGrace

The diesel energy use in BioGrace is 27,000 BTU/tonne of cane and obviously a manual harvest value. The BioGrace values are from the 2004 report by Macedo et al.

6.2.2 Literature Review

The search terms included "sugar cane" "mechanical harvesting" and "energy use". A number of reports were identified.

6.2.2.1 Capaz et al., 2013. Impact of mechanization and previous burning reduction on GHG emissions of sugarcane harvesting operations in Brazil

Capaz et al (2013) has estimated the specific GHG emissions (ton CO_2eq/ ha) in sugarcane harvesting as a function of the simultaneous reduction of previous burning and increase in the use of mechanization. The report has some detailed information on diesel fuel use by type of equipment employed. The diesel fuel use by the harvester ranged from 61.4 to 93.7 l/ha and for the cane loader the fuel use ranged from 12.7 to 16.3 l/ha. The yields ranged from 81 to 95 tonnes/ha. Fuel use ranged from 1 to 1.2 l/tonne for these two activities, but there are other activities that are included in the production stage.

6.2.2.2 Ramos et al., 2016. Fuel consumption of a sugarcane harvester in different operational settings

Ramos et al (2016) evaluated the fuel consumption of a sugarcane harvester in different forward speeds and engine rotations. Harvesting was conducted in a green cane plot. Fuel consumption just for the harvester ranged from 0.8 to 1.2 l diesel/ton (it is assumed that this is a metric tonne given that all other units in the paper are metric).

6.2.2.3 Rein, 2010. The Carbon Footprint of Sugar

This paper by Rein considered the carbon footprint for a typical sugar cane mill. 50% of the field was burnt prior to harvest. Diesel fuel use was reported to be 1.25 l/tonne of cane. In addition there was 6.75 kWh of power/tonne of cane used for irrigated and other uses in the field.

6.2.2.4 Want et al., 2014. Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward

This paper by Wang et al (2014) undertakes an environmental and economic analysis of sugarcane ethanol in Brazil. Diesel fuel consumption for the 100% mechanized harvest scenarios was forecast to be 3.7 litres diesel/tonne of cane.

6.2.2.5 Seabra and Macedo, 2010. Energy balance and GHG emissions in the production of organic sugar and ethanol at São Francisco Sugar Mill

This 2010 paper by Seabra and Macedo only has data for a single mill but it is a very detailed assessment of all of the inputs and outputs of this mill. The diesel fuel use for sugar cane production was 115,000 BTU/tonne (LHV).

6.2.2.6 de Oliveira Bordonal, R., de Figueiredo, E. B. and La Scala, N. 2014. Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest, considering other conservationist management practices

This paper reported fuel use for all field operations for three different scenarios, all with mechanical harvesting. The results are shown in the following table. It has been assumed that there would be a 6-year cycle for the tillage and planting energy use.

Table 1-94 Fuel Consumption Sugarcane Production

	Green harvest, conv tillage	Green harvest, reduced tillage	Green harvest, reduced tillage and hemp in rotation
	Litres/ha		
Tillage and planting	166.7	107.4	114.5
Ratoon treatment	20.4	17.7	17.7
Harvesting	95.2	95.2	95.2
Mean Total	189.0	177.4	178.6

If the average yield was 80 tonnes/ha then the diesel energy use would be 2.2 to 2.4 l/tonne of sugarcane. Mechanical harvesting increased diesel fuel use by about 1 litre of diesel/tonne of sugar cane.

6.2.3 Data Sources

Some of the large, multi-facility companies produce an annual sustainability report. These reports contain a significant amount of data but it is highly aggregated and doesn't have the detail necessary to enhance the LCA models.

6.2.4 Trends

There is a trend towards more mechanical harvesting but other potential movements to no tillage and straw collection, which would also impact diesel fuel energy use, are less clear.

6.2.5 Mechanical Harvesting Findings

Industry average data for fuel use in the sugarcane production stage is not available in the public domain. This is not unusual, as other crops have the same issues. The available literature has a wide range from 2.2 to 3.7 l diesel/tonne of cane. The values that are used in the models are in the middle of the range.

6.3 METHANE EMISSIONS

Methane emissions from the transportation and application of vinasse were identified in the previous work as a source of emissions that wasn't included in most sugarcane ethanol LCA's and that the impact could be important.

6.3.1 Existing Model Values

Methane emissions from vinasse is a relatively new source of emissions and it is only GREET 2016 that includes them in the pathway.

6.3.1.1 GREET

GREET added methane emissions from open channel distribution of vinasse to the GREET 2016 model (ANL, 2016). Mills that produce sugar and ethanol have different vinasse production rates from mills that produce only. The GREET developers have estimated that average vinasse production is 615 litres per tonne of sugar cane.

Based on measurements at one mill (Oliveira, 2015) values of 18 grams of methane and 0.006 g of N_2O per tonne of sugarcane are used in GREET.

6.3.1.2 GHGenius

Methane emissions are not included in GHGenius but the issue was flagged in the 2012 update of the sugarcane ethanol pathway. A number of papers were identified that have some estimates and a range of emissions between 10 and 100 g of methane per tonne of cane was suggested.

6.3.1.3 BioGrace

This source is not considered in BioGrace.

6.3.2 Literature Review

The search terms used were “methane emissions”, “vinasse”, and “sugarcane”. The top results since 2010 are shown in the appendix. There were relatively few papers identified.

6.3.2.1 Oliveira et al 2015. Greenhouse Gas Emissions from Sugarcane Vinasse Transportation by Open Channel: A Case Study in Brazil

This paper formed the basis of the GREET 2016 calculations, however the authors of the paper used a GWP for methane of 21 and the GREET team assumed that the methane GWP was 30 and thus the methane emissions are 50% higher than reported in GREET 2016. This also is just for the transportation and Oliveira also reported methane emissions after the product is applied to the field. The methane emission rate that Oliveira reports is 85 g CH_4/m^3 of vinasse. With 13 litres of vinasse produced per litre of ethanol produced and 80 litres of ethanol per tonne of cane. The methane emission rate is 90 g CH_4/tonne of cane at this mill. The GREET team discount this to account for the fact that not all vinasse is transported by open channel (only 63% in their calculation) and they use a lower production rate of vinasse that Oliveira assumes (60%). However, after making these adjustments, the emissions should be twice the value used in GREET. Oliveira calculates that these emissions increase the GHG emissions for ethanol production by 4.4%. In GREET 2016 they account for less than a 1% increase in emissions.

6.3.3 Data Sources

No sources of information other than the peer-reviewed literature were identified.

6.3.4 Trends

There is insufficient data available to identify any trends for this source of emissions.

6.3.5 Methane Findings

There has been additional research on methane emissions from sugarcane vinasse since the issue was first identified in the earlier CRC work. GREET 2016 has added this emission source to the sugarcane pathway. However the value used in GREET covers only a portion of the total methane sources and it appears that the information in the paper that was used for the data may have been misinterpreted as using GWP factors from the 5th Assessment report rather than the 3rd report that the original authors actually used.

6.4 CO-PRODUCTS

The primary co-product from sugar cane ethanol is electricity. Most mills combusted the bagasse (the cellulosic portion of the stalk after the sugar has been removed) to produce steam and electricity to operate the mill. In efficient mills there is more energy available from the bagasse than the mill needs. Historically, mills in Brazil were not allowed to sell excess power, however that has now changed and more mills are moving to increase power production to sell to the grid.

6.4.1 Existing Model Values

The excess electricity values and the credit provided from the three models are shown in the following table.

Table 1-95 Excess Power Quantity and Emission Credit

Model	Excess Power	GHG Credit
	kWh/tonne cane	Kg CO_2eq/mm BTU
GREET 2014	25	1,157
GREET 2015	25	1,160
GREET 2016	75	3,009
GHGenius	10.5	4,200
BioGrace	0.0	0

The latest version of GREET has increased the quantity of electricity that is exported from the mills. The reason for the changes and a reference for the value is not stated in the documentation for GREET 2016.

6.4.2 Literature Review

The literature was reviewed using the search terms “sugarcane ethanol” and “power production”. A number of papers were identified and some of them are summarized below.

6.4.2.1 Seabra and Macedo, 2010. Energy balance and GHG emissions in the production of organic sugar and ethanol at São Francisco Sugar Mill

This 2010 paper by Seabra and Macedo only has data for a single mill but it is a very detailed assessment of all of the inputs and outputs of this mill. The power production was 12 kWh/tonne of cane.

6.4.2.2 Rocha, M., Capaz, R., Lora, E., Nogueira, L., Leme, M., Renó, M., del Olmo, O 2014. Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis

This paper, while it purports to be a meta-analysis, is based on data from a single mill in the 2007/08 harvest year. The power production was 12 kWh/tonne of cane.

6.4.2.3 Flausinio et al., 2015. Potential of the Bagasse Sugarcane to Electric Power Generation

This 2015 paper by Flausinio et al calculated the maximum potential power exports for sugarcane mills in Brazil. They estimate this to be 177 kWh/tonne of cane process, significantly higher than the current values in the models.

6.4.3 Data Sources

There is some data available on the power production and exports in the Brazilian sugar industry and these are discussed below. The surplus power produced was one of the uncertainty issues identified for this pathway.

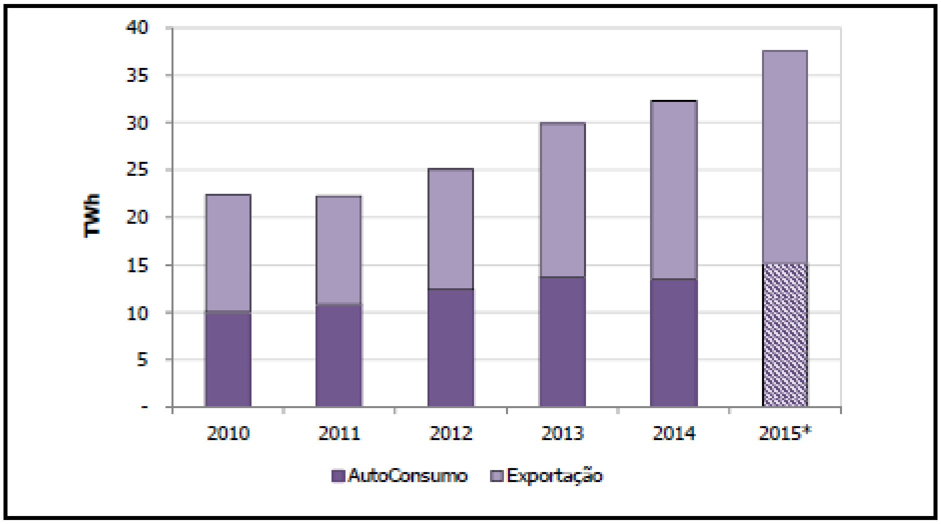
6.4.3.1 NovoCana

There is a private company, NovoCana, which provides benchmarking services for the sugarcane industry in Brazil. The power production in 2015 was reported to be 26.1 kWh/tonne or 1.16 kWh/gal of ethanol (Cavalett, 2016).

6.4.3.2 Ministry of Mines and Energy

The Brazilian Ministry of Mines and Energy published a report in Portuguese with data on electricity production from sugarcane mills (2016). The report states that of the 376 sugarcane biomass plants in operation in 2015, 40% exported energy to the grid. The quantity of electricity produced and exported to the grid has increased in recent years, as shown in the following figure from the report.

Figure 1-37 Electricity from Sugarcane mills



Combining this data with the quantity of sugarcane processed, it is estimated that 23 kWh/tonne of cane is produced and consumed by the mills and that 35 kWh/tonne of cane is exported. This is a little higher than the NovoCana estimate but the data does not differentiate between mills that just produce ethanol from mills that produce sugar or sugar and ethanol.

The ministry also publishes an annual report of electricity statistics. However, power produced from biomass also includes power from the pulp and paper sector.

6.4.4 Trends

The data from the Brazilian Ministry of Mines and Energy shows that power exports from sugarcane mills is increasing. This will reduce the carbon intensity of sugarcane ethanol in the future.

6.4.5 Co-product Findings

The quantity of electricity that is exported to the grid in Brazil from sugarcane processing facilities is increasing. A breakdown of power exports by the type of sugarcane mill was not identified but ethanol plants likely export between 25 and 35 kWh/tonne of cane (0.3 to 0.4

kWh/gal of ethanol). The value in GREET 2016 is much higher than the industry average value.

6.5 ADDITIONAL PARAMETERS

No additional significant parameters were found.

6.6 SUGAR CANE ETHANOL SUMMARY

Four sugar cane ethanol parameters were investigated, the N_2O emissions in the sugar cane production stage, the energy used for mechanical harvesting, methane emissions from vinasse distribution, and the quantity of co-product electricity produced. All four parameters were subjects of a literature search. In most cases the literature searches turned up limited real world information.

The N_2O emissions are a function of the quantity of N applied and the emission factor. There remains very little information available on N_2O emissions for Brazilian sugarcane, especially compared to crops such as corn and soybeans in other parts of the world. The information that is available would suggest that the synthetic N fertilizer rates in GREET (0.8 kg) and GHGenius (1.1 kg) are too low and should be increased to about 1.2 kg N/tonne of cane.

The data on N_2O emission factors is limited in the literature. GREET uses a factor that is less than the IPCC Tier 1 default values. Many of the papers did use the Tier 1 default values in their analyses. There were also a few papers that did attempt to measure the N_2O emissions and develop overall emission factors. The range for an overall N_2O emission factor would be from 1.22% (GREET) to 1.84% (Otto et al).

Industry average data for fuel use in the sugarcane production stage is not available in the public domain. This is not unusual, as other crops have the same issues. The available literature has a wide range from 2.2 to 3.7 l diesel/tonne of cane. The values that are used in the models are in the middle of the range.

There has been additional research on methane emissions from sugarcane vinasse since the issue was first identified in the earlier CRC work. GREET 2016 has added this emission source to the sugarcane pathway. However the value used in GREET covers only a portion of the total methane sources and it appears that the information in the paper that was used for the data may have been misinterpreted as using GWP factors from the 5th Assessment report rather than the 3rd report that the original authors actually used. Since not all mills transport the vinasse in open channels the range for this source should be from zero to 90 g CH_4/tonne of cane.

The quantity of electricity that is exported to the grid in Brazil from sugarcane processing facilities is increasing. In 2015 40% of the mills exported power. A breakdown of power exports by the type of sugarcane mill was not identified but ethanol plants likely export between 25 and 35 kWh/tonne of cane (0.3 to 0.4 kWh/gal of ethanol) on average. The value in GREET 2016 is much higher than the industry average value. The range of power exported to the grid is from zero to 177 kWh/tonne of cane. The industry average is likely about 30 kWh/tonne in 2015.

There is an underlying trend for more of the sugar cane to be harvested mechanically and without burning. This suggests that more nitrogen will be used and more diesel fuel will be used as the trend develops. There is also a trend to more electricity being exported from the mills to the grid. This trend increases the co-product credits for the process and will offset the trend to higher nitrogen and diesel fuel use.

7. Cellulosic Ethanol

Several large demonstration projects have become operational in the past several years but very little operating data has been released for these plants. In the United States there is a 20 million gal/year Poet/DSM plant in Emmetsburg, Iowa, a 25 million gal/year former Abengoa plant in Hugoton Kansas, and a 30 million gal/year DuPont plant in Nevada, Iowa. In Europe there is a 15 million gal/year Beta Renewables plant in Crescentino Italy, and in South America there is a 22 million gal/year GranBio in the State of Alagos, Brazil and a 10 million gal/year Raízen Energia Participacoes S/A plant in the State of San Paulo Brazil.

The overall process design can have an impact on the carbon intensity of the final product as well as specific aspects such as the co-product power produced, and the consumption of enzymes and other process chemicals. Unlike the other pathways, there is very little actual real world experience with these processes and what is available is treated as confidential business information.

7.1 Process Design

There are biochemical and thermochemical pathways for producing ethanol from cellulosic feedstocks. The available models all have biochemical pathways and all of the demonstration plants identified above are also biochemical pathways; however there are differences in the feedstocks and in the processes between the operating plants that can influence the emissions performance of the operations.

7.1.1 Existing Model Values

The existing approaches considered in the models are discussed below. This includes information on all of the key variables as well as overall design.

7.1.1.1 GREET

GREET models a corn stover to ethanol process via a biochemical process and a gasification process. The model inputs for the biochemical pathway in GREET are shown in the following table for different versions of GREET.

Table 1-96 GREET Corn Stover Ethanol Inputs

Parameter	GREET 2013	GREET 2014	GREET 2015	GREET 2016
Yield, gal/ton	80	80	80	85
Excess power production, kWh/gal	2.50	2.56	2.56	2.56
Cellulase (kg/gallon)	0.009	0.125	0.125	0.118
Yeast (kg/gallon)	0.002	0.031	0.031	0.029
Sulfuric acid (H_2SO_4, kg/gallon)	0.019	0.346	0.346	0.346
Ammonia (NH_3, kg/gallon)	0.011	0.042	0.042	0.042
Corn steep liquor (kg/gallon)		0.132	0.132	0.132
DAP (kg/gallon)		0.014	0.014	0.014
NaOH (kg/gallon)		0.118	0.118	0.118
CaO (kg/gallon)		0.076	0.076	0.076
Urea (kg/gallon)		0.021	0.021	0.021

The credit for the excess power in GREET can be calculated using the grid average (model default), a natural gas combined cycle (NGCC) plant, or a biomass integrated gasification combined cycle (IGCC) plant.

There was a large change in the GREET inputs for the 2014 model and since then only the yield changed in GREET 2016 but that impacted all of the chemicals. The data is described in the report by Dunn et al (2013). The values were derived from NREL process modelling.

The GHG emissions for the cellulosic ethanol pathway in the various GREET versions are shown in the following table. It is not clear why the 2015 model produced very different results considering that the inputs were basically the same as 2014.

Table 1-97 GREET Corn Stover Ethanol Inputs

Parameter	GREET 2013	GREET 2014	GREET 2015	GREET 2016
	kg CO_2eq/mm BTU			
Feedstock	17.4	15.4	5.0	15.6
Fuel Production	-4.3	-0.4	0.0	2.0
Total	13.1	15.0	5.0	17.7

7.1.1.2 GHGenius

GHGenius has an enzymatic cellulosic pathway that has default data from a US National Renewable Energy Laboratory report (NREL, 2011) that has detailed information on one variation of the biochemical process. The process is conceptually the same as modelled by GREET.

The ethanol yield is modelled as 329 litres/tonne (79 gal/ton) and the process produces surplus power of 0.50 kWh/litre (1.9 kWh/gal) for sale to the grid. It is assumed that this power displaces natural gas single cycle power. The model is capable of considering any mix of electric 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 1-98 Process Chemicals Biochemical Process

Input	Kg/litre ethanol	Kg/gal
Glucose	0.088	0.333
Caustic	0.082	0.310
Sulphuric acid	0.072	0.273
Corn steep liquor	0.048	0.182
Ammonia	0.043	0.163
Lime	0.033	0.125
Diammonium phosphate	0.005	0.019
Yeast	0.004	0.015
Host nutrients	0.002	0.008
Sorbitol	0.002	0.008
Sulphur dioxide	0.001	0.004
Boiler chemicals	0.000	0.000

The GHG emissions for this pathway are compared to the GREET 2016 values in the following table.

Table 1-99 GHGenius and GREET Corn Stover Ethanol Emissions

Parameter	GREET 2016	GHGenius 4.03a
	K22.8 kg CO2eq/mm BTU)g CO_2eq/mm BTU (LHV)	
Feedstock	15.6	11.7
Fuel Production	2.0	20.0
Total	17.7	31.7

7.1.1.3 BioGrace

There is no cellulosic ethanol pathway in BioGrace. There is a pathway in Version 4a of the JEC WTW study. The values are very similar to version 3 of the WTW study and are reported to be based on Iogen data from the early 2000s. The process achieves an ethanol yield of 237 litres/tonne and produces a small amount of surplus electricity 0.014 kWh/MJ of ethanol (1.0 kWh/gal).

The modelled process uses wheat straw as the feedstock and burns all of the lignin and unfermentables to produce the steam and power to drive the process.

The only process inputs that are modelled are the wheat straw, sulphuric acid and lime. The process results in a very low GHG emission rate of 9.2 g CO_2eq/MJ.

7.1.2 Literature Review

Several search terns were employed looking for new data on cellulosic ethanol (“cellulosic ethanol”, “enzyme consumption”, chemical consumption”, electricity production”). These were mostly looking for information for the following sections and not on the plant configuration. Both GREET and GHGenius utilize NREL techno economic assessments for cellulosic ethanol for the basic design process. A review of NREL publications did not identify any new detail techno economic analysis other than the ones already used in the models. There was one update paper discussed below.

7.1.2.1 2014. NREL 2012. Achievement of Ethanol Cost Targets: Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover

This 2014 report discussed progress that has been made in the development of the ethanol process. Some of the findings are shown in the following table.

Table 1-100 Biochemical State of the Art

Parameter	GREET 2016	2011 Design Case	State of the Art 2012
Yield, gal/ton	85	79	71
Excess power production, kWh/gal	2.56	1.84	2.64
Cellulase (kg/gallon)	0.118	-	-
Yeast (kg/gallon)	0.029	-	-
Sulfuric acid (H_2SO_4, kg/gallon)	0.346	0.271	0.344
Ammonia (NH_3, kg/gallon)	0.042	0.160	0.057
Corn steep liquor (kg/gallon)	0.132	0.181	0.157
DAP (kg/gallon)	0.014	0.019	0.016
NaOH (kg/gallon)	0.118	0.309	0.115
CaO (kg/gallon)	0.076	-	-
Urea (kg/gallon)	0.021	-	-

Other than the yield, the 2016 GREET values are quite close to the state of the art values. The GHGenius values are based on the 2011 design case.

7.1.2.2 McKechnie et al., 2015. Exploring impacts of process technology development and regional factors on life cycle greenhouse gas emissions of corn stover ethanol

This paper by McKechnie et al (2015) examined the impacts of regional factors affecting biomass and process input supply chains and ongoing technology development on the life cycle greenhouse gas emissions of ethanol production from corn stover in the U.S.

Biorefinery emissions based on the 2011 National Renewable Energy Laboratory (NREL) process model are the single greatest emissions source (18 gCO_2eq/MJ ethanol) and are approximately double those assessed for the 2002 NREL design model, due primarily to the inclusion of GHG-intensive inputs (caustic, ammonia, glucose). Energy demands of on-site enzyme production included in the 2011 design contribute to reducing the electricity co-product and associated emissions credit, which is also dependent on the GHG-intensity of regional electricity supply. Life cycle emissions vary between 1.5 and 22 gCO_2eq/MJ ethanol (2011 design) depending on production location (98% to 77% reduction vs. gasoline). The conclusions were that regional factors and on-going technology developments significantly influence these results.

7.1.3 Data Sources

Three of the plants, Poet, Abengoa, and GranBio applied for CARB LCFS pathways in 2014 and 2015. There are heavily redacted reports that are available for these pathways that do provide some forecast operational information.

7.1.3.1 Poet Project Liberty

The carbon intensity of the Poet Project Liberty plant was done with CA GREET 2.0 by Air Improvement Resource, Inc. and was calculated to be 18.64 g CO_2eq/MJ (19.7 kg CO_2eq/mm BTU) excluding denaturant.

This plant purchases electricity from the grid and anaerobically digests the unfermentable material to produce biogas for the adjacent corn ethanol plant. The plant also burns biomass and some natural gas from the grid to produce steam and exportable steam to the corn plant. The process concept is quite different from that modelled in most LCA models but it does still result in low GHG emissions. The emissions are summarized in the following table.

Table 1-101 Poet-DSM GHG Emissions

	GREET2016	Poet-DSM
	kg CO_2eq/mm BTU	
Feedstock	15.6	20.5
Process chemicals	14.5	16.0
NG	-	5.2
Purchased power	-	78.8
Other	3.6	10.2
Co-product (displacement)	-16.1	-111.1
Total	17.7	19.7

There was no change in the CI when the pathway was recertified in 2016.

7.1.3.2 Abengoa

Abengoa registered both corn stover and wheat straw as feedstocks for ethanol production. The report is heavily redacted but the fermentation residuals are combusted to produce steam and electricity and a portion of the electricity is exported to the grid. Biogas from the wastewater treatment plant is also produced and combusted for steam and power. The GHG emissions for the corn stover feedstocks are shown in the following table and compared to the GREET values.

Table 1-102 Abengoa GHG Emissions

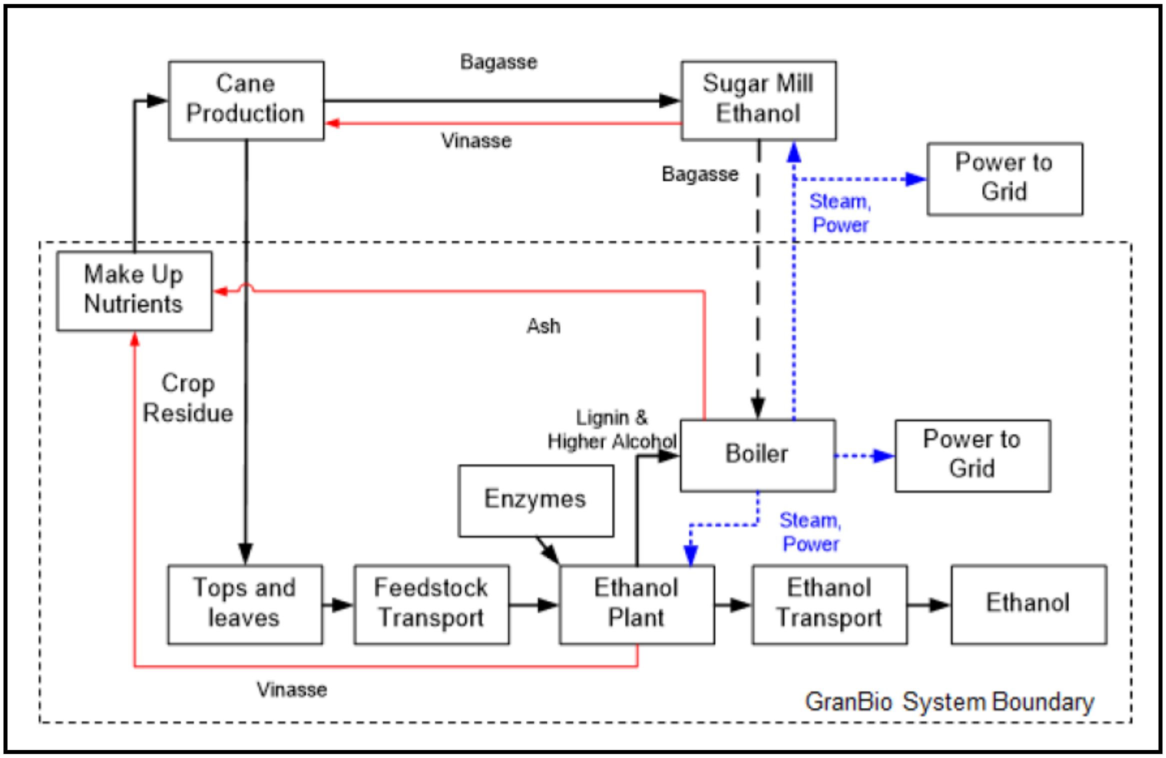
	GREET2016	Abengoa
	kg CO_2eq/mm BTU	
Feedstock	15.6	19.4
Process chemicals	14.5	23.3
Other	3.6	8.2
Co-product (displacement)	-16.1	-24.4
Total	17.7	28.4

There was an increase in the CI of 3.5 grams/mm BTU when the pathway was recertified in 2016, due to the change in the displaced power from marginal to average.

7.1.3.3 GranBio

The GranBio plant uses the Beta Renewable process and utilizes sugar cane straw as the feedstock. The CARB application was prepared by Life Cycle Associates (2014). Ethanol is produced via hydrolysis and subsequent fermentation. The lignin by-product is combusted on-site along with additional bagasse from the neighboring sugar refinery to provide all of the steam and electricity needs of both the BioFlex cellulosic ethanol plant and the 1G ethanol/sugar refinery. Excess power is exported to the local electricity grid. The system boundary is shown below.

Figure 1-38 GranBio System Boundary



The modelling was done with the original CA GREET. Most of the process information was redacted but the excess power was reported as 2.98 kWh/gal from both bagasse and lignin combustion. The emissions are summarized in the following table. The ethanol transportation emissions have been excluded.

Table 1-103 GranBio GHG Emissions

	GREET2016	GranBio
	kg CO_2eq/mm BTU	
Feedstock	15.6	7.5
Process chemicals	14.5	15.8
Other	3.6	1.9
Co-product (displacement)	-16.1	-22.2
Total	17.7	3.0

In the LCFS recertification process, the carbon intensity was increased from 6.98 to 33.82 g CO_2/MJ ethanol delivered to California. The recertification process changed the treatment of exported power from a credit from the marginal source of power to the average source of power.

7.1.4 Trends

There is insufficient information available to establish any trends in the design of cellulosic ethanol plants. These plants are still first-of-kind plants that are experiencing normal development issues. Issues are being addressed as they arise but this means that the development is a slow process. With the possible exception of the Italian plant, none of the facilities have achieved normal commercial operations.

It would appear that the actual plant performance might not be as good as the models predict. That should not be a surprise given that the models are built around an assumed n^{th} plant and the real world plants are first-of-kind and dealing with development issues. Even the recertified plants may be modelled based on the design parameters and not the actual performance, which has been limited.

7.1.5 Process Design Findings

The available information on the emissions for three of the plants that have registered in California is summarized in the following table.

Table 1-104 Comparison of GHG Emissions for CARB Registered Plants

Stage	Poet-DSM	Abengoa	GranBio
	g CO_2eq/MJ		
Feedstock	20.5	19.4	7.5
Process Chemicals	16.0	23.3	15.8
Other	94.2	8.2	1.9
Co-products	-111.1	-24.4	-22.2
Total	19.7	28.4	3.0

Some of the differences can be attributed to the different feedstocks used but there are still some obvious differences in the approach taken by the different process developers. Some of this may be due to minimizing risk with the first demo plants but it is more likely that an optimized configuration has not yet been selected by the process developers.

7.2 Power Production

Exported power is a significant contributor to the carbon intensity of cellulosic ethanol. Forecasting power consumption from process models is always a challenge since the power consumption is influenced by actual plant layout, piping sizes, and the level of “over building” included in the final physical plant. It is likely that process designs will underestimate the final power consumption.

7.2.1 Literature Review

The search terms “cellulosic ethanol” and “electricity production” returned 1440 papers published since 2010. The top 20 are shown in the Appendix. Substituting consumption for production reduced the number of papers to 522. None of the papers have any real world data in them.

7.2.2 Power Production Findings

The only real world information that is available is the Poet CARB application. This plant purchased power from the grid and the CI assigned to power production suggests that the power use is 7.1 kWh/gal of ethanol. This is a very high value, much higher than the NREL design of 2011, which has power use of 3.9 kWh/gal.

Electric power production and consumption remains a significant component of the CI of cellulosic ethanol. GREET and GHGenius allow the user to adjust this value but it is too early to have confidence that the current default values in the model are representative of real world operations.

7.3 Enzyme and Chemical Consumption

Enzyme and chemical use addition to GREET were responsible for the large increase in emissions between GREET 2013 and later models.

7.3.1 Literature Review

The search terms used were “cellulosic ethanol” and either “enzyme consumption” or chemical consumption”. No real world data that would be useful for modelling was found.

7.3.2 Enzyme and Chemical Use Findings

The data from the two corn stover plants has significantly higher emissions associated with chemicals and other inputs than does the GREET model. The sugarcane straw plant has emissions that were about the same as the GREET model.

7.4 Additional Parameters

No additional parameters were identified that would improve the modelling of cellulosic pathways at this time. The GREET and GHGenius models have adequately detailed inputs that will allow for accurate modelling of the carbon intensity of the ethanol produced. The GREET model is much improved in this aspect compared to GREET 2013.

The challenge for this pathway remains the availability of real world data that is reflective of actual plant operations.

7.5 Cellulosic Ethanol Summary

The modelling of the cellulosic ethanol pathway in GREET 2014 onward is much more comprehensive than it was in GREET 2013. However, the default values used in GREET, GHGenius, and BioGrace continue to have a high degree of uncertainty.

The recent peer reviewed literature does not contain any information from the few operating demonstration plants, as the process developers consider this kind of information confidential.

The CARB applications that have been submitted for three of the operating demonstration plants are heavily redacted but they do indicate that different process philosophies are being used by different developers. There is an order of magnitude difference in the overall CI for the three applications. The limited information that can be discerned from the applications confirms that the chemical usage and the electric power production are parameters that are variable and have a significant impact on the results. It is not possible to confidently predict a range of values for these two sets of parameters.

There is no information available in the literature that would allow any potential future trends for the important parameters to be developed.

8. MONTE CARLO AND SENSITIVITY ANALYSES

A Monte Carlo analysis has been undertaken using the range of values identified in the report. This has been done using each of the models for the six pathways that exist in the models.

An effort has also been made to harmonize the input parameters for each of the pathways. GHGenius is run for the United States. BioGrace has the power emissions set to USA Power using the BioGrace standard values. BioGrace is also set up to use the IPCC N_2O emission calculation that is an option for that model. Finally the 40% extra energy used in the BioGrace default values is removed when the input parameters are changed. All models use the 100 year GWPs from the IPCC 4th Assessment Report.

In some cases, further harmonization has been done for input values that are very different in the models, such as some transportation distances and co-product treatment. However, there are some limitations on what can be simply done with the models where harmonization is not feasible, such as the use of energy allocation for co-products in the BioGrace model.

A Monte Carlo tool was developed to be able to be used with GREET and BioGrace. It is similar to the tool built in to GHGenius. It allows any input variable to be randomly changes according to a prescribed probability distribution function. The tool can monitor up to 10 outputs cells in the models. For this work 10,000 iterations were run for each case.

The Monte Carlo analysis was only undertaken for the well to wheel portion of the fuel pathway, with the one exception of the natural gas pathway, where the uncertainty related to the relative efficiency of the natural gas engine to the diesel engine was also considered.

Where possible, the probability distribution functions chosen for the pathways and the parameters that define the probability distribution function have been selected to match the available empirical data. In cases where there was a lack of empirical data defining the range was available, some judgement was employed to arrive at reasonable estimates.

In addition, the sensitivity of the emissions to the uncertain parameters has been investigated looking at each of the parameters individually using the GREET model.

8.1 CORN ETHANOL

The corn ethanol work investigated three parameters, the N_2O emission factors, the thermal energy requirement for the plant, and the treatment of co-products. For the N_2O emissions and the energy use, data was available that showed a range of results for specific regions and specific plants and a distribution of the results was also available.

The first two values (N_2O and thermal energy) can be harmonized between the models, but due to the structures of the models, it is not possible to align the co-product treatments in the three models. BioGrace is built with only energy allocation possible. GREET has many more options for modelling the emissions displaced from the co-products than GHGenius does.

The energy use, N_2O emission factor, and in the case of GREET, a co-product variable used for the base case and the probability function employed are summarized in the following table. The natural gas values are all equivalent in the units used in each model. The standard deviation values chosen for the Monte Carlo analysis give a range of results that are similar to those of the actual datasets.

Table 1-105 Corn Ethanol Variables

Parameter	GREET	GHGenius	BioGrace
Natural gas	23,900 BTU/gal (LHV)	7.38 MJ/litres (HHV)	0.308 MJ/MJ ethanol
Distribution	Normal	Normal	Normal
Std Dev	3,000	0.93	0.038
N_2O EF_1	0.0125	0.0125	0.0125
Distribution	Lognormal	Lognormal	Lognormal
Std Dev	0.0015	0.0015	0.0015
% DDG to beef	40%	-	-
Distribution	Normal	-	-
Std Dev	5%	-	-

8.1.1 GREET

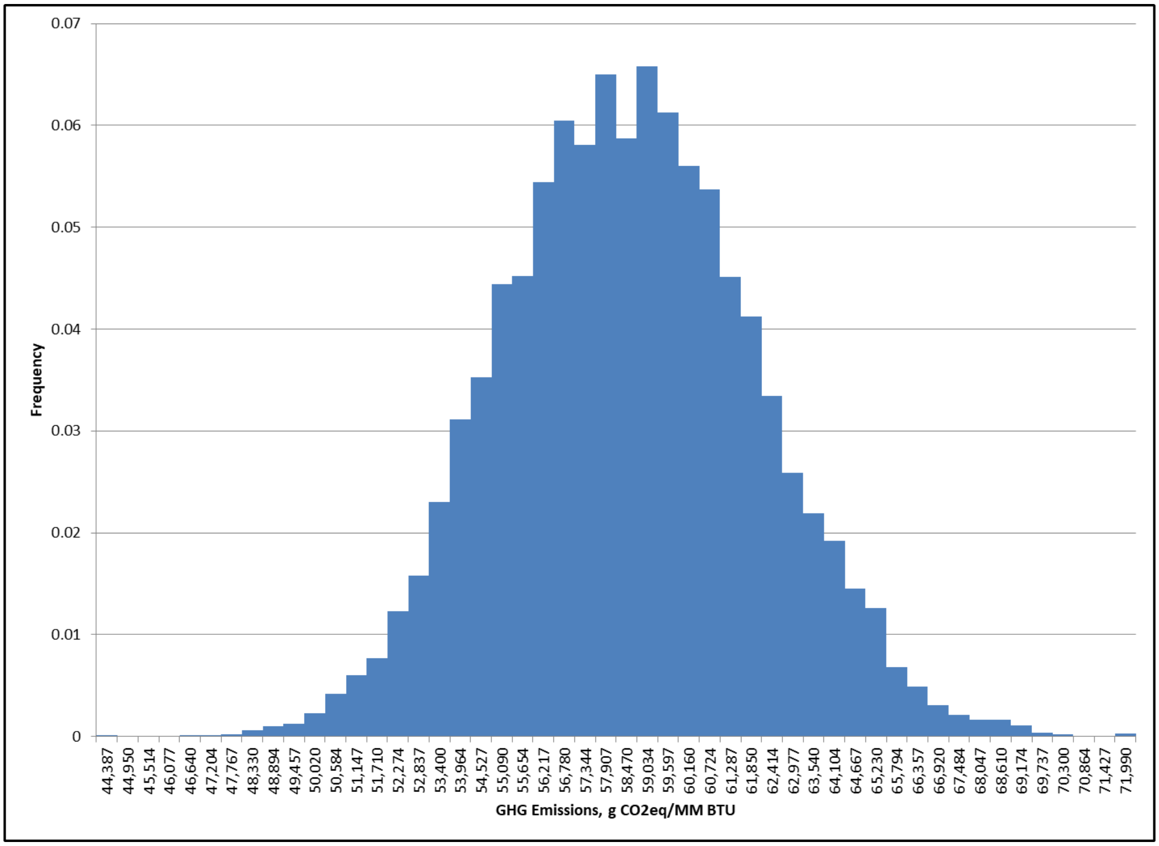
GREET1 2016 has been modified with the input values shown in the previous table. The same N_2O EF1 is applied to the crop residue as to the synthetic fertilizer and this value is separated from the total emission factor in GREET so that the impact of just EF1 can be evaluated. The same value for EF1 is used for soybeans as is used for corn as the soybean emissions influence the corn ethanol co-product credit. The base values with these changes are shown in the following table.

Table 1-106 GREET1 2016 Corn Ethanol Base Case

Stage	kg CO_2eq/MM BTU	g CO_2eq/MJ
Feedstock	25.9	24.5
Fuel production	32.8	31.1
Total	58.7	55.6

The Monte Carlo results are shown in the following figure.

Figure 1-39 GREET Corn Ethanol Monte Carlo Results



The mean result was 58,825 CO_2eq/MM BTU (55.8 g CO_2eq/MJ), with a standard deviation of 3,446 g CO_2eq/MM BTU (3.3 g CO_2eq/MJ). The skewness is 0.12, indicating that the results are not quite a normal distribution. The excess kurtosis is -0.05, again indicating a small deviation from a normal distribution.

Looking at the two components, the standard deviation for the corn cultivation was 1,354 g CO_2eq/MM BTU (1.3 g CO_2eq/MJ), and the standard deviation for ethanol production was 3,193 g CO_2eq/MMBTU (3.0 g CO_2eq/MJ).

8.1.2 GHGenius

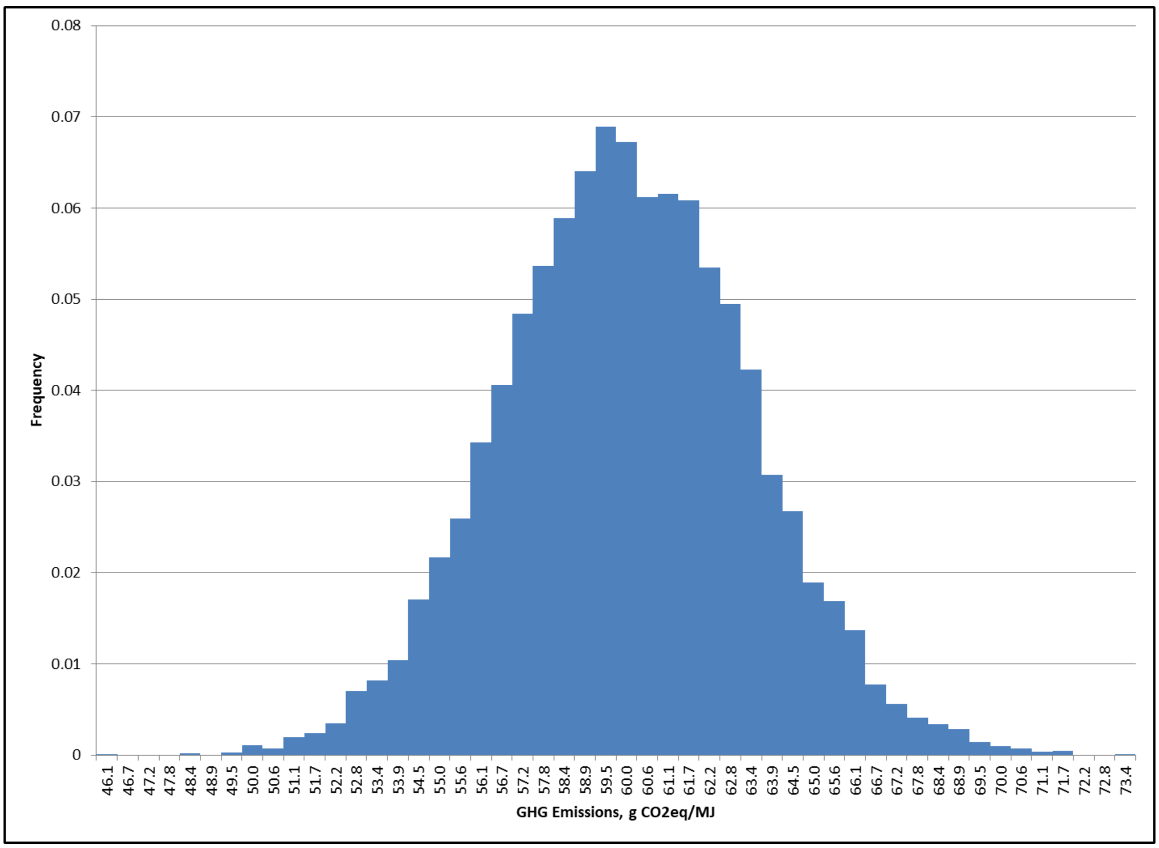
GHGenius 4.03a was set up using the parameters in Table 8-1. The model doesn't have the same flexibility in modelling the co-products as GREET so there was no co-product parameter modelled in the Monte Carlo analysis. The emissions for the base case are shown in the following table.

Table 1-107 GHGenius Corn Ethanol Base Case

Stage	GHG Emissions
	g CO_2eq/MJ (LHV)
Fuel dispensing	0.6
Fuel distribution and storage	1.0
Fuel production	38.2
Feedstock transmission	1.7
Feedstock recovery	6.8
Feedstock Upgrading	0
Land-use changes, cultivation	20.4
Fertilizer manufacture	9.0
Gas leaks and flares	0
CO_2, H_2S removed from NG	0
Emissions displaced	-17.4
Total	60.4

The distribution of the Monte Carlo results is shown in the following figure.

Figure 1-40 GHGenius Monte Carlo Results



The mean result was 60.4 g CO_2eq/MJ, with a standard deviation of 3.3 g CO_2eq/MJ. The skewness is 0.06, indicating that the results are not quite a normal distribution. The excess kurtosis is 0.08, again indicating a small deviation from a normal distribution.

Looking at the two components, the standard deviation for the corn cultivation was 2.0 g CO_2eq/MJ, and the standard deviation for ethanol production was 2.9 g CO_2eq/MJ.

8.1.3 BioGrace

A number of changes were made to the BioGrace model in order to run the Monte Carlo simulations and make the results more comparable to the other models. The first was that the GWPs were set to the 2007 values from the 4th Assessment Report; the second was that the electric power for ethanol production was set to use the standard value for the USA (648 g CO_2eq/kWh). The third was that the N_2O default value for corn production was changed to use the IPCC methodology, as that is included in the model as an option. The final change was to purchase power (0.68 kWh/gal) from the grid rather than use the co-generation option.

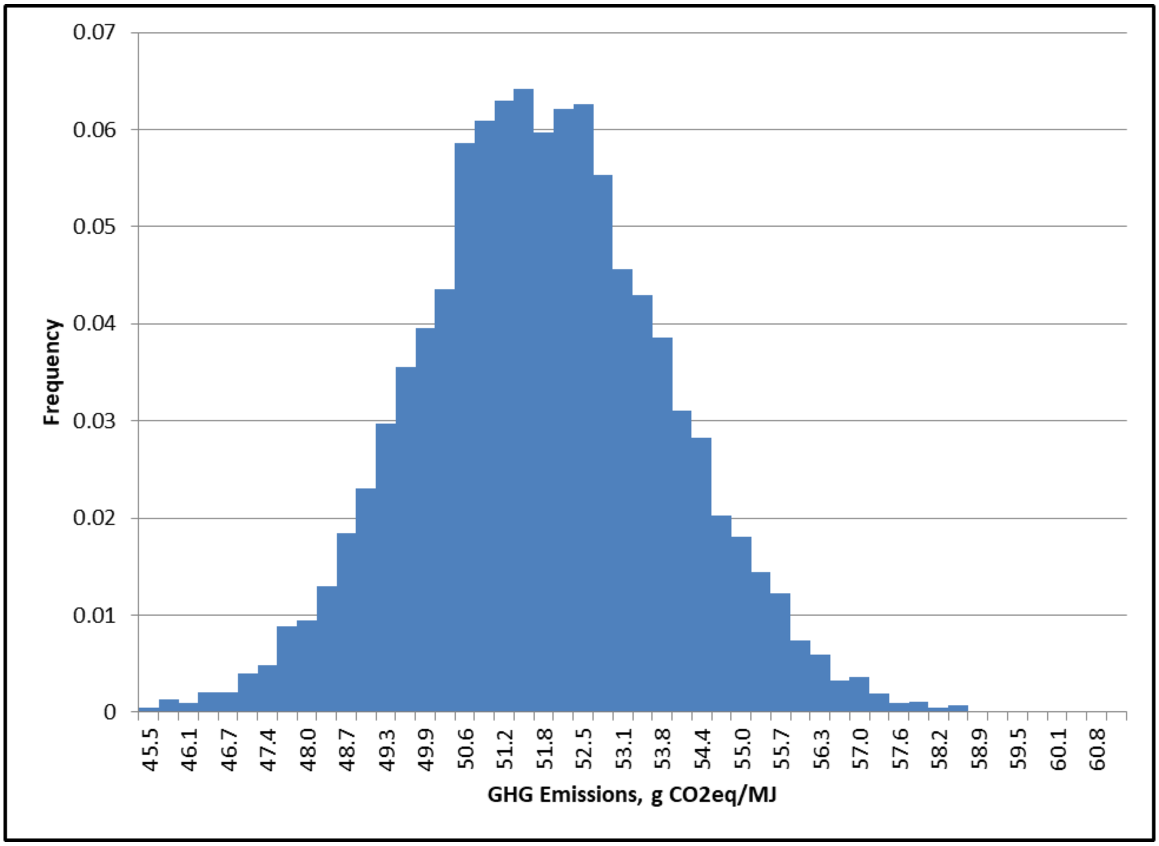
The base case emissions are shown in the following table. The RED default value is 43 g CO_2eq/MJ. One of the primary reasons that the BioGrace emissions shown here are higher than the RED default value is that we have used a significantly higher N_2O emission rate (the RED default value is based in an EF1 of about 0.32%). One of the reasons that the emissions are lower than the GREET and GHGenius results is that the energy allocation method used in BioGrace provides a larger credit for the DDGS than the displacement method does.

Table 1-108 BioGrace Corn Ethanol Base Case

Stage	Un-allocated	Allocated
	g CO_2eq/MJ (LHV)	
Corn Cultivation	49.10	32.58
Ethanol plant	26.36	17.49
Transport of corn	0.51	0.34
Transport of ethanol to depot	0.60	0.60
Transport to filling station	0.94	0.94
Total	77.5	51.9

The Monte Carlo tool was run for 10,000 iterations. The distribution of the allocated emissions is shown in the following figure.

Figure 1-41 BioGrace Monte Carlo Results



The mean result was 52.3 g CO_2eq/MJ, with a standard deviation of 2.0 g CO_2eq/MJ. The skewness is 0.09, indicating that the results are not quite a normal distribution. The excess kurtosis is 0.07, again indicating a small deviation from a normal distribution.

Looking at the two components, the standard deviation for the corn cultivation was 1.3 g CO_2eq/MJ, and the standard deviation for ethanol production was 1.6 g CO_2eq/MJ.

8.1.4 Model Comparison

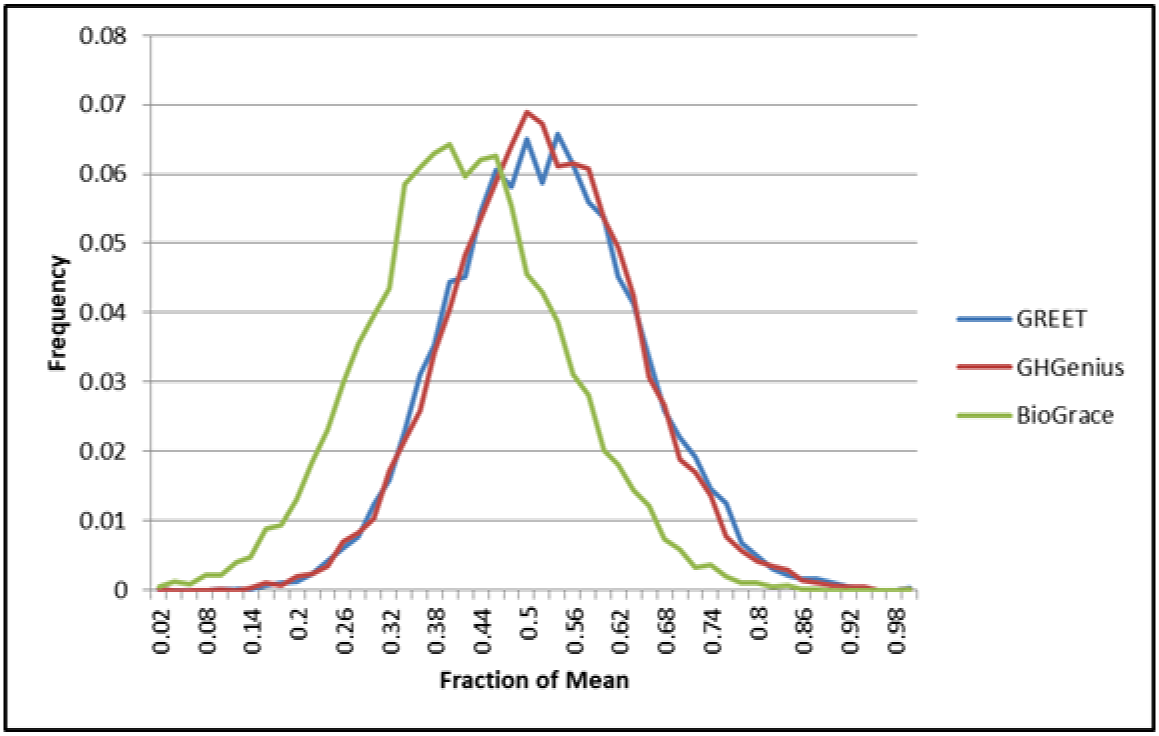
The mean results from the three models are compared in the following table. The BioGrace values used energy allocation so the emissions are not directly comparable to the other two models. From the other two models it is known than energy allocation increases the co-product credit and reduces the lifecycle emissions. The dispensing emissions are not shown for GHGenius to align the system boundaries with GREET.

Table 1-109 Comparison of Models

	GREET	GHGenius	BioGrace
	g CO_2eq/MJ		
Feedstock	24.5	29.6	32.6
Ethanol	31.1	30.3	19.3
Total	55.6	59.9	51.9

The distribution of the results from the three models is shown in the following figure. The results have been normalized with the horizontal axis related to the range rather than the actual values returned by the models.

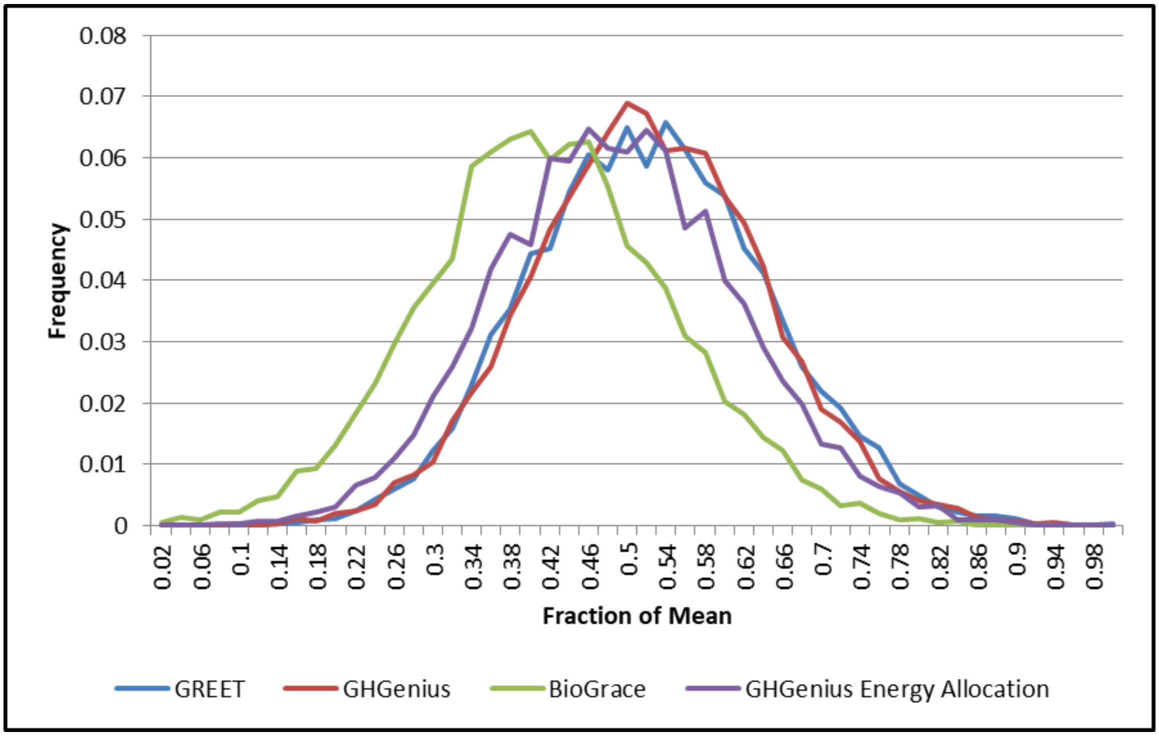
Figure 1-42 Comparison of Monte Carlo Results - Corn Ethanol



The GREET and GHGenius models produce very similar Monte Carlo results. This would indicate that the impact of the percentage of beef cattle in the use of the DDGS has a small impact on the results. The BioGrace values are different and are more lognormal in distribution. The feedstock emissions in BioGrace are larger than the ethanol plant emissions (the model has high crop residue quantities and therefore high N_2O emissions) so the total should be more influenced by the feedstock emissions, which in turn are driven by the lognormal probability distribution function for the N_2O emissions.

GHGenius was run using energy allocation for the co-product and there was no significant difference in the distribution of the results compared to the displacement approach results as shown below. Thus the different allocation in BioGrace is not likely the cause of the different distribution.

Figure 1-43 Monte Carlo Comparison Including GHGenius Energy Allocation

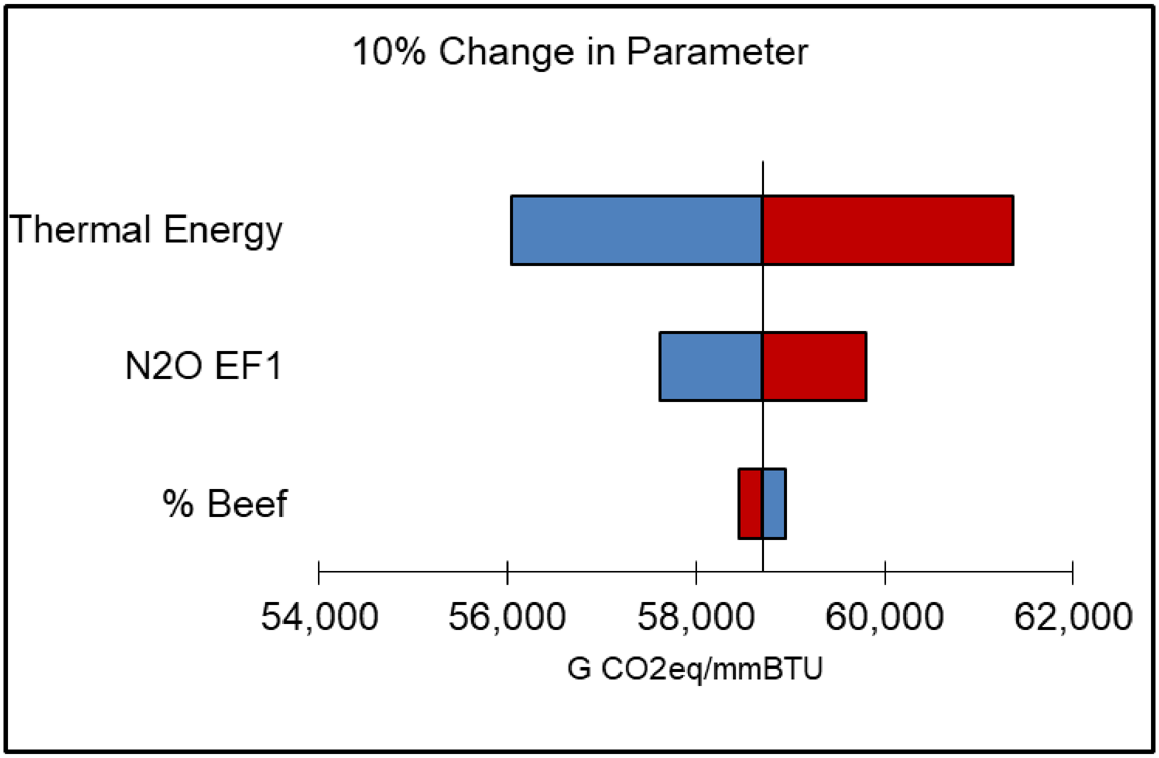


The previous work (E-102) also found slightly higher feedstock emissions in GHGenius than in GREET. GHGenius 4.03a includes some soil carbon loss due to cultivation and this value is zero in GREET. Setting the soil carbon change to zero in GHGenius results in GHG emissions of 54.0 g CO_2eq/MJ, slightly lower than the emissions in GREET.

8.1.5 Sensitivity Analysis

Looking at the three investigated parameters separately produces the information in the following figure. In each case the base parameter was increased and decreased by 10%. The most sensitive parameter is the plant energy use, followed by the N_2O emission factor for corn production and then the % of DDG consumed by beef (note that more beef reduces the GHG emissions). This figure was generated with the GREET model.

Figure 1-44 Corn Ethanol Sensitivity



While there is plant to plant variability in energy use, the average value is derived from about half of the operating plants in the US and there is little uncertainty in the average value.

8.2 PETROLEUM FUELS

This work investigated four parameters in the lifecycle of petroleum fuels, the energy use in crude oil production and refining, and the methane emissions from crude oil production and refining. These are the parameters identified in the literature review. The variables used for the Monte Carlo analyses are shown in the following table. The standard deviations used to define the distributions are estimates since there are no available data sets that provide guidance. The GHGenius parameters are equivalent to the GREET values. There is no petroleum fuel pathway in BioGrace.

Table 1-110 Petroleum Fuel Variables

Parameter	GREET	GHGenius
Crude Oil Energy Recovery	2.0%	2.0%
Distribution	Lognormal	Lognormal
Std Dev	0.5%	0.5%
Oil Recovery Methane	155 g CH_4/MMBTU	1.02 kg CH_4/tonne
Distribution	Lognormal	Normal
Std Dev	25 g CH_4/MMBTU	0.16
Refining Efficiency	88.6%	88.6
Distribution	Normal	Normal
Std Dev	1%	1%
Refinery Methane	0.33 g CH_4/MMBTU	0.01 kg CH_4/kl
Distribution	Normal	Normal
Std Dev	0.10 g CH_4/MMBTU	0.003 kg CH_4/kl

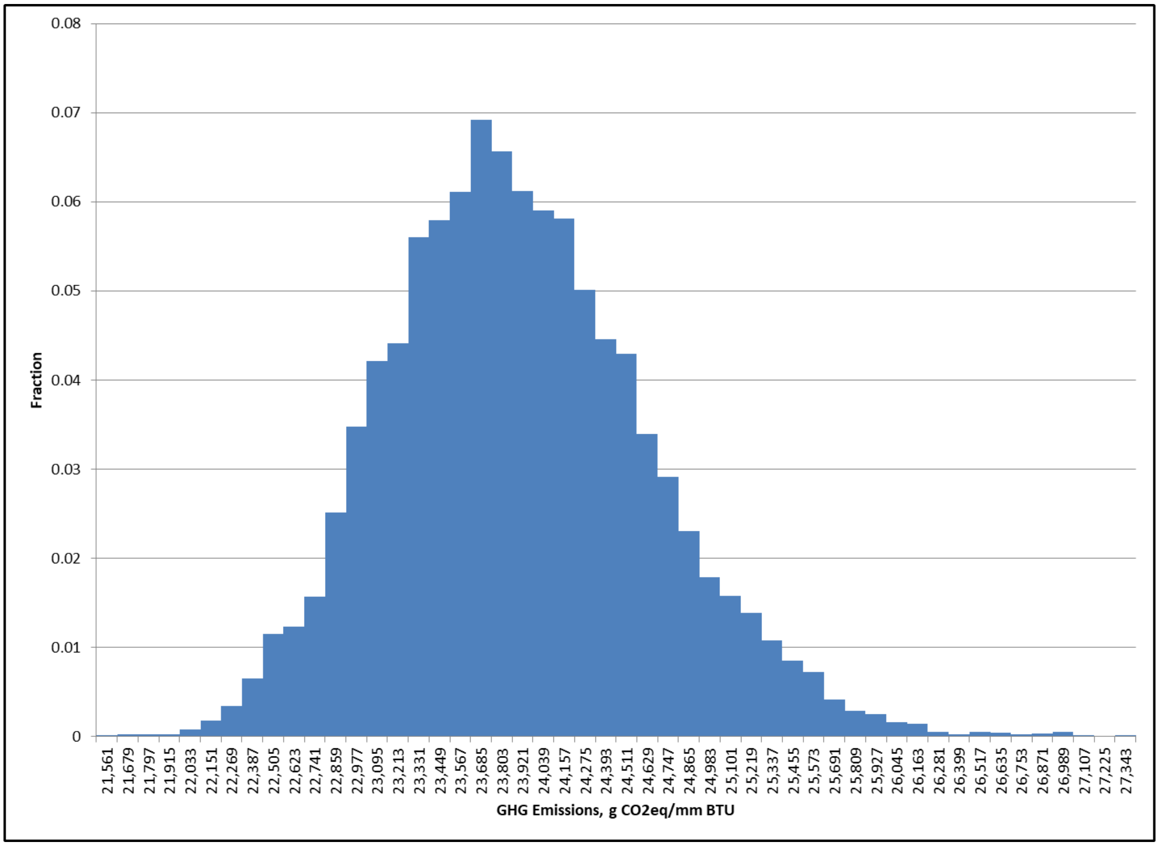
8.2.1 GREET

The crude oil pathway in GREET has three streams, conventional oil (~70%), shale oil (17%) and oil sands derived crudes (13%). The calculation approach for each category is different. The energy use in conventional oil is the most uncertain, the same value of 2% energy use has been used in GREET for decades. This parameter is used for the Monte Carlo work and the energy used in the other 30% of the production is not changed. Similarly the methane emissions from crude oil production are only varied for the conventional oil production.

The gasoline refinery efficiency value is considered. GREET has no fugitive methane emissions from the refinery. This work identified a small emission rate from the US National Inventory. The gasoline parameters apply to all of the production, not just the conventional oil production.

The Monte Carlo Results are shown in the following figure. The mean value is 23,933 g CO_2eq/mm BTU (22.6 g CO_2eq/MJ). This is only 5 g higher than the GREET value and indicates that the methane emissions in the refinery have a very small impact on the lifecycle emissions. The standard deviation of the analysis was 737 g CO_2eq/mm BTU. The skewness was 0.4 and the excess kurtosis was 0.3, indicating a close to normal type distribution of the results.

Figure 1-45 GREET Petroleum Monte Carlo Results

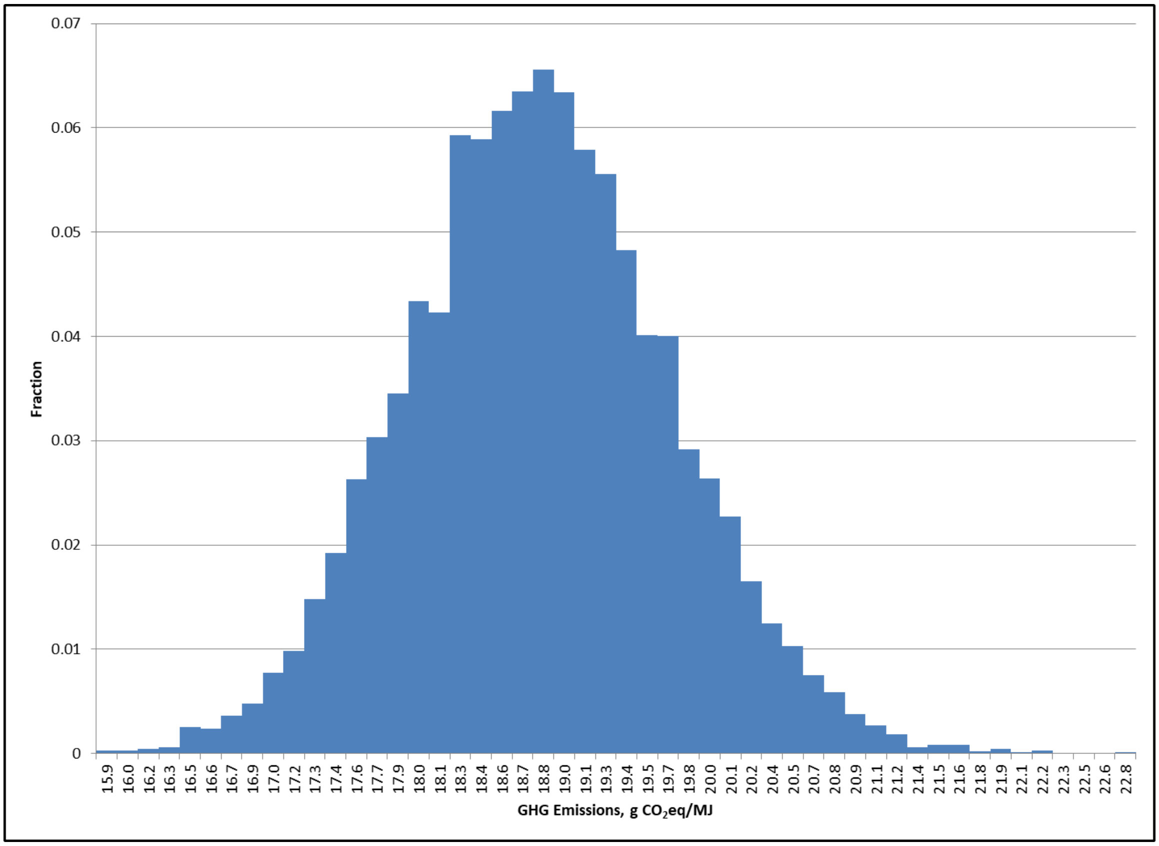


8.2.2 GHGenius

GHGenius was set up using the parameters in Table 8-6. There were no changes to the Canadian oil sands production parameters but US shale oil is not segregated in GHGenius the way that it is in GREET so the modelled parameters apply to a larger percentage of total oil production compared to GREET. The changes made to GHGenius for oil production to align with GREET result in lower GHG emissions. For the refining emissions the energy efficiency is almost identical in the two models.

The mean value from GHGenius was 18.9 g CO_2eq/MJ (LHV) and the standard deviation was 0.9 g CO_2eq/MJ (LHV). The skewness was 0.1 and the excess kurtosis was 0.1, indicating very close to a normal distribution of the results.

Figure 1-46 GHGenius Monte Carlo Results - Gasoline



8.2.3 Model Comparison

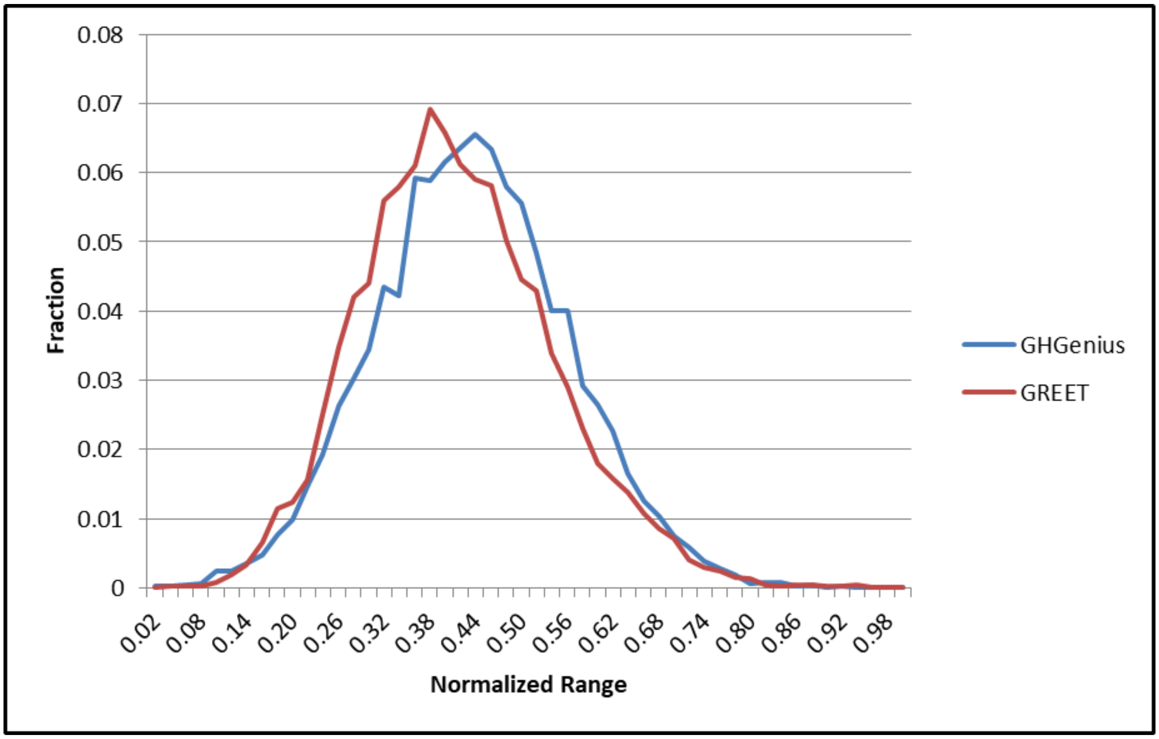
The mean results from the two models are compared in the following table. This comparison is not between the default values in GHGenius but rather GHGenius using the four GREET equivalent inputs. The default value for US gasoline in GHGenius is 27.3 g CO_2eq/MJ.

Table 1-111 Comparison of Models - Gasoline

	GREET	GHGenius
	g CO_2eq/MJ	
Feedstock	9.5	7.9
Fuel	13.1	11.5
Total	22.6	18.9

The two models respond similarly to the variables and return very similar normalized distributions as shown in the following figure.

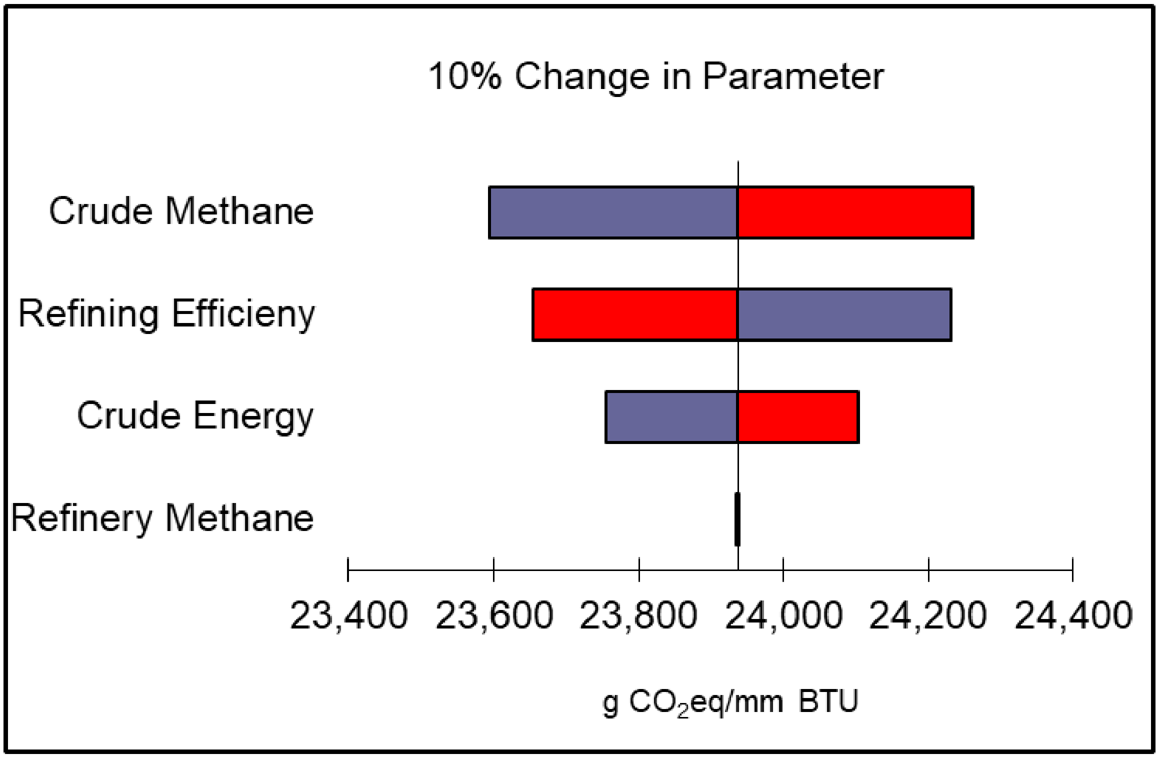
Figure 1-47 GREET and GHGenius Monte Carlo Comparison



8.2.4 Sensitivity Analysis

Looking at the four investigated parameters separately produces the information in the following figure. In each case the base parameter was increased and decreased by 10%. This figure was generated with the GREET model.

Figure 1-48 Sensitivity Gasoline GHG Emissions - GREET



8.3 NATURAL GAS

The literature review focussed on three parameters, the fugitive emissions in the production of natural gas, the energy used in the compression of the gas to CNG, and the efficiency of the gas engines.

GREET and GHGenius have similar data in the models for the US natural gas system. There is significant variability in the supply chain. The impact on three aspects is evaluated, the methane leakage from gas processing, the efficiency of CNG compressors, and the relative energy use of HD vehicles due to different load cycles. The GREET parameters are shown in the following table along with the equivalent parameters in GHGenius.

Table 1-112 Compressed Natural Gas Variables

Parameter	GREET	GHGenius
Methane Leakage from Production	134.9 g CH_4/mm BTU	0.6%
Distribution	Lognormal	Lognormal
Std Dev	25	0.1%
Compression Efficiency	97.9%	0.021 J/J
Distribution	Normal	Normal
Std Dev	0.3%	0.003 J/J
HD Relative energy use	0.90	0.87
Distribution	Normal	Normal
Std Dev	0.03	0.03

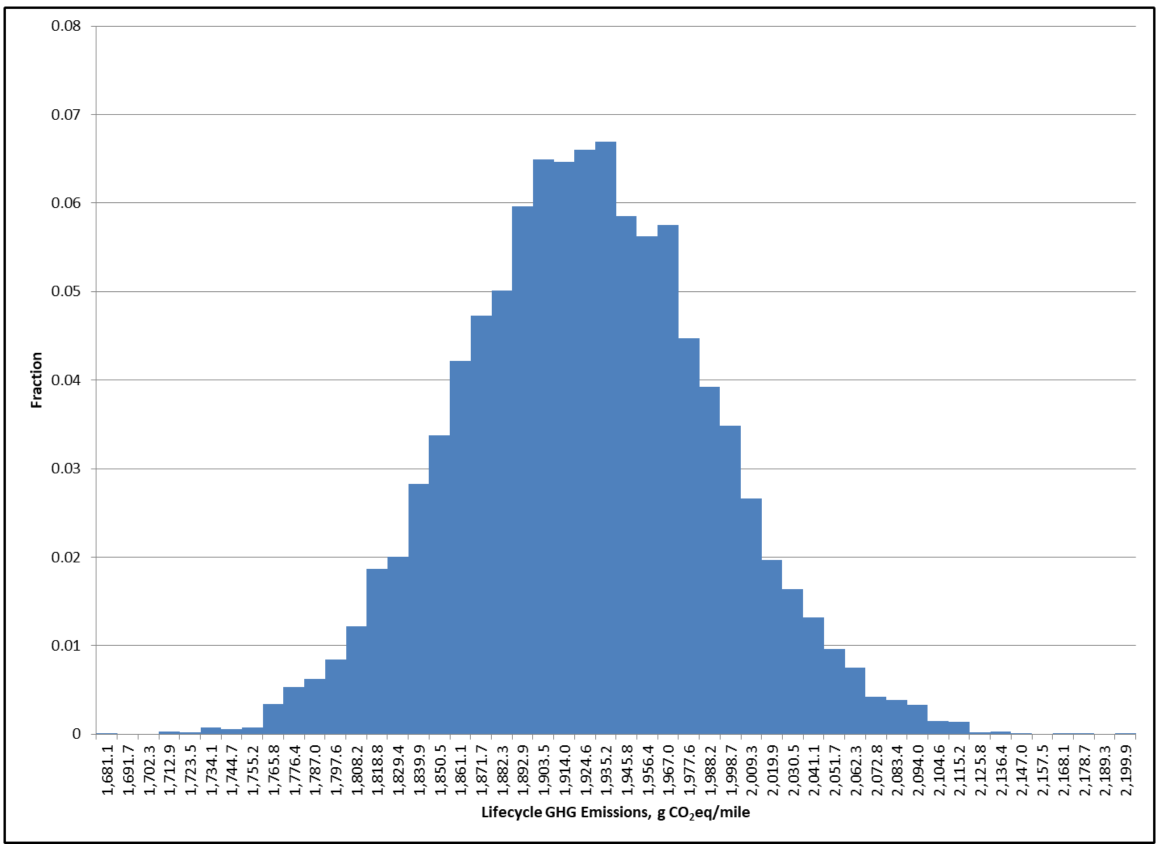
A lognormal distribution was used for methane leakage as it is know that there are some ‘high emitters” which contribute a significant portion of the total emissions. Less data is available on the compression efficiency and the engine relative energy use so these parameters are estimated.

8.3.1 GREET

The GREET model was run using the parameters in the previous table. The full lifecycle emissions (production and combustion) for the Combination Long-Haul Vans were one of the outputs. The diesel equivalent vehicle has emissions of 2,085 g CO_2eq/mile. The mean value for the natural gas Monte Carlo analysis for the natural gas vehicle as 1,930 g CO_2eq/mile, a 7.4% reduction. The standard deviation was 64 g CO_2eq/mile.

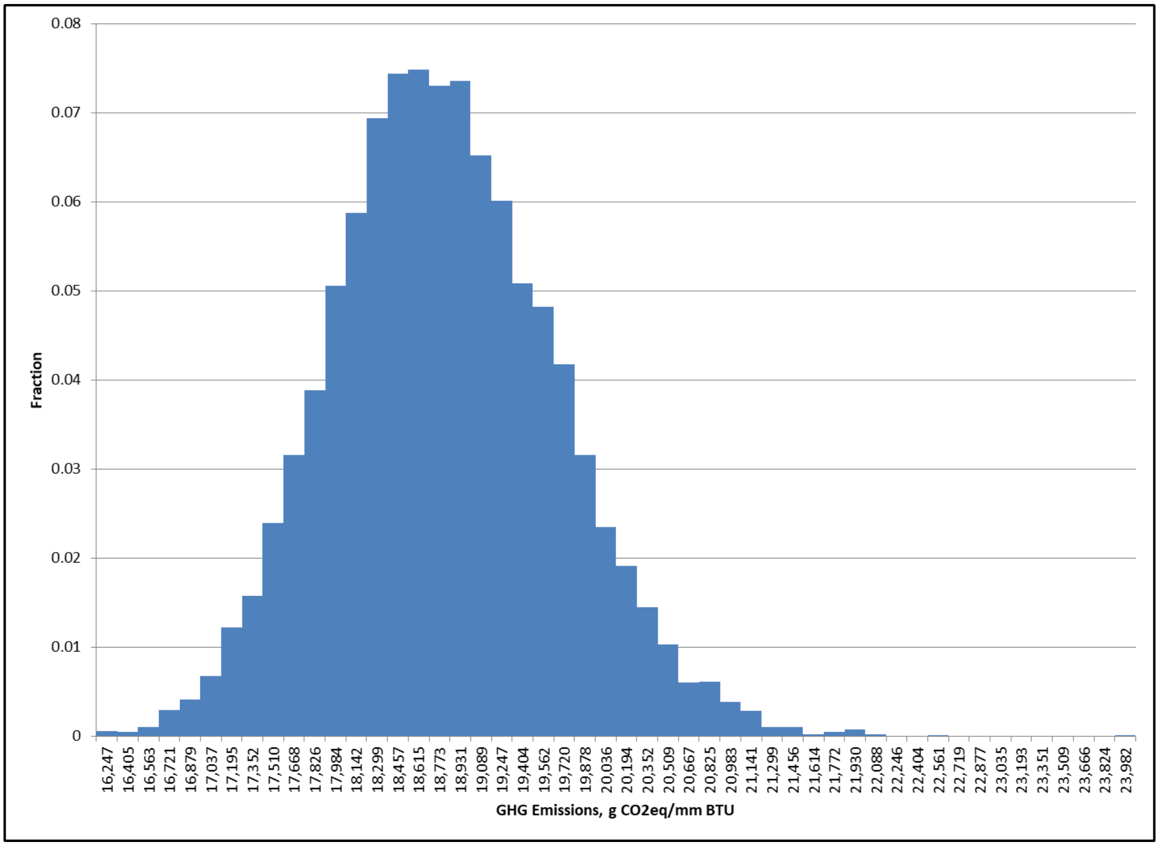
The results are shown in the following figure. The emissions are almost always below the diesel vehicle emissions. The standard deviation is 64 g CO_2eq/mile. The skewness is 0.1 and excess kurtosis is 0.0, indicating close to a normal distribution.

Figure 1-49 GREET Natural Gas Monte Carlo Lifecycle Results



Looking at just the CNG production emissions with the two variables of methane emissions and compression energy the results are shown in the following figure. The mean result is 18,885 g CO_2eq/mm BTU with a skewness of 0.3 and an excess kurtosis of 0.2, indicating less of a normal distribution than the full lifecycle emissions.

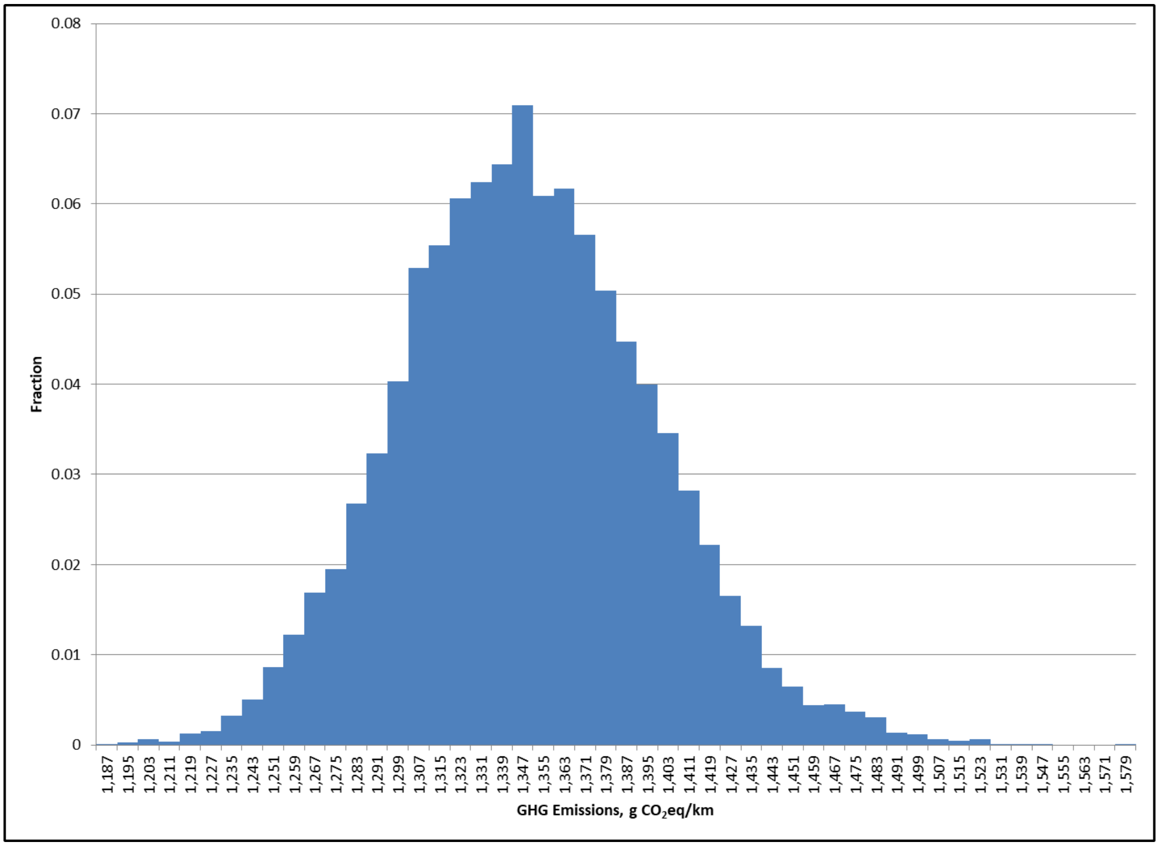
Figure 1-50 GREET CNG Production Monte Carlo Results



8.3.2 GHGenius

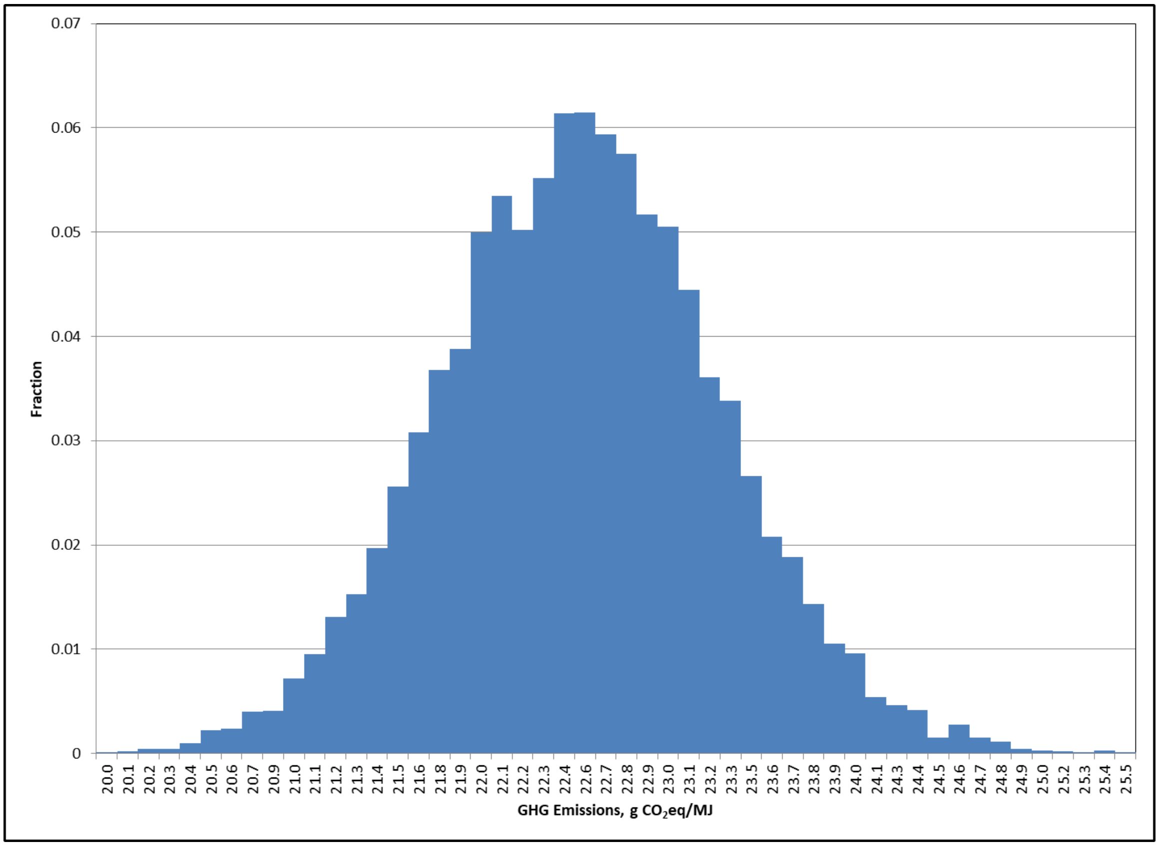
GHGenius was set up using the equivalent parameters used in GREET as shown in Table 8-8. The heavy duty vehicle fuel consumption was not changed. The full lifecycle emissions (production and combustion) for the heavy duty vehicles were one of the outputs. The mean value for the natural gas Monte Carlo analysis for the natural gas vehicle as 1,353 g CO_2eq/km. The standard deviation was 49 g CO_2eq/km. This was an 8.3% reduction in GHG emissions compared to diesel fuel compared to the 7.4% reduction that GREET returned. The distribution of the results is shown in the following figure.

Figure 1-51 GHGenius Natural Gas Monte Carlo Lifecycle Results



Looking at just the CNG production emissions with the two variables of methane emissions and compression energy the results are shown in the following figure. The mean result is 22.6 g CO_2eq/MJ with a skewness of 0.1 and an excess kurtosis of 0.1, indicating close to a normal distribution than the full lifecycle emissions. GHGenius includes some fugitive emissions for the dispensing station, a source that is not included in GREET. Higher fugitive emissions in the distribution and dispensing of the natural gas are the primary driver of the difference in the model results.

Figure 1-52 GHGenius CNG Production Monte Carlo Results



8.3.1 Model Comparison

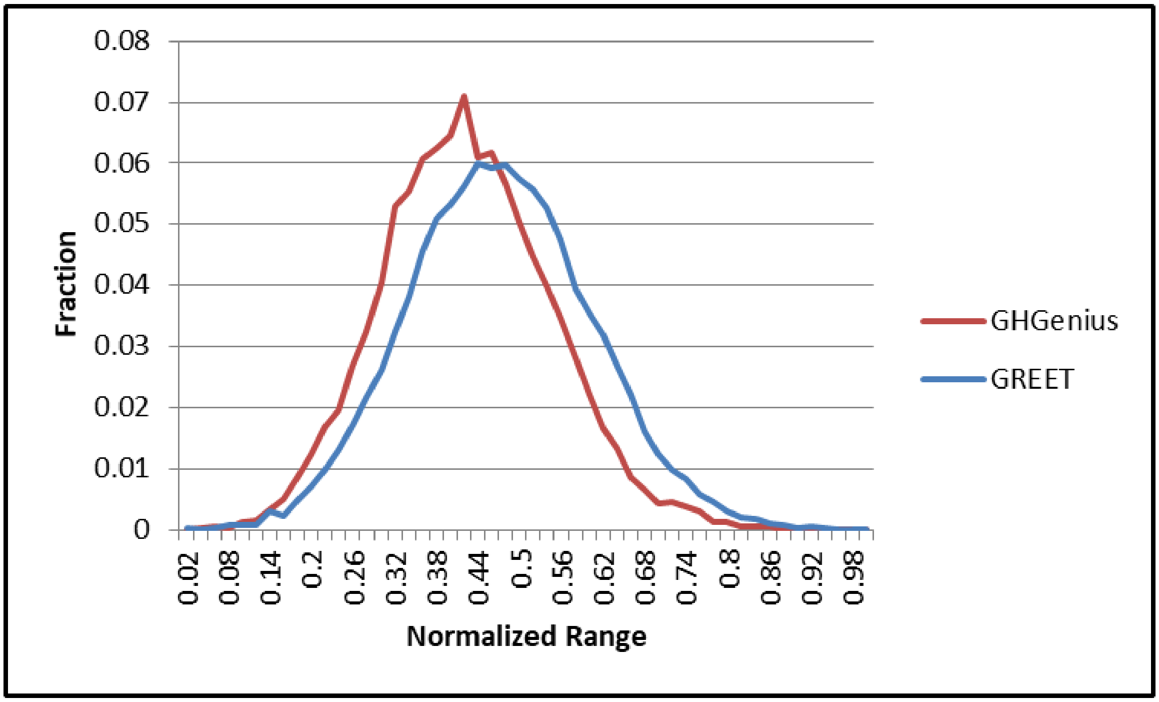
The mean results from the two models are compared in the following table. The distribution of the emissions between feed and fuel may not be the same in the two models.

Table 1-113 Comparison of Models - Gasoline

	GREET	GHGenius
	g CO_2eq/MJ	
Feedstock	14.7	21.6
Fuel	3.2	1.3
Total	17.9	22.6

The distribution of the results from the two models for the full lifecycle emissions are shown in the following figure. Both models return similar distributions for the results.

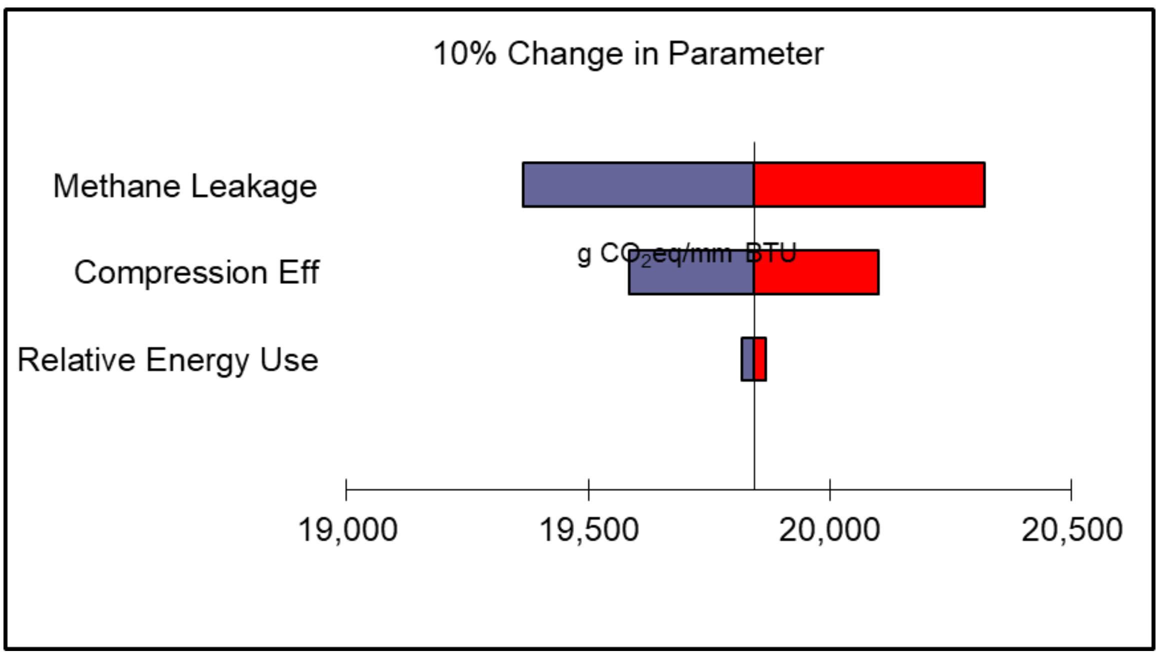
Figure 1-53 Comparison of Distribution of NG Lifecycle Emissions



8.3.2 Sensitivity Analysis

Looking at the four investigated parameters separately produces the information in the following figure. In each case the base parameter was increased and decreased by 10%. This figure was generated with the GREET model. The methane leakage has the greatest impact.

Figure 1-54 Sensitivity CNG GHG Emissions - GREET



8.4 SOYBEAN BIODIESEL

The soybean biodiesel work investigated four parameters, the N_2O emission factors, the thermal energy requirements for farming, soybean crushing, and biodiesel production. All four values can be harmonized between the three models, but due to the structures of the models, it is not possible to align the co-product treatments in the three models. BioGrace is built with only energy allocation possible. GREET and GHGenius use mass, energy and displacement allocation.

The four parameters for the Monte Carlo analysis used for the base case and the probability function employed are summarized in the following table. The soybean crushing and biodiesel production input values are equivalent in the units used in each model.

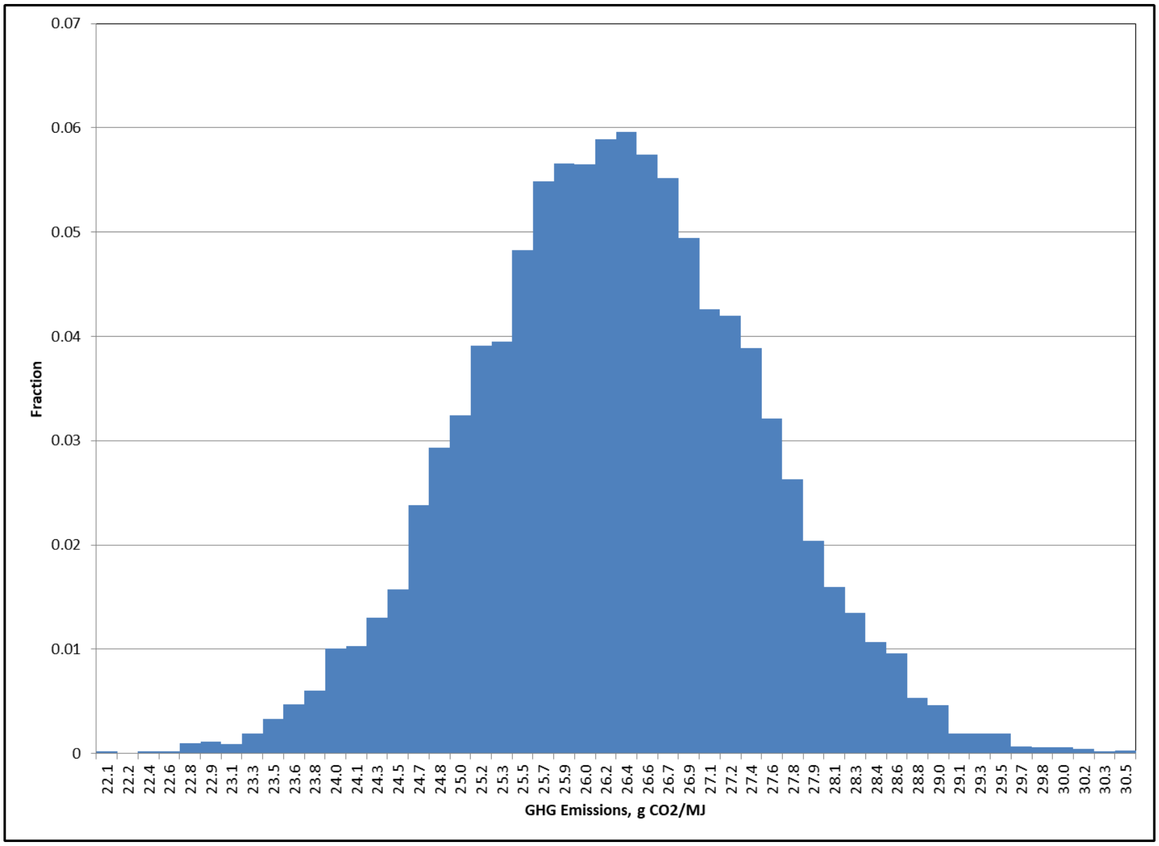
Table 1-114 Soybean Biodiesel Variables

Parameter	GREET	GHGenius	BioGrace
N_2O EF_1	0.0125	0.0125	0.0125
Distribution	Lognormal	Lognormal	Lognormal
Std Dev	0.0015	0.0015	0.0015
Farm Energy	19,443 BTU/bu	1,520 MJ/ha	2,100 MJ/ha
Distribution	Normal	Normal	Normal
Std Dev	2,560 BTU/bu	200 MJ/ha	300 MJ/ha
Soybean Crushing	3,687 BTU/lb Oil	152 l NG (HHV)/l oil	0.20 MJ/MJ oil
Distribution	Normal	Normal	Normal
Std Dev	460 BTU/lb oil	19 l NG (HHV)/l oil	0.025 MJ/MJ oil
BD Production	1,213 BTU/lb BD	20 l NG (HHV)/l BD	0.023 MJ/MJ BD
Distribution	Normal	Normal	Normal
Std Dev	160 BTU/lb BD	2.6 l NG (HHV)/l BD	0.003 MJ/MJ BD

8.4.1 GREET

The GREET default values are used with the exception of the N_2O emission factor. The mean emissions are 26.4 g CO_2eq/MJ. The distribution of the results of the 10,000 iterations is shown in the following figure.

Figure 1-55 GREET Soybean BD Monte Carlo Results

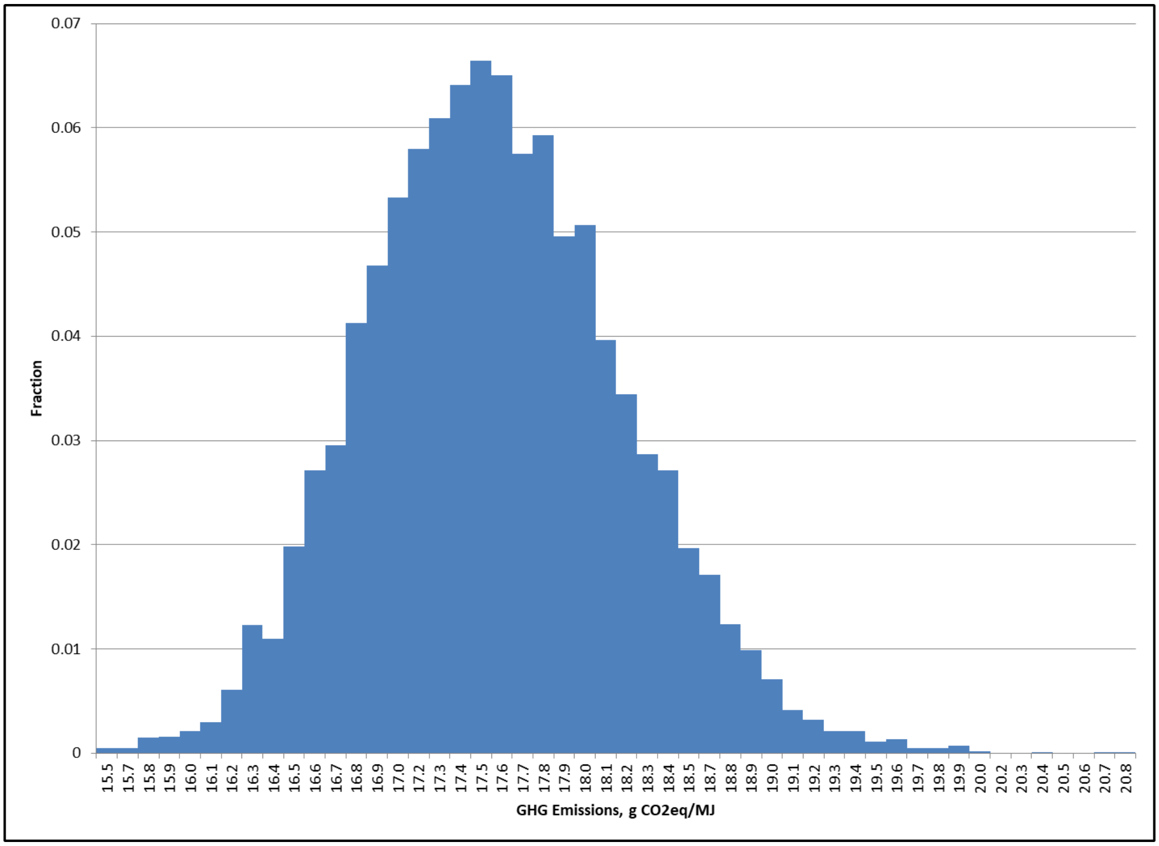


The mean result was 26.4 g CO_2eq/MJ, with a standard deviation of 1.2 g CO_2eq/MJ. The skewness is 0.0, indicating that the results are a normal distribution. The excess kurtosis is 0.0, again indicating a normal distribution.

8.4.2 GHGenius

GHGenius has been set up using the inputs in Table 8-7. In addition energy allocation is applied to the glycerine co-product in addition to mass allocation for the soybean crushing. This aligns the options with GREET. The mean emissions are 17.9 g CO_2eq/MJ. The distribution of the results of the 10,000 iterations is shown in the following figure.

Figure 1-56 GHGenius Soybean BD Monte Carlo Results



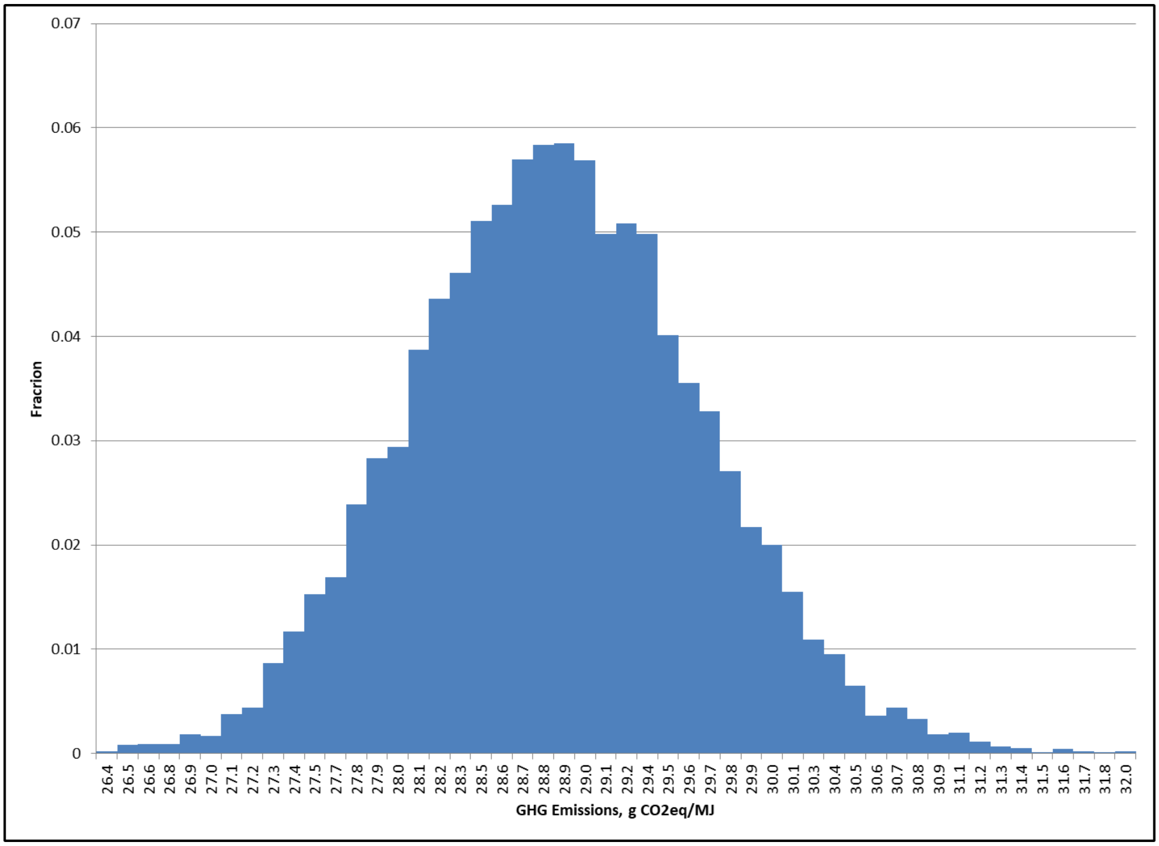
The mean result was 17.6 g CO_2eq/MJ, with a standard deviation of 0.7 g CO_2eq/MJ. The skewness is 0.3, indicating that the results are not quite a normal distribution. The excess kurtosis is 0.2, again indicating a very small deviation from a normal distribution.

8.4.3 BioGrace

In addition to the input values identified in Table 8-7, the BioGrace model was set up so that soybeans were trucked 50 km to the crushing facility, which is adjacent to the biodiesel plant. This is a similar scenario to that used in GREET and GHGenius. The 40% excess chemical usage was also removed from the model so that the underlying inputs were used directly.

The BioGrace Monte Carlo results are shown in the following figure. The RED default value is 58 g CO_2eq/MJ, whereas the inputs used here produce a result of 28.9 g CO_2eq/MJ.

Figure 1-57 BioGrace Soybean Biodiesel Monte Carlo Results



The mean result was 28.9 g CO_2eq/MJ, with a standard deviation of 0.8 g CO_2eq/MJ. The skewness is 0.14, indicating that the results are not quite a normal distribution. The excess kurtosis is 0.02, again indicating a very small deviation from a normal distribution.

8.4.4 Model Comparison

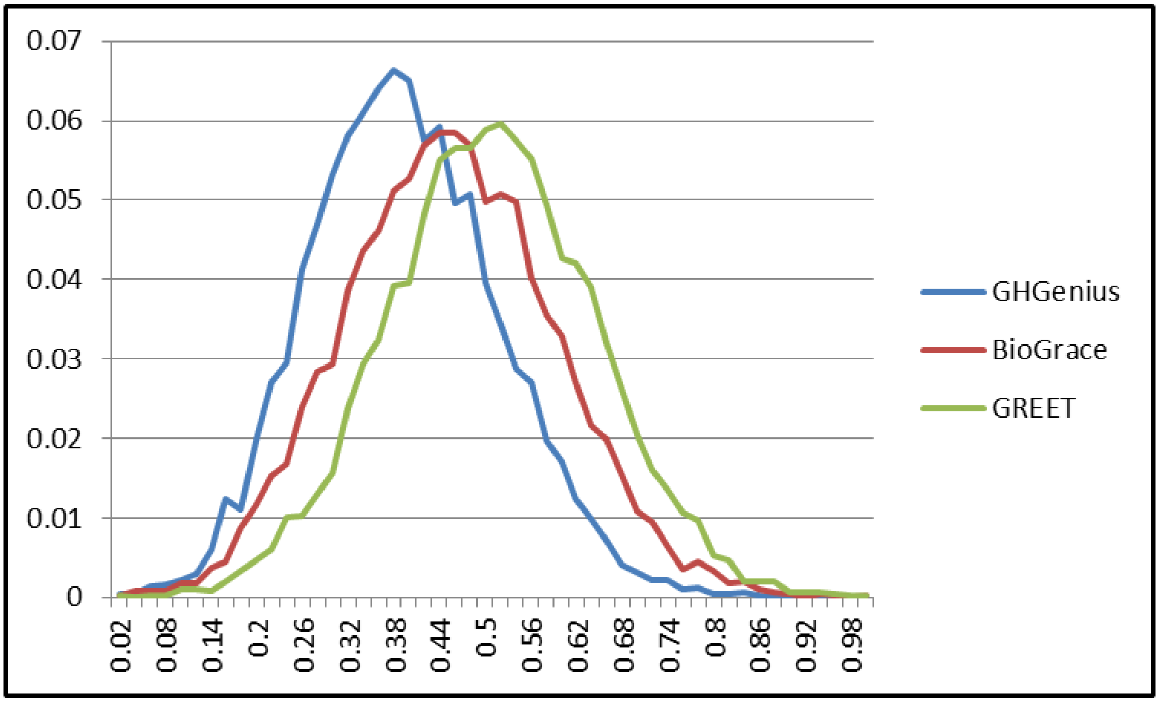
The mean results from the three models are compared in the following table. The BioGrace values used energy allocation so the emissions are not directly comparable. From the other two models it is known than energy allocation increases the co-product credit and reduces the lifecycle emissions.

Table 1-115 Comparison of Models

	GREET	GHGenius	BioGrace
	g CO_2eq/MJ		
Feedstock	11.2	6.4	12.3
Fuel	15.2	11.2	15.1
Total	26.4	17.6	28.9

One of the drivers of the difference between GREET and GHGenius is the treatment of the carbon in the co-products. The system inputs include biogenic carbon from the feedstock and fossil carbon from the methanol. The fossil carbon ends up in the biodiesel but the biogenic carbon is in the glycerine co-product. Energy allocation does not differentiate between the biogenic and fossil carbon. GREET includes the fossil carbon in the biodiesel emissions and GHGenius deals with it as part of the co-product emissions, as displacement is the primary allocation approach used in GHGenius. The fossil carbon accounts for ~5 g CO2eq/MJ, if these emissions were included in biodiesel production then the GHGenius and GREET results are much closer.

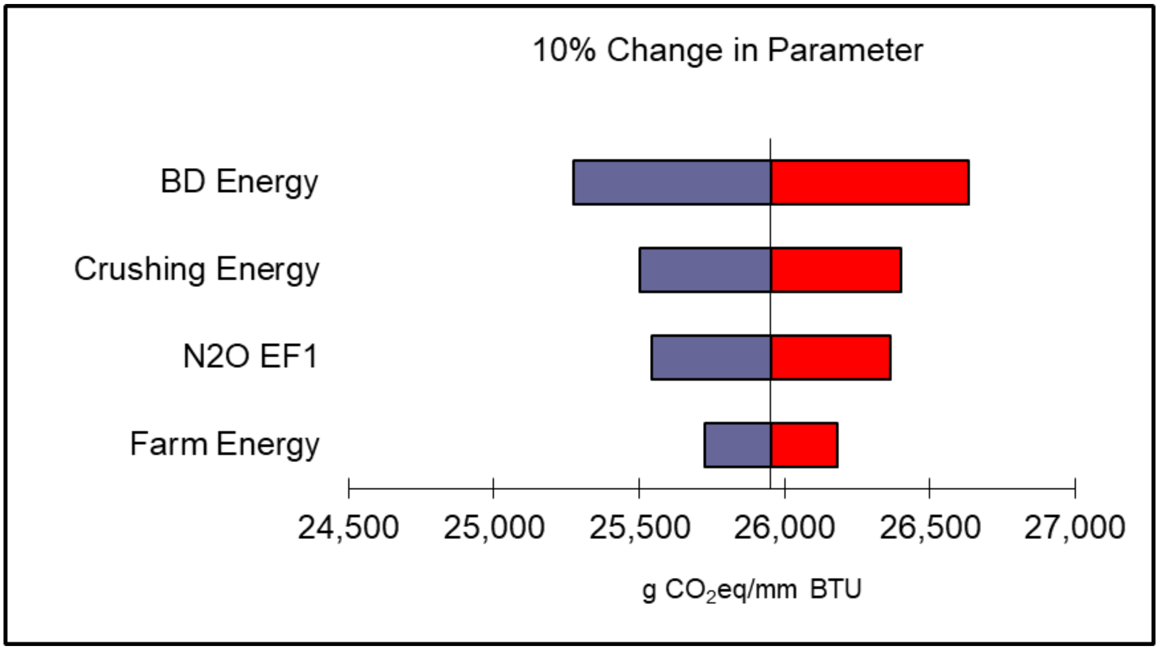
Figure 1-58 Comparison of Monte Carlo Results - Soybean Biodiesel



8.4.5 Sensitivity

The GREET model for soybean biodiesel is used to investigate the sensitivity of the results to the four parameters reviewed in the literature survey and the Monte Carlo analysis. In each case the base value in the GREET model is increased and decreased by 10%. The results are shown in the following figure. The biodiesel plant energy has the greatest impact and the farm energy has the lowest impact.

Figure 1-59 Sensitivity Analysis Soybean Biodiesel



8.5 SOYBEAN RENEWABLE DIESEL

Only GREET and GHGenius have a soybean oil renewable diesel pathway. There is very little real world data on the energy requirements of the renewable diesel production process. The Monte Carlo analysis will be undertaken with the same parameters as used for biodiesel, except that the hydrogen requirements will be varied in place of the energy use in the biodiesel process. The parameters are shown in the following table.

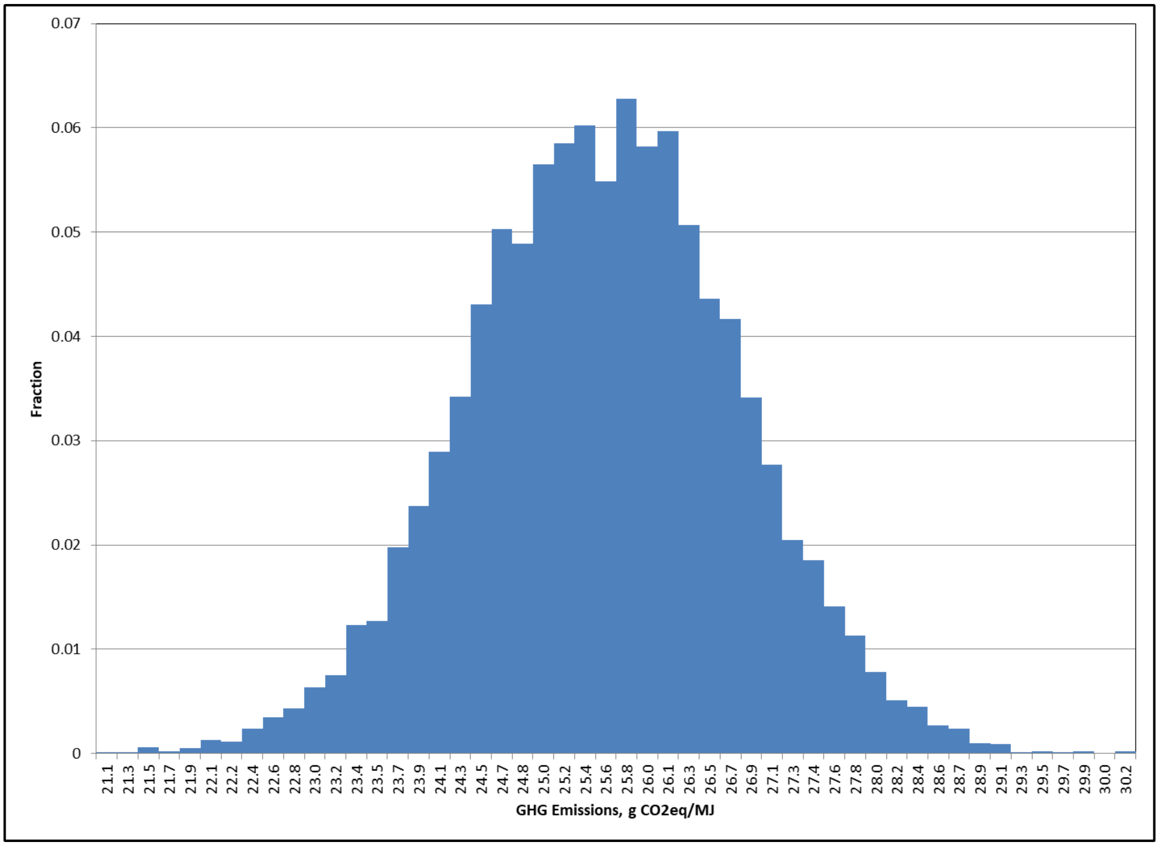
Table 1-116 Soybean Renewable Diesel Variables

Parameter	GREET	GHGenius
N_2O EF_1	0.0125	0.0125
Distribution	Lognormal	Lognormal
Std Dev	0.0015	0.0015
Farm Energy	19,443 BTU/bu	1,520 MJ/ha
Distribution	Normal	Normal
Std Dev	2,560 BTU/bu	200 MJ/ha
Soybean Crushing	3,687 BTU/lb Oil	152 l NG (HHV)/l oil
Distribution	Normal	Normal
Std Dev	460 BTU/lb oil	19 l NG (HHV)/l oil
Hydrogen Use	2,000 BTU/lb RD	30 g H2 (HHV)/l RD
Distribution	Normal	Normal
Std Dev	200 BTU/lb RD	3 l NG (HHV)/l RD

8.5.1 GREET

The GREET model was run with the parameters shown in the previous table. For all other parameters the default values were used. The mean value is 25.7 g CO_2eq/MJ. The standard deviation is 1.2 g CO_2eq/MJ, the skewness is -0.02 and the excess kurtosis is 0.02. The results are close to normal distribution. The distribution of the results is shown in the following figure.

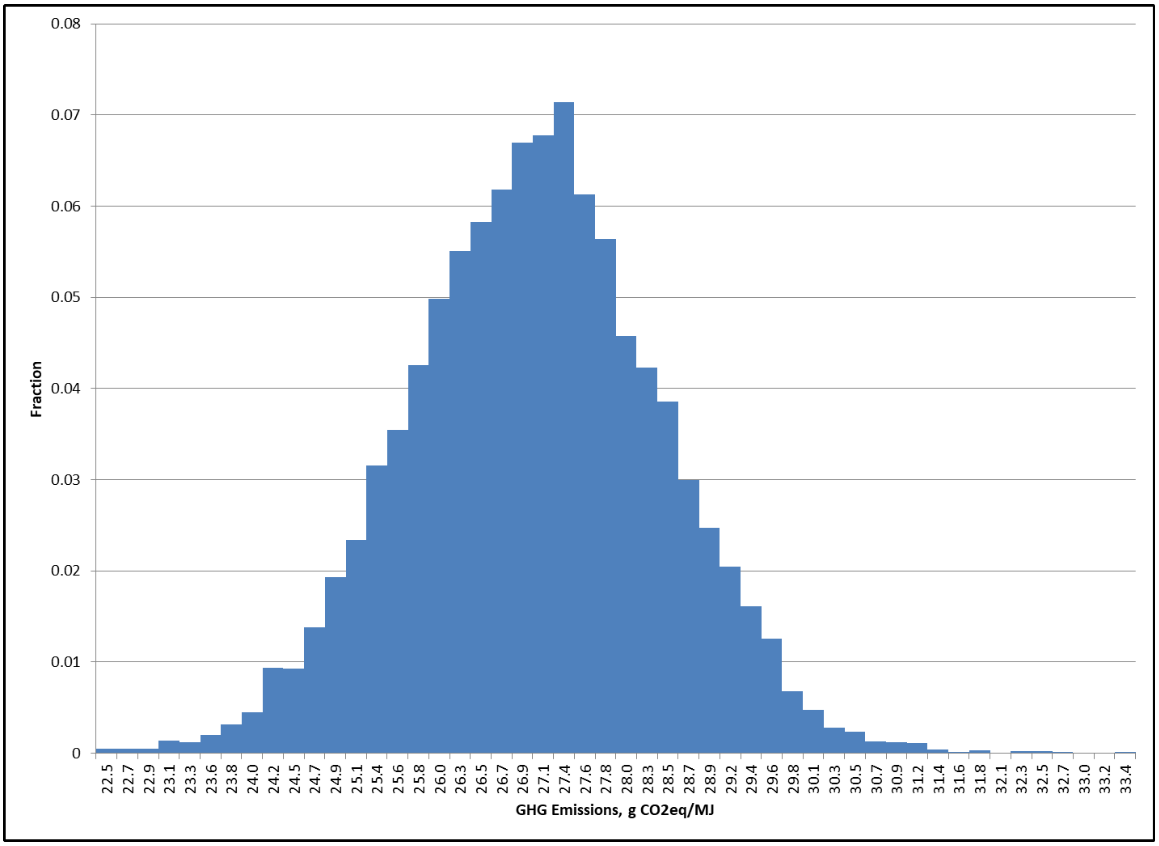
Figure 1-60 GREET Soybean Renewable Diesel Monte Carlo Results



8.5.2 GHGenius

The GHGenius model has been run using the parameters shown in the previous table. In addition the co-product allocation was set to energy allocation, the same as GREET. The mean value is 27.2 g CO_2eq/MJ. The standard deviation is 1.3 g CO_2eq/MJ, the skewness is 0.03 and the excess kurtosis is 0.14. The results are close to normal distribution. The distribution of the results is shown in the following figure.

Figure 1-61 GHGenius Soybean Renewable Diesel Monte Carlo Results



8.5.3 Model Comparison

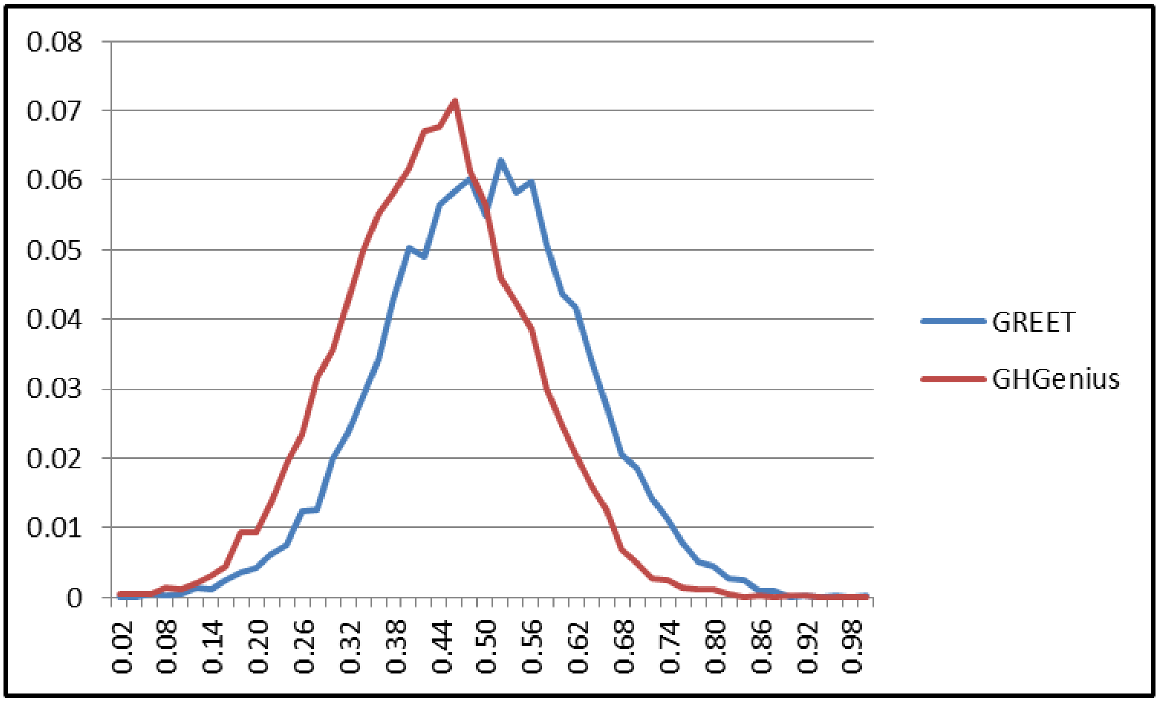
The mean results from the two models are compared in the following table. The results for the two models are closer together as there are no fossil carbon introduced into the system.

Table 1-117 Comparison of Models SB Renewable Diesel

	GREET	GHGenius
	g CO_2eq/MJ	
Feedstock	9.7	16.9
Fuel	16.0	10.2
Total	25.7	27.2

The following figure shows the two Monte Carlo distributions normalized. The shape of the curves is very similar to the shapes for the soybean biodiesel results from the two models.

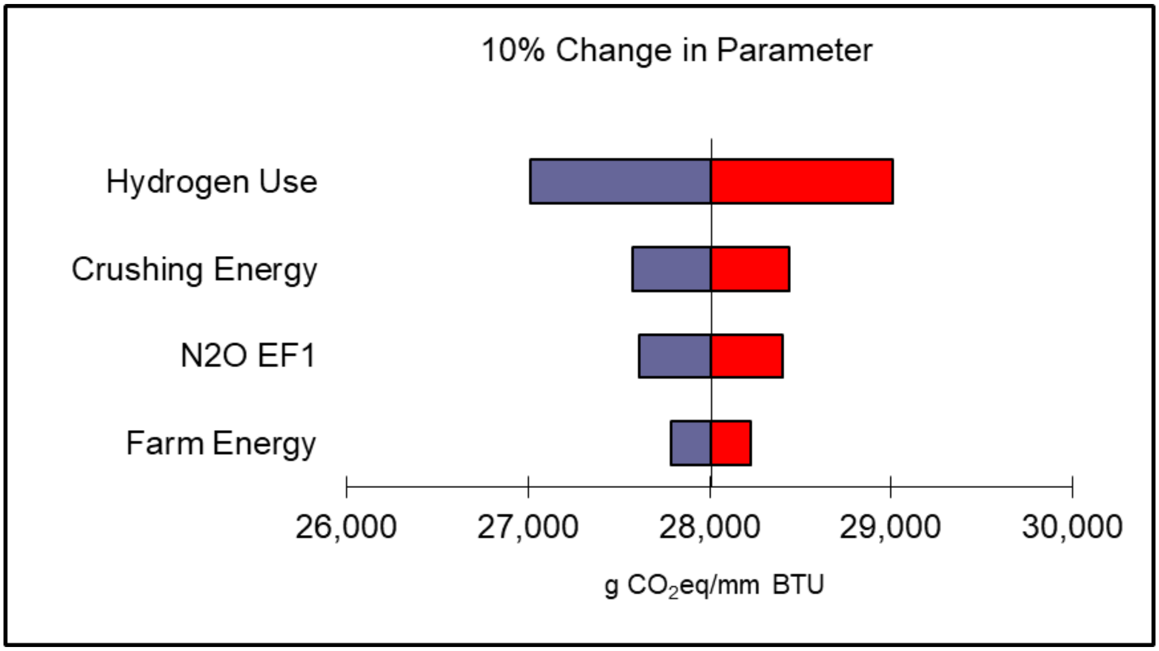
Figure 1-62 Comparison of Monte Carlo Results - Soybean Renewable Diesel



8.5.4 Sensitivity

The GREET model for soybean biodiesel is used to investigate the sensitivity of the results to the four parameters reviewed in the literature survey and the Monte Carlo analysis. In each case the base value in the GREET model is increased and decreased by 10%. The results are shown in the following figure. The hydrogen use has the greatest impact and the farm energy has the lowest impact.

Figure 1-63 Sensitivity Analysis Soybean Renewable Diesel



8.6 SUGARCANE ETHANOL

Four parameters were investigated for the sugarcane ethanol pathway: the N_2O emissions for producing sugarcane, the energy consumed in mechanical harvesting, methane emissions from the vinasse application systems, and the quantity of co-products produced (primarily electricity). The methane emissions are only included in the GREET model.

There is not a lot of information in the literature that could be used to develop a range of values. The Monte Carlo analysis has been undertaken on three variables for GHGenius and BioGrace and four (methane emissions) for GREET. The variables are shown in the following table. The models are set for mechanical harvesting with no residue burning. The ethanol transportation is set to 100 km.

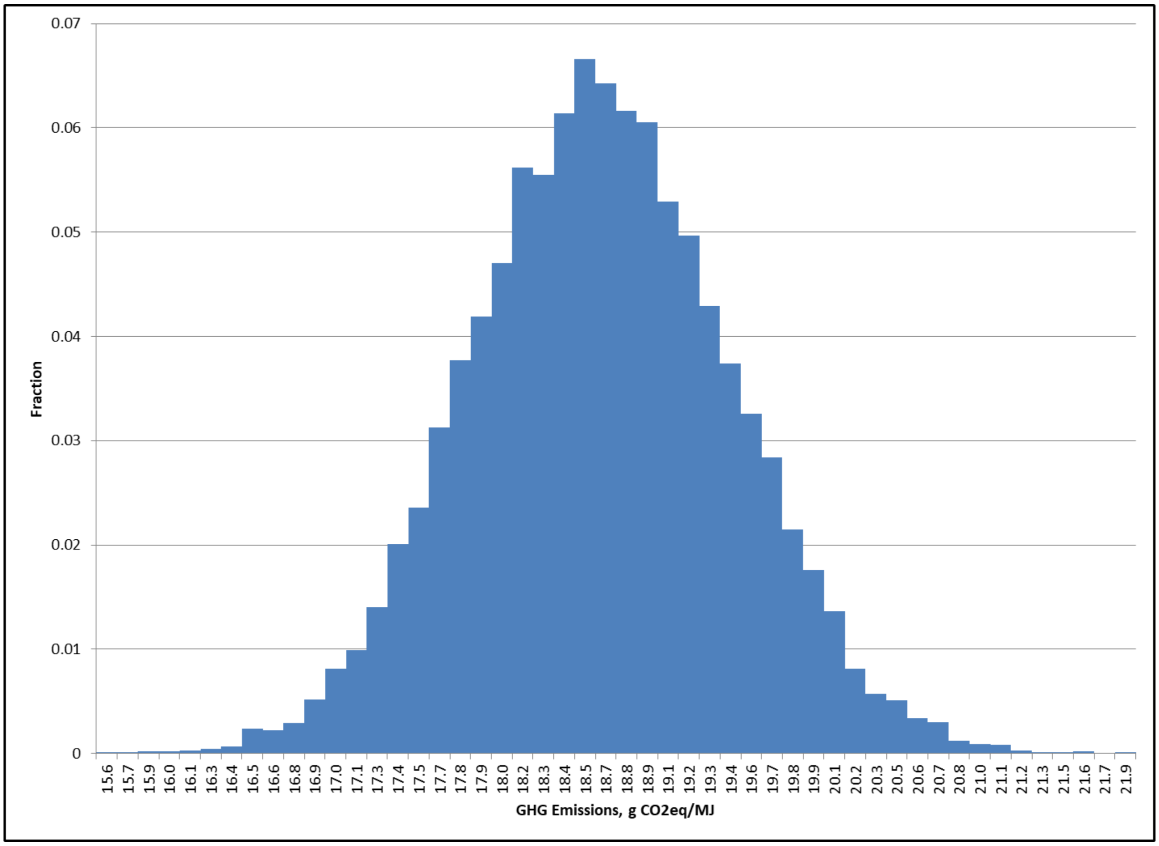
Table 1-118 Monte Carlo Variables – Sugarcane Ethanol

Parameter	GREET	GHGenius	BioGrace
N_2O EF1	0.0125	0.0125	0.0125
Distribution	Lognormal	Lognormal	Lognormal
Std Dev	0.0015	0.0015	0.0015
Farm Energy	95,000 BTU/tonne Cane	2.7 litres/tonne cane	6,870 MJ/ha
Distribution	Normal	Normal	Normal
Std Dev	15,000 BTU/tonne cane	0.4 litres/tonne cane	1,000 MJ/ha
Methane emissions	30 g CH_4/tonne cane	-	-
Distribution	Lognormal	-	-
Std Dev	5 g CH_4/tonne cane	-	-
Power Sold	30 kWh/tonne cane	0.375 kWh/litre	0.065 MJ/MJ Etoh
Distribution	Lognormal	Lognormal	Lognormal
Std Dev	5 kWh/tonne cane	0.0625 kWh/litre	0.01 MJ/MJ

8.6.1 GREET

The GREET model was set up to use the parameters in the previous table. The model was also set to 100% mechanical harvesting, no burning, and 62 miles transportation distance. The mean value is 18.7 g CO_2eq/MJ. The standard deviation is 0.8 g CO_2eq/MJ, the skewness is 0.05 and the excess kurtosis is 0.0. The results follow a normal distribution, even though three of the four variables had a lognormal distribution. The distribution of the results is shown in the following figure.

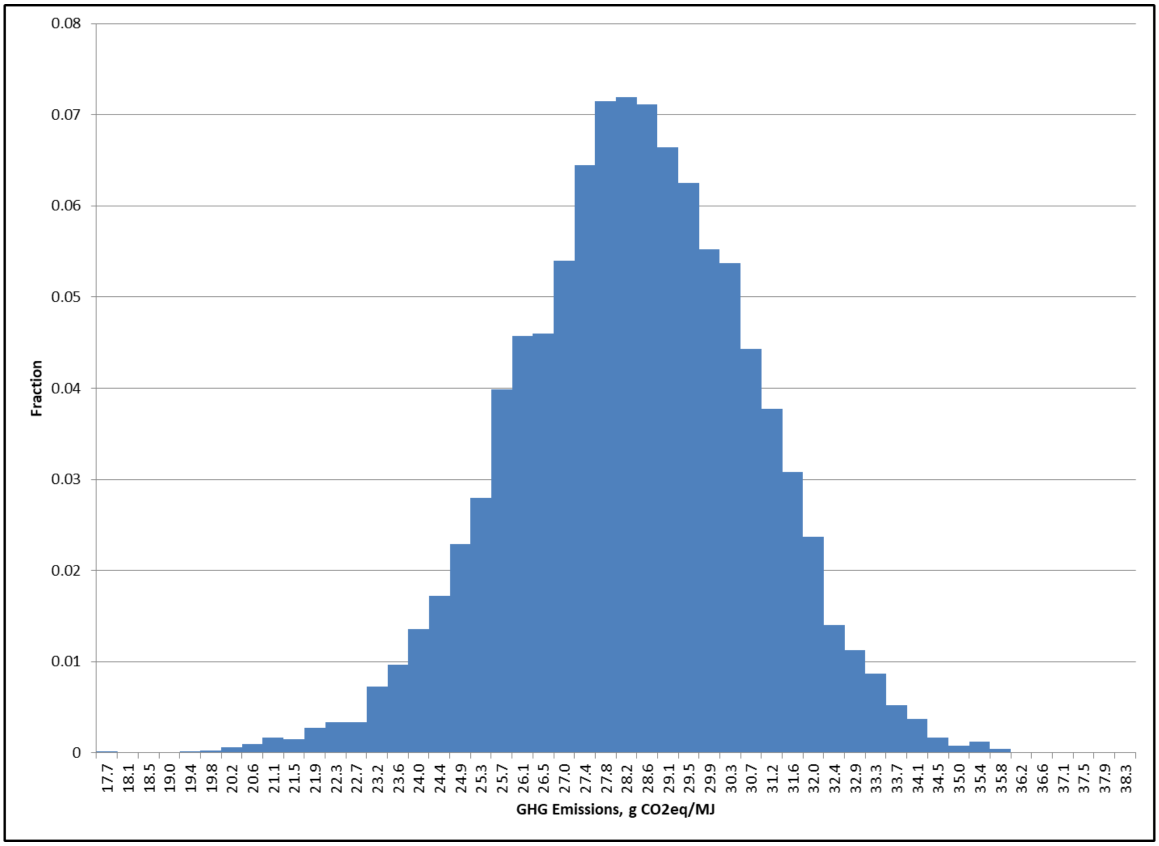
Figure 1-64 GREET Sugarcane Ethanol Monte Carlo Results



8.6.2 GHGenius

GHGenius has also been set up for 100% mechanical harvesting with no burning. The transportation distance for the ethanol has been set to 100 km, the same as GREET. The mean value is 28.6 g CO_2eq/MJ. The standard deviation is 2.4 g CO_2eq/MJ, the skewness is -0.2 and the excess kurtosis is 0.2. The results show a slight reverse lognormal type distribution. The distribution of the results is shown in the following figure.

Figure 1-65 GHGenius Sugarcane Ethanol Monte Carlo Results

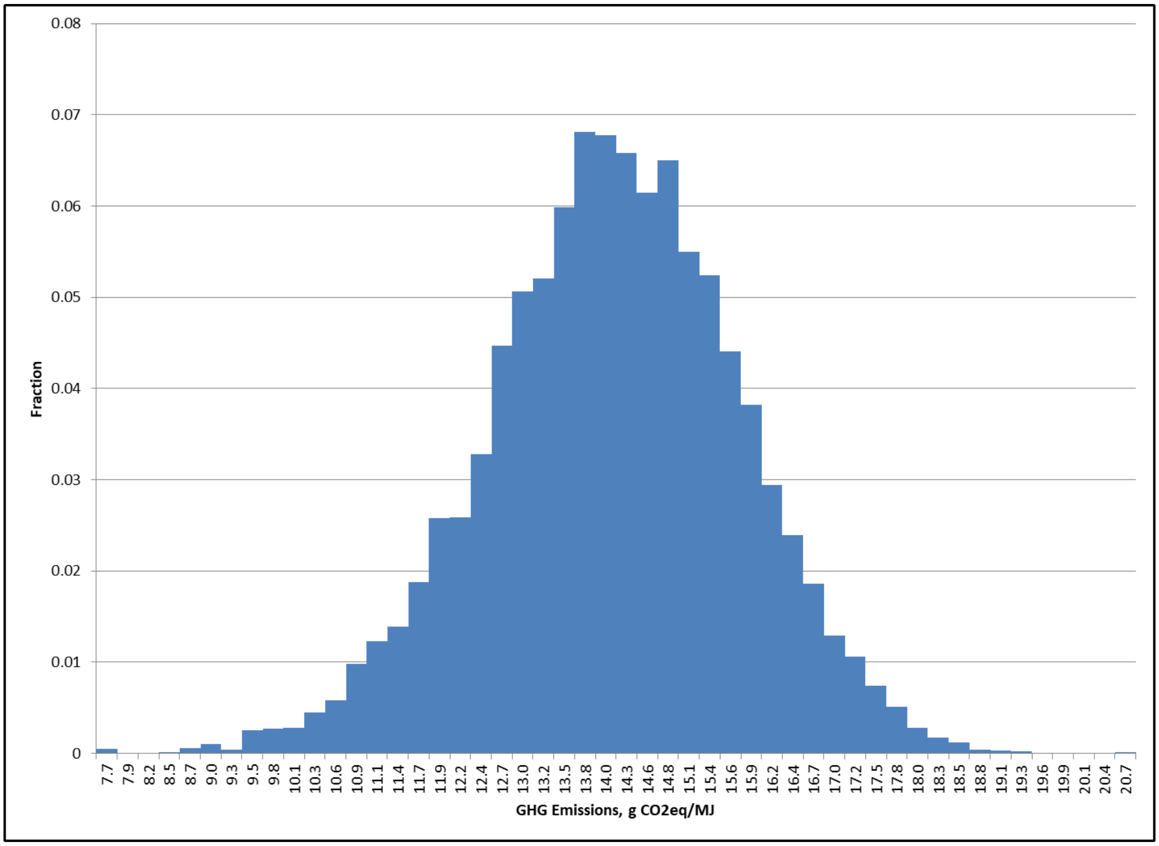


8.6.3 BioGrace

BioGrace has been set up to use the IPCC N_2O emission approach rather than the default fixed value. The values in Table 8-9 are installed by the Monte Carlo tool. The electricity credit is calculated based on a natural gas combined cycle gas turbine plant.

The mean value is 14.3 g CO_2eq/MJ. The standard deviation is 1.6 g CO_2eq/MJ, the skewness is -0.2 and the excess kurtosis is 0.1. The distribution of the results is shown in the following figure.

Figure 1-66 BioGrace Sugarcane Ethanol Monte Carlo Results



The BioGrace mean emissions for the base case are shown in the following table. The RED default value (excluding most of the freight) is 15 g CO_2eq/MJ. The cultivation emissions for the base case are higher than the default case but those are offset by the emission credit for the power produced (zero in the RED case).

Table 1-119 BioGrace Sugarcane Ethanol Base Case

	Emissions, g CO_2eq/MJ
Cultivation	15.8
Processing	5.0
Power Credit	-8.4
Other	1.9
Total	14.3

8.6.4 Model Comparison

The mean results from the three models are compared in the following table.

Table 1-120 Comparison of Models

	GREET	GHGenius	BioGrace
	g CO_2eq/MJ		
Feedstock	15.6	22.8	15.8
Ethanol	3.1	5.8	-1.5
Total	18.7	28.6	14.3

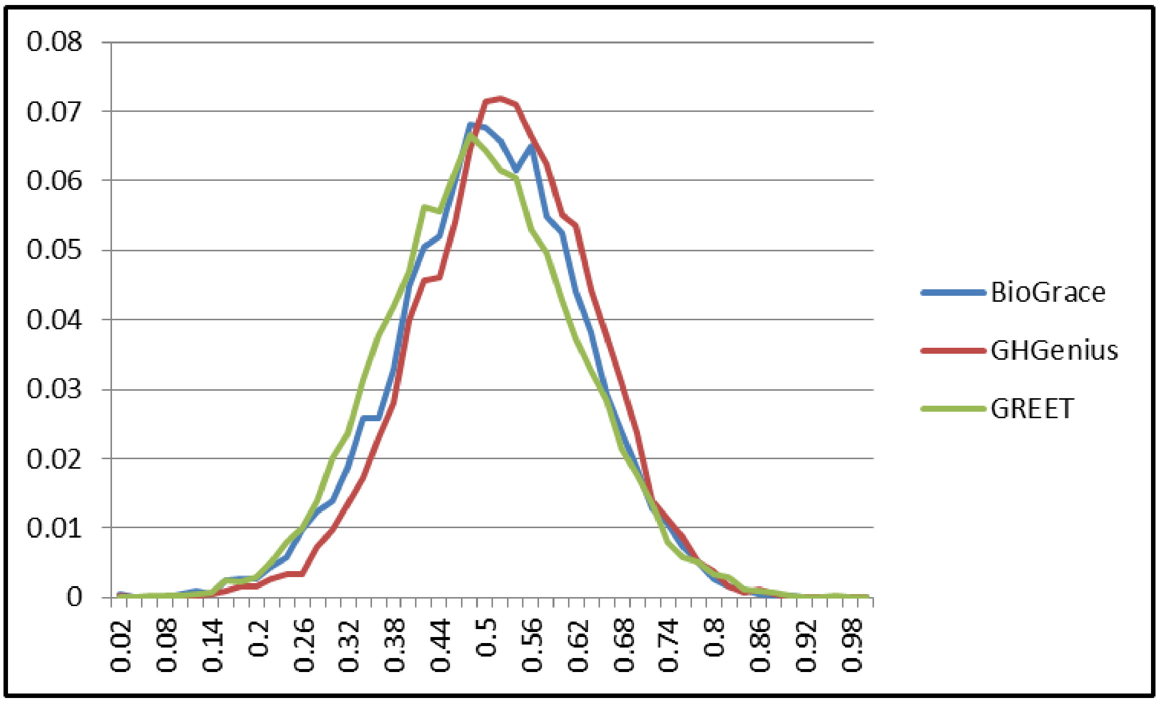
Much of the difference in the feedstock emissions is related to the application rates and the emission factors for lime/limestone. These are compared in the following table. The uncertainty is related to the use of limestone vs lime and the faction of CO_2 that is released from limestone when it is applied to the soil.

Table 1-121 Lime for Sugarcane Production

	GREET	GHGenius	BioGrace
Lime rate, kg/tonne cane	5.2	11.5	5.3
Lime Emissions, kg CO_2/kg lime	0.228	1.37	0.13
Emissions, kg/tonne cane	1.2	15.7	0.7

The distribution of the results from the three models is shown in the following figure.

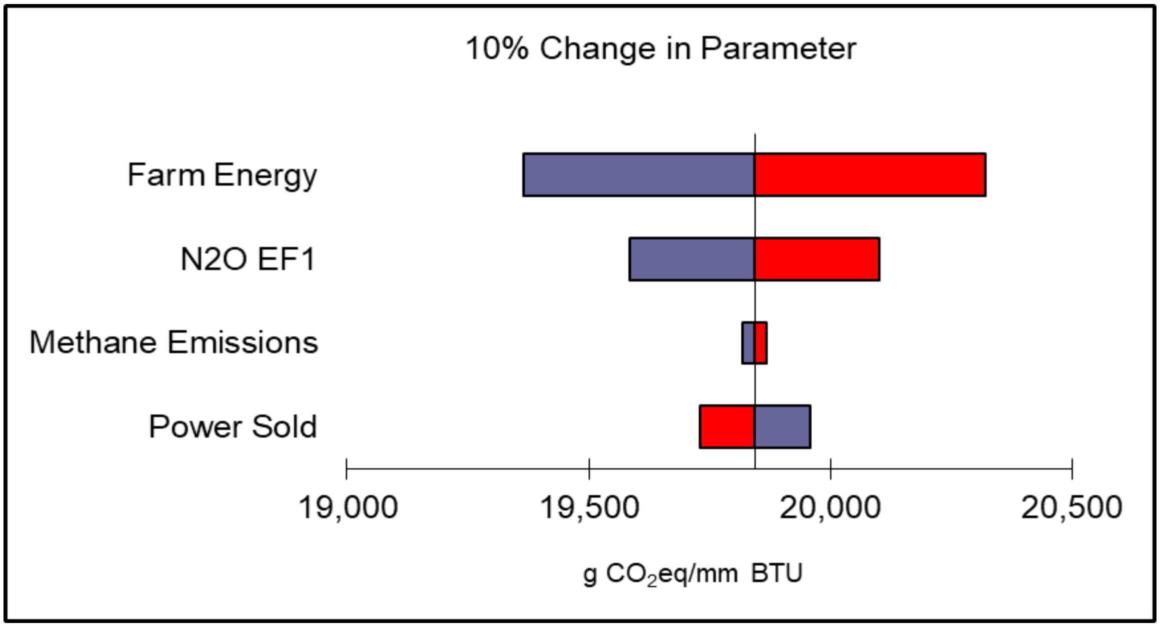
Figure 1-67 Comparison of Monte Carlo Results - Sugarcane Ethanol



8.6.5 Sensitivity

The GREET model for sugarcane ethanol is used to investigate the sensitivity of the results to the four parameters reviewed in the literature survey and the Monte Carlo analysis. In each case the base value used for the GREET model is increased and decreased by 10%. The results are shown in the following figure. The farm energy use has the greatest impact and the vinasse methane emissions have the lowest impact.

Figure 1-68 Sensitivity Analysis Sugarcane Ethanol



8.7 Cellulosic Ethanol

There was very little actual plant data identified in the literature review. For the Monte Carlo analysis, GREET and GHGenius have been run using the parameters in the following table. The inputs are comparable in the different units of the models.

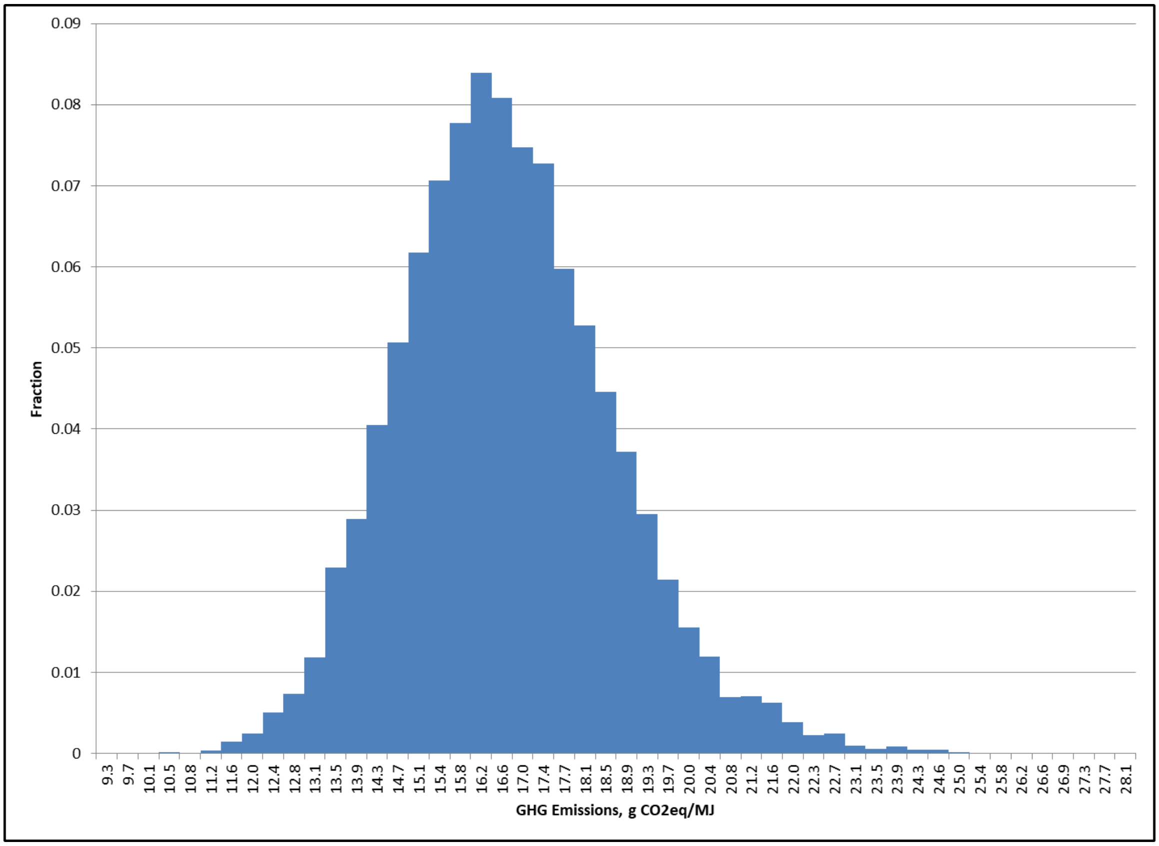
Table 1-122 Cellulosic Ethanol Variables

Parameter	GREET	GHGenius
Yield	85 gal/ton	2.82 Kg/litre
Distribution	Normal	Normal
Std Dev	10 gal/ton	0.28
Power Export	205 kWh/ton biomass	0.64 kWh/litre
Distribution	Normal	Normal
Std Dev	20 kWh/ton	0.064
Enzyme cons	0.010 ton/ton biomass	0.028 kg/litre
Distribution	Normal	Normal
Std Dev	0.001 ton/ton biomass	0.003 kg/litre
NaOH	10 kg/ton biomass	0.028 kg/litre
Distribution	Normal	Normal
Std Dev	1.0 kg/ton biomass	0.003 kg/litre

8.7.1 GREET

The GREET model was set up to use the parameters in the previous table. Enzymes and NaOH were chosen as inputs as they are relatively emission intensive products. The default approach of the power displacing the average grid power was retained. The mean value is 16.9 g CO_2eq/MJ. The standard deviation is 2.0 g CO_2eq/MJ, the skewness is 0.5 and the excess kurtosis is 0.7. The distribution of the results is shown in the following figure.

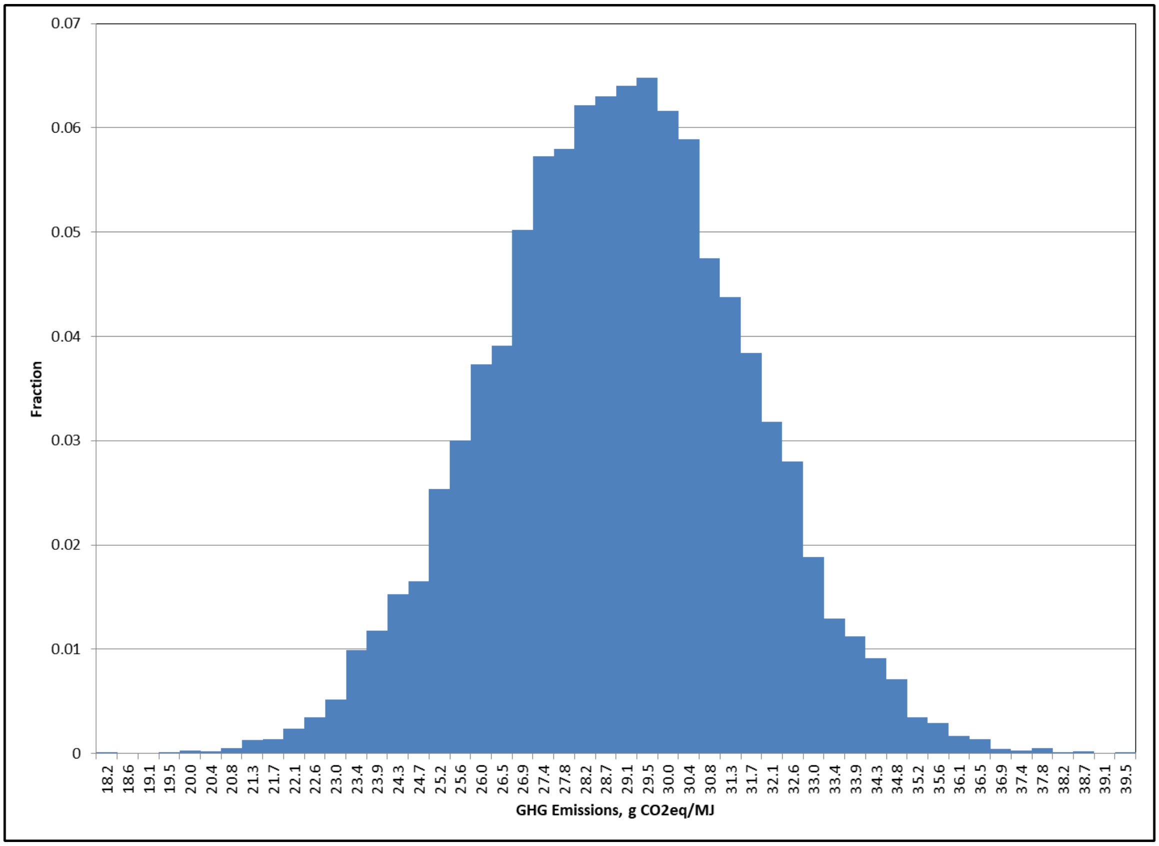
Figure 1-69 GREET Cellulosic Ethanol Monte Carlo Results



8.7.2 GHGenius

The GHGenius inputs in the previous table were used. In addition the sugar input was set to zero as the GREET model purchases enzymes instead of producing them. The power produced is credited with the average grid emissions, the same approach as used in the GREET runs. The mean value is 29.1 g CO_2eq/MJ. The standard deviation is 2.6 g CO_2eq/MJ, the skewness is 0.0 and the excess kurtosis is 0.0, indicating a normal distribution. The distribution of the results is shown in the following figure.

Figure 1-70 GHGenius Cellulosic Ethanol Monte Carlo Results



8.7.3 Model Comparison

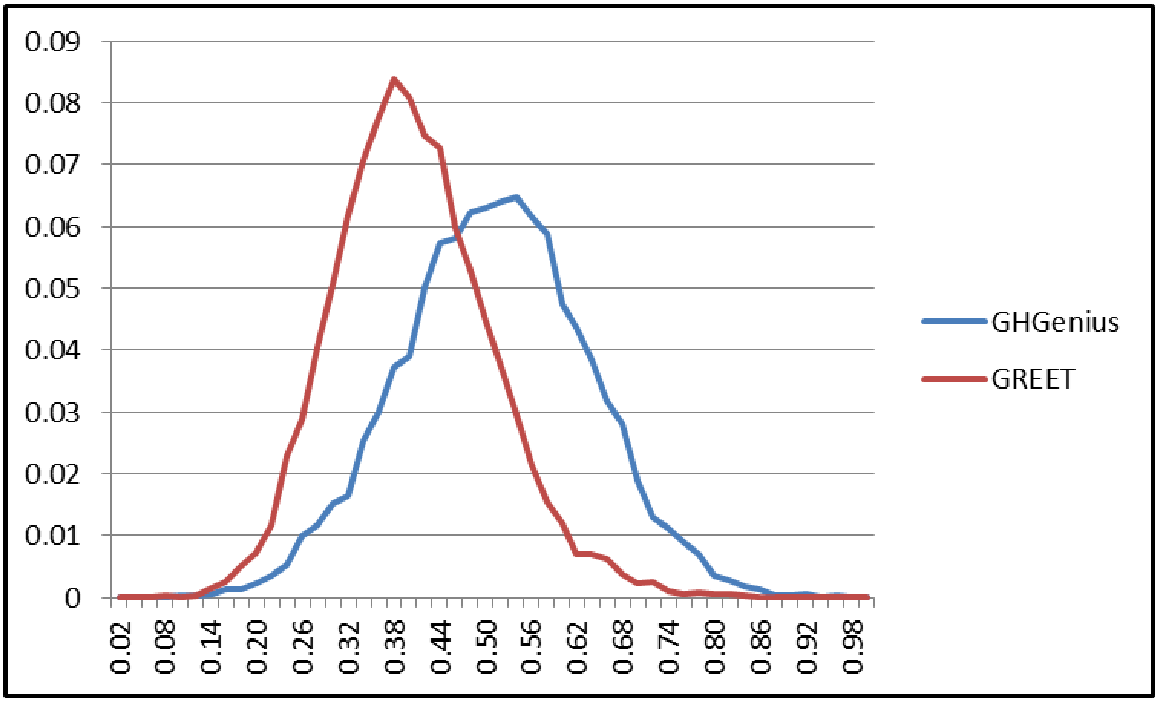
The mean results from the two models are compared in the following table. The distribution of the emissions between the feedstock and the fuel is influenced by the way that the credit for the power is allocated between the two categories.

Table 1-123 Comparison of Models Cellulosic Ethanol

	GREET	GHGenius
	g CO_2eq/MJ	
Feedstock	15.1	5.5
Fuel	1.8	23.6
Total	16.9	29.1

The following figure shows the two Monte Carlo distributions normalized.

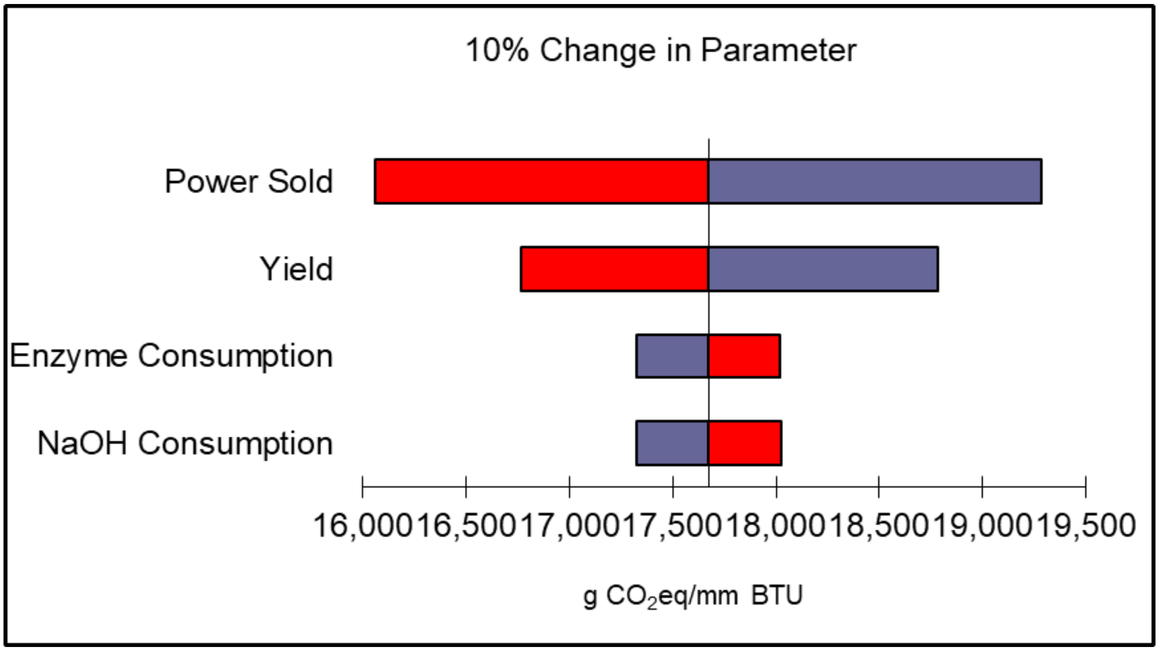
Figure 1-71 Comparison of Monte Carlo Results - Cellulosic Ethanol



8.7.4 Sensitivity

The GREET model for cellulosic ethanol is used to investigate the sensitivity of the results to the four parameters reviewed in the literature survey and the Monte Carlo analysis. In each case the base value in the GREET model is increased and decreased by 10%. The results are shown in the following figure. The power sold has the greatest impact and the enzyme and NaOH consumption have the lowest impact.

Figure 1-72 Sensitivity Analysis Cellulosic Ethanol



8.8 SUMMARY

Monte Carlo simulations and sensitivity analysis was undertaken on the six pathways for the parameters that were investigated as part of the literature review. The same values for the parameters were used in each model. This also involved some harmonization of the models where it was feasible to align the systems being modelled. Due to the different structures of the models a complete harmonization of the modelling frameworks is not possible.

For the corn ethanol pathway, the GREET and GHGenius models provide very similar carbon intensity results (after aligning the system boundaries to exclude changes in soil carbon) and the distribution of the Monte Carlo results is also very similar. The BioGrace model uses energy allocation for the co-product and as a result provides lower GHG emissions than the other two models. Harmonizing the production system to use purchased power rather than exporting power and using the same thermal energy and N_2O emission factors as the other two models, increased the GHG emissions compared to the RED default value. BioGrace did produce a different Monte Carlo distribution than GREET and GHGenius but it doesn't appear to be related to the different method for allocation emissions to the co-product.

The literature search did not find a significant amount of data on the distribution of the key parameters investigated for the pathways other than the corn ethanol pathway. As a result, the definition of the probability distribution functions for the input parameters for the other five pathways are mostly estimates.

The structures of the petroleum pathways in GREET and GHGenius are quite different and it is not possible to fully harmonize the two models. However, using the four parameters investigated in the literature search and using the same input values for those parameters in each of the models did produce quite similar Monte Carlo distributions. Changes in the refining efficiency produced larger changes in the GHG emissions than changes in the energy used to produce crude oil but the quality of the refinery efficiency data is much higher than the quality of the data on crude oil energy use so the uncertainty of the crude oil energy use may still have a greater impact on the overall results.

The GREET and GHGenius natural gas pathways are quite similar and relatively easy to harmonize. The largest difference in the CNG pathways between the models is in the distribution of the natural gas where GHGenius has higher methane emissions. One of the very recent papers in this area would indicate that these emissions in GHGenius are two high and in GREET are too low. Updating both models would bring the results even closer together.

Aligning the transportation assumption for the soybean biodiesel pathway between the models greatly reduced the soybean biodiesel GHG emissions in BioGrace and brought the emissions into the same range as the other models. The energy allocation approach used in BioGrace compared to the mass allocation for oilseed crushing used in GREET and GHGenius will produce higher GHG emissions and that is seen in the results.

The soybean renewable diesel results for GREET and GHGenius are quite close in magnitude and in the Monte Carlo distribution. It is easier to align the renewable diesel pathways in the two models than the biodiesel pathways due to the lack of significant fossil carbon inputs to the process and the need to deal with the fossil carbon in the fuel and co-products. BioGrace does not have a soybean renewable diesel pathway.

The sugarcane ethanol pathways were also aligned with similar transportation scenarios to eliminate that variability between the models. The normalized Monte Carlo results for the three models are very similar. Most of the differences between the models are due to different assumptions regarding lime and limestone.

The literature survey found very little real world data on cellulosic ethanol production systems. Even when the yield, power produced, and two of the key chemical inputs were harmonized there are significant differences in the results from GREET and GHGenius. The distributions of the normalized Monte Carlo results were also quite different.

9. References

(S&T)[2] Consultants Inc. 2013. Transportation Fuel Life Cycle Assessment: Validation and Uncertainty of Well-To-Wheel GHG Estimates. CRC Report No. E-102. http://www.crcao.org/reports/recentstudies2013/E-102/CRC%20E%20102%20Final%20Report.pdf

Agricultural Marketing Resource Centre. 2015. DDGS Balance Sheet. http://www.extension.iastate.edu/agdm/crops/outlook/dgsbalancesheet.pdf

Air Improvement Resource, Inc. 2015. Lifecycle GHG Emissions from Poet-DSM project Liberty Cellulosic Ethanol Plant. https://www.arb.ca.gov/fuels/lcfs/2a2b/apps/poet-lib-rpt-121715.pdf

Allan K. Chambers , Melvin Strosher , Tony Wootton , Jan Moncrieff & Philip McCready. 2008. Direct Measurement of Fugitive Emissions of Hydrocarbons from a Refinery, Journal of the Air & Waste Management Association, 58:8, 1047-1056. http://dx.doi.org/10.3155/1047-3289.58.8.1047

ampCNG. 2015. The per-mile Costs of Operating Compressed Natural Gas Trucks. https://static1.squarespace.com/static/54df8befe4b0419b74c936c2/t/55f706f8e4b0c1c31ccc861d/1442252536965/ampCNG+White+Paper+on+12L+Operating+Costs+per+Mile.pdf

Argonne National Laboratory, Systems Assessment Group. 2016. Summary of Expansions, Updates, and Results in Greet® 2016 Suite of Models. https://greet.es.anl.gov/files/summary-updates-2016

Barnard, Geoffrey & Kristoferson, Lars & Kungl. Svenska vetenskapsakademien & Beijer Institute & Energy Information Programme 1985, Agricultural residues as fuel in the Third World, Earthscan, London.

Brandt, A., Yeskoo, T., McNally, S., Vafi, K., Cai, H., Wang, M. 2015. Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Bakken Formation: Input Data and Analysis Methods. https://greet.es.anl.gov/files/bakken-oil

Brandt, A.R., Sun, Y., Bharadwaj, A., Livingston, D., Tan, E., Gordon, D. 2015. Energy Return on Investment (EROI) for Forty Global Oilfields Using a Detailed Engineering-Based Model of Oil Production. http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0144141

Burnham, A. 2016. Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in the GREET1_ 2016 Model. https://greet.es.anl.gov/files/updated-ghg-2016

Burnham, A., Elgowainy, A., Wang, M. 2015. Updated Fugitive Greenhouse Gas Emissions for Natural Gas Pathways in GREET1 2015 Model. https://greet.es.anl.gov/files/emissions-ng-2014

Cai, H, Burnham, A., Wang, M., Hang, W., Vyas, A. 2015. The GREET Model Expansion for Well-to.-Wheels Analysis of Heavy-Duty Vehicles. https://greet.es.anl.gov/files/heavy-duty

Cai, H. Burnham, A., Wang, M. Vyas, A. 2015. The GREET Model Expansion for Well to Wheels Analysis of heavy-Duty Vehicles. https://greet.es.anl.gov/files/heavy-duty

Cai, H., Brandt, A., Yeh, S., Englander, J., Han, J., Elgowainy, A., and Wang, M. 2015. Well-to-Wheels Greenhouse Gas Emissions of Canadian Oil Sands Products: Implications for U.S. Petroleum Fuels. Environmental Science & Technology 2015 49 (13), 8219-8227. http://dx.doi.org/10.1021/acs.est.5b01255

Cai, H., Burnham, A., Wang, M., 2013. Updated Emission Factors of Air Pollutants from Vehicle Operations in GREET Using MOVES. https://greet.es.anl.gov/publication-vehicles-13.

Cai, H., Han, J. Elgowainy, A. Wang, M. 2014. Updated Vented, Flaring, and Fugitive Greenhouse Gas Emissions for Crude Oil Production in the GREET Model. https://greet.es.anl.gov/files/emissions-crude-oil-2014

Cai, H., Wang, M., Elgowainy, A., Han, J. 2015. Updated N_2O Emissions for Soybean Fields. https://greet.es.anl.gov/files/update-n2o-soybean

Capaz, R., Carvalho, V., Nogueira L. 2013. Impact of mechanization and previous burning reduction on GHG emissions of sugarcane harvesting operations in Brazil. Applied Energy, Volume 102, February 2013, Pages 220-228. http://dx.doi.org/10.1016/j.apenergy.2012.09.049

CARB. 2016. Natural Gas as a Transportation Fuel. https://www.arb.ca.gov/fuels/lcfs/lcfs_meetings/12022016discussionpaper_ng.pdf

Carder, D.K., Thiruvengadam, A., Besch, M.C., Gautam, M., 2014. In-Use Emissions Testing and Demonstration of Retrofit Technology for Control of On-Road Heavy-Duty Engines. Prepared for the South Coast Air Quality Management District (Contract No. 11611).

Carmo JBD, Filoso S, Zotelli LC, Neto ERDS, Pitombo LM, Duarte-Neto PJ, Vargas VP, Andrade CA, Gava GJC, Rossetto R, Cantarella H, Neto AE and Martinelli LA. 2012. Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation. Global Change Biology Bioenergy http://dx.doi.org/10.1111/j.1757-1707.2012.01199.x

Cavalett, O. 2016. CTBE. Personal communication July 21, 2016.

Christianson & Associates PLLP. 2016. Ethanol Evolution: The Data and Deals Driving the Future. http://www.christiansoncpa.com/wp-content/uploads/2016/04/Ethanol-Evolution-Data-and-Deals.pdf

Christianson & Associates, PLLP. 2008. US Ethanol Industry Efficiency Improvements 2004 to 2007. http://www.ethanolrfa.org/objects/documents/1916/usethanolefficiencyimprovements08.pdf

Clark, N., McKain, D., Johnson, Wayne, S., Li, H., Akkerman, V., Sandoval, C., Covington, A., Mongold, R., Hailer, J., and Ugarte, O. 2017. Pump-to-Wheels Methane Emissions from the Heavy-Duty Transportation Sector. Environmental Science & Technology 2017 51 (2), 968-976. http://dx.doi.org/10.1021/acs.est.5b06059

Clearstone Engineering Ltd. 2014. Volume 1 Overview of the GHG Emissions Inventory

Conab. 2013. Perfil do Setor do Açúcar e do Álcool no Brasil. http://www.conab.gov.br/OlalaCMS/uploads/arquivos/15_03_27_12_10_01_perfil_sucro_2011-12.pdf

Cooney, A., Jamieson, M., Marriott, J., Bergerson, J., Brandt, A., Skone, T.J. 2016. Updating the U.S. Life Cycle GHG Petroleum Baseline to 2014 with Projections to 2040 Using Open-Source Engineering-Based Models. http://pubs.acs.org/doi/full/10.1021/acs.est.6b02819

Coordinating Research Council, INC. 2014. Natural Gas Vehicle Fuel Survey. http://www.crcao.org/reports/recentstudies2014/PC-2-12/CRC%20PC-2-12%20CNG%20Survey%20final%20report.pdf

David S. Hirshfeld and Jeffrey A. Kolb. 2012. Analysis of Energy Use and CO2 Emissions in the U.S. Refining Sector, With Projections for 2025. Environmental Science & Technology 2012 46 (7), 3697-3704. http://dx.doi.org/10.1021/es204411c

de Oliveira Bordonal, R., de Figueiredo, E. B. and La Scala, N. 2012. Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest, considering other conservationist management practices. Glob. Change Biol. Bioenergy, 4: 846–858. http://dx.doi.org/10.1111/j.1757-1707.2012.01193.x

de Oliveira, B., Carvalho, J., Cerri, C., Cerri, C., Feigl, B. 2015. Greenhouse gas emissions from sugarcane vinasse transportation by open channel: a case study in Brazil. Journal of Cleaner Production, Volume 94, 1 May 2015, Pages 102-107.http://dx.doi.org/10.1016/j.jclepro.2015.02.025

Dunn, J. Eason, J. Wang, M. 2011. Updated Sugarcane and Switchgrass Parameters in the GREET Model. https://greet.es.anl.gov/files/updated_sugarcane_switchgrass_params

Dunn, J., Johnson, M., Wang, Z., Wang, M. 2013. Supply Chain Sustainability Analysis of Three Biofuel Pathways. https://greet.es.anl.gov/publication-scsa-2014

Elgowainy, A., Han, J., Cai, H., Wang, M., Forman, G., and DiVita, V. 2014. Energy Efficiency and Greenhouse Gas Emission Intensity of Petroleum Products at U.S. Refineries. http://dx.doi.org/10.1021/es5010347

Englander, J., Brandt, A. 2014. Oil Sands Energy Intensity Analysis for GREET Model Update. https://greet.es.anl.gov/files/lca-update-oil-sands

ePure. 2014. State of the Industry Report 2014. http://epure.org/media/1137/state-of-the-industry-report-2014.pdf

Exergia S.A. 2015. Study on Actual GHG Data for Diesel, Petrol, Kerosene, and Natural Gas. https://ec.europa.eu/energy/sites/ener/files/documents/Study%20on%20Actual%20GHG%20Data%20Oil%20Gas%20Final%20Report.pdf

Fan J, et al. 2013. A life cycle assessment of pennycress (Thlaspi arvense L.) -derived jet fuel and diesel. Biomass and Bioenergy. http://dx.doi.org/10.1016/j.biombioe.2012.12.040

FAO. 2016. Livestock Environmental Assessment and Performance (LEAP) Partnership. http://www.fao.org/partnerships/leap/overview/goals-and-objectives/en/

Fediol. 2013. Life Cycle Assessment of EU Oilseed Crushing and Vegetable Oil Refining. http://www.fediol.eu/data/Full%20FEDIOL%20LCA%20report_05062013_CR%20statement.pdf

Flausinio, B., Costa, A., Pinheiro, R., Fortini, A. 2015. Potential of the Bagasse Sugarcane to Electric Power Generation. http://www.ijetae.com/files/Volume5Issue11/IJETAE_1115_34.pdf

Flugge, M., J. Lewandrowski, J. Rosenfeld, C. Boland, T. Hendrickson, K. Jaglo, S. Kolansky, K. Moffroid, M. Riley-Gilbert, and D. Pape, 2017. A Life-Cycle Analysis of the Greenhouse Gas Emissions of Corn- Based Ethanol. Report prepared by ICF under USDA Contract No. AG-3142-D-16-0243. January 12, 2017. https://www.usda.gov/oce/climate_change/mitigation_technologies/USDAEthanolReport_20170107.pdf

Fore, S., Porter, P., Lazarus,W. 2011. Net energy balance of small-scale on-farm biodiesel production from canola and soybean, Biomass and Bioenergy, Volume 35, Issue 5, May 2011, Pages 2234-2244, ISSN 0961-9534, http://dx.doi.org/10.1016/j.biombioe.2011.02.037

Forman, G., DiVita, V., Han, J., Cai, H., Elgowainy, A., and Wang, M. 2014. U.S. Refinery Efficiency: Impacts Analysis and Implications for Fuel Carbon Policy Implementation. http://dx.doi.org/10.1021/es501035a

Gao, Z., LaClair, T., Daw, C.S., Smith, D.E., 2012. Fuel Consumption and Cost Savings of Class 8 Heavy-Duty Trucks Powered by Natural Gas. Presented at the Transportation Research Board 92nd Annual Meeting. http://docs.trb.org/prp/13-2945.pdf

Ghandi, A., Yeh, S., Brandt, A., Vafi, K., Cai, H., Wang, W., Scanlon, B., Reedy, R. 2015. Energy Intensity and Greenhouse Gas Emissions from Crude Oil Production in the Eagle Ford Region: Input Data and Analysis Methods. https://greet.es.anl.gov/files/eagle-ford-oil

GTI. 2009. Field Measurement Program to Improve Uncertainties for Key Greenhouse Gas Emission Factors for Distribution Sources. https://www.otd-co.org/reports/Documents/77b_OTD-10-0002_GHG_Emission_Factors_FinalReport_v2.pdf

Guilford, M.C., Hall, C.A.S., O'Connor, P., Cleveland, C.J. 2011. A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and Gas Discovery and Production. http://www.mdpi.com/2071-1050/3/10/1866

Han, J. Dunn, J., Cai, H., Elgowainy A. and Wang, M. 2012. Updated Sugarcane Parameters in GREET1_2012, Second Revision. https://greet.es.anl.gov/files/greet-updated-sugarcane

Hettinga, W. 2007. Technological Learning in U.S. Ethanol Production. Quantifying Reductions in Production Costs and Energy Use. A Master Thesis, Utrecht University, The Netherlands. http://dspace.library.uu.nl/bitstream/handle/1874/27305/NWS-E-2007-52.pdf?sequence=1

Hoffan, L., Baker, A. 2011. Estimating the Substitution of Distillers' Grains for Corn and Soybean Meal in the U.S. Feed Complex. USDA FDS-11-1-01. http://www.biofuelscoproducts.umn.edu/sites/biodieselfeeds.cfans.umn.edu/files/cfans_asset_417548.pdf

Hopkins, F. 2016. Building a scientific basis for tackling anthropogenic methane emissions. http://postdocs.jpl.nasa.gov/files/ura/Hopkins_seminar.pdf

Hopkins, F. M., Ehleringer, J. R., Bush, S. E., Duren, R. M., Miller, C. E., Lai, C.-T., Hsu, Y.-K., Carranza, V. and Randerson, J. T. 2016. Mitigation of methane emissions in cities: How new measurements and partnerships can contribute to emissions reduction strategies. Earth's Future, 4: 408–425. http://dx.doi.org/10.1002/2016EF000381

Hosein Shapouri, James A. Duffield, and Michael S. Graboski. 1995 Estimating the Net Energy Balance of Corn Ethanol. U.S. Department of Agriculture, Economic Research Service, Office of Energy. Agricultural Economic Report No. 721.http://www.ers.usda.gov/media/926108/aer721.pdf

Hoyt, D., & Raun, L. 2015. Measured and estimated benzene and volatile organic carbon (VOC) emissions at a major U.S. refinery/chemical plant: Comparison and prioritization, Journal of the Air & Waste Management Association, 65:8, 1020-1031. http://dx.doi.org/10.1080/10962247.2015.1058304

Huo, H., Wang, M., Bloyd, C., and Putsche, V. 2008.Life-Cycle Assessment of Energy and Greenhouse Gas Effects of Soybean-Derived Biodiesel and Renewable Fuels. https://greet.es.anl.gov/files/e5b5zeb7

IPCC. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/

JEC. 2014. "Well-to-Tank Report" Version 4a. http://iet.jrc.ec.europa.eu/about-jec/downloads

Jones, C. 2015. Seeing STAARS: Six State Life Cycle Analysis for Corn and Soy Production. http://www.isafarmnet.com/2015OFNConf/pdf/Jones_Life_Cycle_Analysis.pdf

JRC. 2016. Definition of input data to assess GHG default emissions from biofuels in EU legislation.

Kaercher, J., Schneider, R., Klamt, R., Teixeira da Silva, W., Schmatz, W., Szarblewski, M., Machado, E. 2013. Optimization of biodiesel production for self-consumption: considering its environmental impacts, Journal of Cleaner Production, Volume 46, May 2013, Pages 74-82, ISSN 0959-6526, http://dx.doi.org/10.1016/j.jclepro.2012.09.016

Kim, S., Dale, B. 2015.Comparing alternative cellulosic biomass biorefining systems: Centralized versus distributed processing systems, Biomass and Bioenergy, Volume 74, March 2015, Pages 135-147. http://dx.doi.org/10.1016/j.biombioe.2015.01.018

Klassing, K. 2012. Displacement Ratios for US Corn DDGS. http://www.theicct.org/displacement-ratios-us-corn-ddgs

Kraus, K.; Niklas, G.; Tappe, M. 1999. Aktuelle Bewertung des Einsatzes von Rapsöl/RME im Vergleich zu DK. (Currently the use of rapeseed oil / RME compared to DK) Umweltbundesamt (UBA). Deutschland.

Lee, J., Cha, K., Lim, T.,Hur, T. 2011. Eco-efficiency of H_2 and fuel cell buses, International Journal of Hydrogen Energy, Volume 36, Issue 2, January 2011, Pages 1754-1765, ISSN 0360-3199, http://dx.doi.org/10.1016/j.ijhydene.2010.10.074

Life Cycle Associates. 2014. GranBio-Modified GREET Pathway for the Production of Ethanol from Sugarcane Straw. https://www.arb.ca.gov/fuels/lcfs/2a2b/apps/gb-rpt-082514.pdf

Life Cycle Associates. 2015. Lifecycle GHG Emissions from Abengoa Bioenergy Biomass of Kansas, LLC Hugoton Cellulosic Ethanol Plant. https://www.arb.ca.gov/fuels/lcfs/2a2b/apps/abbk-rpt-012915.pdf

Malins, C., et al. 2014. Upstream Emissions of Fossil Fuel Feedstocks Consumed in the European Union. https://circabc.europa.eu/sd/a/6215286e-eb5f-4870-b92f-26acff386156/ICCT_Upstream-emissions-of-EU-crude_May2014.pdf

McKechnie, J., Pourbafrani, M., Saville, B., MacLean, H. 2015. Exploring impacts of process technology development and regional factors on life cycle greenhouse gas emissions of corn stover ethanol, Renewable Energy, Volume 76, April 2015, Pages 726-734. http://dx.doi.org/10.1016/j.renene.2014.11.088

Miller, P., Kumar, A. 2013. Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina, Energy, Volume 58, 1 September 2013, Pages 426-437, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2013.05.027.

Ministério de Minas e Energia. 2016. Análise de Conjuntura dos Biocombustíveis. 2015 Annual. http://www.epe.gov.br/Petroleo/Documents/An%C3%A1lise%20de%20Conjuntura%20dos%20Biocombust%C3%ADveis%20-%20boletins%20peri%C3%B3dicos/An%C3%A1lise%20de%20Conjuntura%20dos%20Biocombust%C3%ADveis1%20-%20Ano%202015.pdf

Ministério de Minas e Energia. 2016. Anuário Estatístico de Energia Elétrica 2016. http://www.epe.gov.br/AnuarioEstatisticodeEnergiaEletrica/Anu%C3%A1rio%20Estat%C3%ADstico%20de%20Energia%20El%C3%A9trica%202016.xls

Minnesota Soybean Research & Promotion Council. 2013. Direct Fuel Use in Minnesota Soybean Production 2012.

Mueller, S. 2010. Detailed Report: 2008 National Dry Mill Corn Ethanol Survey. http://ethanolrfa.org/wp-content/uploads/2015/09/Detailed-Report-2008-National-Dry-Mill-Corn-Ethanol-Survey-.pdf

Mueller, S., Kwik, J. 2013. 2012 Corn Ethanol: Emerging Plant Energy and Environmental Technologies. http://ethanolrfa.org/wp-content/uploads/2015/09/2012-Corn-Ethanol-Emerging-Plant-Energy-and-Environmental-Technologies.pdf

National Agricultural Statistics Service. 2007. Ethanol Co-Products Used for Livestock Feed. http://usda.mannlib.cornell.edu/usda/current/EthFeed/EthFeed-06-29-2007_revision.pdf

National Renewable Energy Laboratory. 2011. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Technical Report NREL/TP-5100-47764. May 2011. www.nrel.gov/biomass/pdfs/47764.pdf

Neste. 2015. Mixed Used Cooking Oil Pathway Description. https://www.arb.ca.gov/fuels/lcfs/2a2b/apps/neste-uco-rpt-111915.pdf

Nikander, S. 2008. Greenhouse Gas and Energy Intensity of Product Chain: Case Transport Biofuel. https://www.neste.com/sites/default/files/attachments/case_study_of_nexbtl_ghg_and_energy_intensity.pdf

Otto, R., Castro, S.A.Q., Mariano, E. et al. 2016. Nitrogen Use Efficiency for Sugarcane-Biofuel Production: What Is Next? Bioenerg. Res. (2016) 9: 1272. http://dx.doi.org/10.1007/s12155-016-9763-x

Ouelette, Patric, Goudie, Dale, McTaggart-Cowan, Gordon. 2016. Progress in the development of natural gas high pressure direct injection for Euro VI heavy-duty trucks. http://dx.doi.org/10.1007/978-3-658-12918-7_45

Paredes, D. Alves, B., dos Santos, M., Bolonhezi, D., Sant'Anna, S., Urquiaga, S., Lima, M., and Boddey, R. 2015. Nitrous Oxide and Methane Fluxes Following Ammonium Sulfate and Vinasse Application on Sugar Cane Soil. Environmental Science & Technology 2015 49 (18), 11209-11217. http://dx.doi.org/10.1021/acs.est.5b01504

Peischl, J., et al. (2016), Quantifying atmospheric methane emissions from oil and natural gas production in the Bakken shale region of North Dakota. J. Geophys. Res. Atmos., 121, 6101–6111, http://dx.doi.org10.1002/2015JD024631

Quiros, D., Thiruvengadam, A., Pradhan, S., Besch, M., Thiruvengadam, P., Demirgok, B., Carder, D., Oshinuga, A., Huai, T., Hu, S. 2016. Real-World Emissions from Modern Heavy-Duty Diesel, Natural Gas, and Hybrid Diesel Trucks Operating Along Major California Freight Corridors, Emission Control Science and Technology, 2016, 156-172, http://dx.doi.org/10.1007/s40825-016-0044-0

Rahman, M., Canter, C., Kumar, A. 2014. Greenhouse Gas Emissions from Recovery of Various North American Conventional Crudes. http://www.sciencedirect.com/science/article/pii/S0360544214008482

Rahman, M., Sampa, M. 2012. Combined Effects of Bradyrihizobial Strains, Municipal Solid Waste Compost and Fertilizers on Nodulation, N Content and Uptake of Soybean. J.

Environ. Sci. & Natural Resources, 5(2): 85-90, 2012. www.banglajol.info/index.php/JESNR/article/download/14799/10538

Ramos, Carlos R. G., Lanças, Kléber P., Lyra, Gabriel A. de, & Sandi, Jefferson. 2016. Fuel consumption of a sugarcane harvester in different operational settings. Revista Brasileira de Engenharia Agrícola e Ambiental, 20(6), 588-592. https://dx.doi.org/10.1590/1807-1929/agriambi.v20n6p588-592

Raucci, G., Moreira, C., Alves, P., Mello, F., Frazão, L., Cerri, C. Cerri, C.. 2015. Greenhouse gas assessment of Brazilian soybean production: a case study of Mato Grosso State, Journal of Cleaner Production, Volume 96, 1 June 2015, Pages 418-425, ISSN 0959-6526, http://dx.doi.org/10.1016/j.jclepro.2014.02.064

Rein, P. 2010. Carbon Footprint of Sugar. Proc. Int. Soc. Sugar Cane Technol., Vol. 27, 2010. http://www.issct.org/pdf/proceedings/2010/2010%20Rein,THE%20CARBON%20FOOTPRINT%20OF%20SUGAR%20.pdf

Robinson, Rod and Gardiner, Tom and Innocenti, Fabrizio and Woods, Peter and Coleman, Marc. 2011. Infrared differential absorption Lidar (DIAL) measurements of hydrocarbon emissions. The Royal Society of Chemistry. http://dx.doi.org/10.1039/C0EM00312C

Rocha, M., Capaz, R., Lora, E., Nogueira, L., Leme, M., Renó, M., del Olmo, O. 2014. Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis. Renewable and Sustainable Energy Reviews, Volume 37, September 2014, Pages 435-459. http://dx.doi.org/10.1016/j.rser.2014.05.036

Sandhu, G., Frey, C., Bartlet-Hunt, S., Jones, E. 2014. Real-World Activity and Fuel Use of Diesel and CNG Refuse Trucks. 2014 PEMS International Conference & Workshop. http://www.cert.ucr.edu/events/pems2014/liveagenda/25sandhu.pdf

Schneising, O., Burrows, J. P., Dickerson, R. R., Buchwitz, M., Reuter, M. and Bovensmann, H. (2014), Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations. Earth's Future, 2: 548–558. http://dx.doi.org/10.1002/2014EF000265

Seabra, J., Macedo, I. 2010. Energy balance and GHG emissions in the production of organic sugar and ethanol at São Francisco Sugar Mill. https://www.researchgate.net/publication/237671973_Energy_balance_and_GHG_emissions_in_the_production_of_organic_sugar_and_ethanol_at_Sao_Francisco_Sugar_Mill?enrichId=rgreq-03dba8ebee81610d092d8ecebaad30f2-XXX&enrichSource=Y292ZXJQYWdlOzIzNzY3MTk3MztBUzoxODA5MjYzMDI2NjI2NTZAMTQyMDE0NzYwMDE3Mg%3D%3D&el=1_x_2

Shapouri, H. and Paul Gallagher. P. 2002. USDA's 2002 Ethanol Cost-of-Production Survey http://www.ethanolrfa.org/wp-content/uploads/2015/09/usdacostofproductionsurvey.pdf

Shapouri, H. et al. 2010. 2008 Energy Balance for the Corn-Ethanol Industry. http://www.usda.gov/oce/reports/energy/2008Ethanol_June_final.pdf

Shapouri, H., Duffield, J., Graboski, M. 1995.. Estimating the Net Energy Balance of Corn Ethanol. U.S. Department of Agriculture, Economic Research Service, Office of Energy. Agricultural Economic Report No. 721. http://www.ers.usda.gov/media/926108/aer721.pdf

Shonnard, D. R., Williams, L. and Kalnes, T. N. (2010), Camelina-derived jet fuel and diesel: Sustainable advanced biofuels. Environ. Prog. Sustainable Energy, 29: 382–392. http://dx.doi.org/10.1002/ep.10461

Signor, D., et al. 2013. N_2O emissions due to nitrogen fertilizer applications in two regions of sugarcane cultivation in Brazil. Environ. Res. Lett. 8 015013. http://dx.doi.org/10.1088/1748-9326/8/1/015013

Siqueira Neto, M., Galdos, M. V., Feigl, B. J., Cerri, C. E. P. and Cerri, C. C. (2016), Direct N2O emission factors for synthetic N-fertilizer and organic residues applied on sugarcane for bioethanol production in Central-Southern Brazil. GCB Bioenergy, 8: 269–280. http://dx.doi.org/10.1111/gcbb.12251

Stehfest, E., & Bouwman, L. 2006. N_2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutrient Cycling in Agroecosystems, 74(3), 207–228. http://dx.doi.org/10.1007/s10705-006-9000-7

Tao, L., Schell, D., Davis, R., Tan, E., Elander, R., and Bratis, A. 2014. NREL 2012 Achievement of Ethanol Cost Targets:Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. http://www.nrel.gov/docs/fy14osti/61563.pdf

Thiruvengadam, A., Besch, M. Carder, D., Oshinuga, A., Pasek, R., Hogo, H., and Gautam, N. 2016. Unregulated, Greenhouse Gas and Ammonia Emissions from Current Technology Heavy-Duty Vehicles. Journal of the Air & Waste Management Association, http://dx.doi.org/10.1080/10962247.2016.1158751

US EPA. 2016. U.S. Greenhouse Gas Inventory Report: 1990-2014. https://www.epa.gov/sites/production/files/2016-04/documents/us-ghg-inventory-2016-main-text.pdf

USDA. 2011. U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2008. http://www.usda.gov/oce/climate_change/AFGG_Inventory/1990_2008/USDA_GHG_Inv_1990-2008_June2011.pdf

USDA. 2016. 2015 Energy Balance for the Corn-Ethanol Industry – USDA. https://www.usda.gov/oce/reports/energy/2015EnergyBalanceCornEthanol.pdf

USDA. 2016. Grain Crushings and Co-Products Production. http://usda.mannlib.cornell.edu/MannUsda/viewDocumentInfo.do?documentID=1899

USDA. 2016. U.S. Agriculture and Forestry Greenhouse Gas Inventory: 1990-2013. http://www.usda.gov/oce/climate_change/AFGG_Inventory/USDA_GHG_Inventory_1990-2013_9_19_16_reduced.pdf

Uusitalo, V., Väisänen, S., Havukainen, J., Havukainen, M., Soukka, R., Luoranen, M. 2014. Carbon footprint of renewable diesel from palm oil, jatropha oil and rapeseed oil, Renewable Energy, Volume 69, September 2014, Pages 103-113, ISSN 0960-1481, http://dx.doi.org/10.1016/j.renene.2014.03.020

Wang A J, Ge Y S, Tan J W, Fu M L, Shah A N, Ding Y et al., 2011. On-road pollutant emission and fuel consumption characteristics of buses in Beijing. Journal of Environmental Sciences, 23(3): 419–426. http://dx.doi.org/10.1016/S1001-0742(10)60426-3

Wang, M. et al. 2012. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use. Environ. Res. Lett. 7 045905. http://dx.doi.org/10.1088/1748-9326/7/4/045905

Wang, M., Han, J., Dunn, J., Cai, H. and Elgowainy, A. 2012. Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for

US use. Supplementary material. http://iopscience.iop.org/1748-9326/7/4/045905/media/erl444331suppdata.pdf

Wang, M., Hou, H., Arora, S. 2011. Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context. Energy Policy. Volume 39, Issue 10, October 2011, Pages 5726–5736. http://dx.doi.org/10.1016/j.enpol.2010.03.052

Wang, Z., Dunn, J., Wang, M. 2014. Updates to the Corn Ethanol Pathway and Development of an Integrated Corn and Corn Stover Ethanol Pathway in the GREET Model. https://greet.es.anl.gov/files/update-corn-ethanol-2014

Yoon, S., Collins, J., Thiruvengadam, A., Gautam, M., Herner, J., Ayala, A., 2013. Criteria Pollutant and Greenhouse Gas Emissions from CNG Transit Buses Equipped with Three-Way Catalysts Compared to Lean-Burn Engines and Oxidation Catalyst Technologies. J. Air Waste Manage. Assoc. 63(8):926–933.

Z. Ramedani, S. Rafiee, M.D. Heidari. 2011. An investigation on energy consumption and sensitivity analysis of soybean production farms, Energy, Volume 36, Issue 11, November 2011, Pages 6340-6344, ISSN 0360-5442, http://dx.doi.org/10.1016/j.energy.2011.09.042

Zhang, S., Wu, Y., Liu, H., Huang, R., Yang, L., Li, Z., Fu, L., Hao, J. 2014. Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing, Applied Energy, Volume 113, January 2014, Pages 1645-1655, ISSN 0306-2619, http://dx.doi.org/10.1016/j.apenergy.2013.09.017

10. GLOSSARY

ANL	Argonne National Laboratory
ARMS	Agricultural Resource Management Survey
BTU	British Thermal Unit
Bu	Bushel
CARB	California Air Resources Board
CDO	Corn Distillers' Oil
CDS	Condensed distillers solubles
CH_4	Methane
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
CONCAWE	A division of the European Petroleum Refiners Association
CRC	Coordinating Research Council
CWT	Hundred weight (100 lbs.)
DDG	Distillers' Dried Grains
DDGS	Distillers' Dried Grains with solubles
DOE	Department of Energy
DWG	Distillers' Wet Grains
EDF	Environmental Defense Fund
EF	Emission Factor
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EROEI	Energy Return over Energy Invested
FAO	Food and Agriculture Organization
FLIGHT	Facility Level Information on Greenhouse Gases Tool
FSU	Former Soviet Union
GHG	Greenhouse Gases
GNOC	Global Nitrous Oxide Calculator
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model by Argonne National Laboratory
HHV	Higher heating Value
HPDI	High Pressure Direct Injection
ICCT	International Council on Clean Transportation
IOGP	International Association of Oil & Gas Producers
IPCC	Intergovernmental Panel on Climate Change
JEC	Joint Research Centre-EUCAR-CONCAWE consortium
JRC	Joint Research Centre
Kg	Kilogram
kWh	Kilowatt-hour
lb	Pound
LCA	Lifecycle Assessment
LEAP	Livestock Environmental Assessment and Performance) Partnership
LHV	Lower Heating Value
MJ	Mega Joule
MPa	Mega Pascal
MT	Metric tonne
N_2O	Nitrous Oxide
NIR	National Inventory Report
OPGEE	Oil Production Greenhouse gas Emissions Estimator
PSI	Pounds per Square Inch

RD	Renewable Diesel
RED	Renewable Energy Directive
UNFCCC	United Nations Framework Convention on Climate Change
USDA	United States Department of Agriculture

11. Appendix 1 – Corn Ethanol Literature Search

Google Scholar was used to search for papers that considered various search terms related to corn ethanol production. In all cases the search was limited to the post 2010 period. The number of papers returned is smaller the more specific the search term is made.

11.1 Search Terms - Corn N_2O Emissions

7,860 results

Towards an agronomic assessment of **N_2O emissions**: a case study for arable crops
JW Van Groenigen, GL Velthof… - European Journal of …, 2010 - Wiley Online Library
... function. (b) Possible relationships between N application rate and N_2O **emission**: the IPCC default **emission** factor (I), the default **emission** factor plus background **emissions** (II), and an exponential relationship (III). (c) Yield **...**
Cited by 286

Nitrogen fertilizer management for nitrous oxide (**N_2O**) mitigation in intensive **corn** (Maize) production: an **emissions** reduction protocol for US Midwest agriculture
N Millar, GP Robertson, PR Grace, RJ Gehl… - … Adaptation Strategies for …, 2010 - Springer
Abstract Nitrous oxide (N_2O) is a major greenhouse gas (GHG) product of intensive agriculture. Fertilizer nitrogen (N) rate is the best single predictor of N_2O **emissions** in row-crop agriculture in the US Midwest. We use this relationship to propose a transparent, **...**
Cited by 143

Nonlinear nitrous oxide (**N_2O**) response to nitrogen fertilizer in on-farm **corn** crops of the US Midwest
JP Hoben, RJ Gehl, N Millar, PR Grace… - Global Change …, 2011 - Wiley Online Library
... (2010), 150 compared with 90 kg N ha −1 doubled N_2O **emissions** (16.3 vs. 37.1 g N 2 O–N ha^{-1} day^{-1} , respectively) but only slightly increased **corn** grain yields (9.5 vs. 10.3 Mg ha^{-1}). Others have also found evidence of nonlinear N_2O **emission** responses (Bouwman et **...**
Cited by 168

Global meta analysis of the nonlinear response of soil nitrous oxide (**N_2O**) **emissions** to fertilizer nitrogen
I Shcherbak, N Millar… - Proceedings of the …, 2014 - National Acad Sciences
... For example, estimates of absolute N_2O **emission** rates for moderately fertilized grain crops, (eg, US midwestern **corn** fertilized at an N input of 150 **...** For crops underfertilized at an N input of 50 kg·ha^{-1} for example, N_2O **emissions** will be overestimated by 25% (0.5 vs. **...**
Cited by 103

Climate, duration, and N placement determine **N_2O emissions** in reduced tillage systems: a meta-analysis
C Kessel, R Venterea, J Six… - Global Change …, 2013 - Wiley Online Library
... Moreover, when soil moisture conditions are sub-optimal for heterotrophic denitrification, a third source of soil N_2O **emission** is through the nitrifier denitrification process which can be a more significant contributor to total N_2O **emissions** than denitrification (Kool et al., 2011). **...**
Cited by 81

11.2 SEARCH TERMS - CORN N_2O EMISSIONS "LITERATURE SURVEY"

The inclusion of the "Literature Survey" was meant to identify papers that considered multiple studies or site to reduce the papers that studied a specific field with its unique soil properties, climate, and production practices.

286 results

Towards an agronomic assessment of **N_2O emissions**: a case study for arable crops
JW Van Groenigen, GL Velthof… - European Journal of …, 2010 - Wiley Online Library

... Nitrous oxide emissions expressed as a percentage of applied anhydrous NH_3 fertilizer increased from 0.1% at **...** with largest N fertilizer application rates (12 data points out of 25), but **maize** studies were **...** Finally, indirect **emissions** of N_2O from volatilized NH_3 and leached NO **...**
Cited by 286

Climate, duration, and N placement determine **N_2O emissions** in reduced tillage systems: a meta-analysis
C Kessel, R Venterea, J Six… - Global Change …, 2013 - Wiley Online Library
... to feed a growing world population, there have also been undesirable consequences, including increased **emissions** of **nitrous oxide** (N_2O**...** (2011), USA, Minnesota, 12, **maize**, humid, NT, **...** process which can be a more significant contributor to total N_2O **emissions** than denitrification **...**
Cited by 81

Breeding **maize** for a bioeconomy: a **literature survey** examining harvest index and stover yield and their relationship to grain yield
AJ Lorenz, TJ Gustafson, JG Coors, N Leon - Crop Science, 2010 - dl.sciencesocieties.org
... Breeding **Maize** for a Bioeconomy: A **Literature Survey** Examining Harvest Index and Stover Yield and Their Relationship to Grain Yield. **...** In contrast to what has been observed in other crops, gains in **maize** grain yield over time in the US **Corn** Belt have been accompanied **...**
Cited by 60

Closing the yield gap could reduce projected greenhouse gas **emissions**: a case study of **maize** production in China
Z Cui, S Yue, G Wang, Q Meng, L Wu… - Global change …, 2013 - Wiley Online Library
... Next article in issue: Initial **nitrous oxide**, carbon dioxide, and methane costs of converting conservation reserve program **...** and the corresponding yield using \$0.37 kg −1 and \$0.78 kg^{-1} for **maize** grain and **...** N ha^{-1} , and the N_2O **emission** intensity (ie, N_2O **emissions** per unit **...**
Cited by 37

An agronomic assessment of greenhouse gas **emissions** from major cereal crops
B Linquist, KJ Groenigen… - Global Change …, 2012 - Wiley Online Library
... in **N_2O** flux dynamics in a Danish wetland – effects of plant-mediated gas transport of **N_2O** and O_2 **...** Although rice systems have been identified as a substantial source of CH 4 **emissions**, the radiative **...** that (i) yield-scaled GWP estimates are similar for rice, wheat, and **maize** and (ii **...**
Cited by 166

Differentiation of **nitrous oxide emission** factors for agricultural soils
JP Lesschen, GL Velthof, W de Vries, J Kros - Environmental Pollution, 2011 - Elsevier

... 1. Introduction. **Nitrous oxide** (N_2O) is one of the major greenhouse gasses with a contribution of 8% to the anthropogenic global warming (IPCC, 2007). **...** (2004) found much higher N_2O **emissions** on clay soil compared to sandy soil under **maize** land. **...**
Cited by 64

Mitigating **nitrous oxide emissions** from **corn** cropping systems in the midwestern US: potential and data gaps
C Decock - Environmental science & technology, 2014 - ACS Publications
... first place, N_2O **emissions** could also be mitigated by enhancing the reduction of N_2O to N_2 .(7) **Nitrous oxide** reduction relative **...** Canada were identified through a literature search in March 2012 using the Web of Science (keywords 'N_2O' and '**corn**' or '**maize**'), and through **...**
Cited by 19

Soil **nitrous oxide emissions** following crop residue addition: a meta-analysis
H Chen, X Li, F Hu, W Shi - Global change biology, 2013 - Wiley Online Library
... Soil **nitrous oxide emissions** following crop residue addition: a meta-analysis. **...** when WFPS was <90%, indicating stimulations of crop residue addition on soil N_2O **emissions**, and the **...** A recent study also showed that soil amendment of crop residue (**maize** stover) with C : N ratio **...**
Cited by 40

Closing the N-use efficiency gap to achieve food and environmental security
Z Cui, G Wang, S Yue, L Wu, W Zhang… - … science & technology, 2014 - ACS Publications
... details are listed in Supporting Information Tables S1–S4 for rice systems, Tables S5–S7 for wheat systems, and Tables S8–S10 for **maize** systems. **...** Nr and Total N_2O **Emission** Response to Added N Application The responses of direct N_2O **emissions**, NH_3 **...**
Cited by 16

Best nitrogen management practices to decrease greenhouse gas **emissions**
JW van Groenigen, O Oenema, KJ van Groenigen… - Better …, 2011 - farmresearch.com
... Crops included **maize** (**corn**), wheat, potato, onion, and flooded rice **...** Yield-scaled **N_2O emissions** showed no increase up to a small N surplus of approximately 10 kg N **...** soils are the main source of human-caused **emissions** of the greenhouse gas (GHG) **nitrous oxide** (**N_2O**) to the **...**
Cited by 2

Nitrogen fertilizer effects on irrigated conventional tillage **corn** yields and soil carbon and nitrogen pools
CP Jantalia, AD Halvorson - Agronomy journal, 2011 - dl.sciencesocieties.org
... 1993. ↵ Gregorich, EG, BC Liang, BH Ellert, and CF Drury. Fertilization effects on soil organic matter turnover and **corn** residue c storage. doi:. Soil Sci. **...** Nitrogen, tillage, and crop rotation effects on **nitrous oxide emissions** from irrigated cropping systems. doi:. J. Environ. Qual. **...**
Cited by 24

11.3 Search Terms - Corn N_2O Meta-analysis

3,260 results

Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N_2O **and NO emissions from agricultural soils:** meta-analysis

H Akiyama, X Yan, K Yagi - Global Change Biology, 2010 - Wiley Online Library
... Agricultural fields are an important anthropogenic source of atmospheric nitrous oxide (N_2O) and nitric oxide (NO ... ie, nitrification inhibitors (NIs), polymer-coated fertilizers (PCFs), and urease inhibitors (UIs)] on N_2O and NO emissions, we performed a meta-analysis using field ...
Cited by 204

Climate, duration, and N placement determine N_2O **emissions in reduced tillage systems: a** meta-analysis
C Kessel, R Venterea, J Six… - Global Change …, 2013 - Wiley Online Library
... population, there have also been undesirable consequences, including increased emissions of nitrous oxide (N_2O ... Our objective was to conduct a meta-analysis of peer-reviewed studies to evaluate ... data were readjusted at 14.5% and 16.5% moisture content for maize (Zea mays ...
Cited by 82

Linear and nonlinear dependency of direct nitrous oxide **emissions on fertilizer nitrogen input: A** meta-analysis
DG Kim, G Hernandez-Ramirez, D Giltrap - Agriculture, ecosystems & …, 2013 - Elsevier
... Nitrogen input; Nitrous oxide; Emission factor; IPCC methodology; Meta-analysis; Open-access database. ... Nitrous oxide can be mainly produced from (1) aerobic autotrophic nitrification, the stepwise oxidation ... In maize (Zea mays L.) fields in southwest Michigan USA, direct N_2O...
Cited by 74

Towards an agronomic assessment of N_2O **emissions: a case study for arable crops**
JW Van Groenigen, GL Velthof… - European Journal of …, 2010 - Wiley Online Library
... Nitrous oxide emissions expressed as a percentage of applied anhydrous NH 3 fertilizer increased from ... Because of the wide variety of agroecosystems included in the meta-analysis study, N ... For example, maize studies dominated in the group with largest N fertilizer application ...
Cited by 287

Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis **of literature data**
X Liu, A Zhang, C Ji, S Joseph, R Bian, L Li, G Pan… - Plant and soil, 2013 - Springer
... S, Enders A, Hanley K, Hyland C, Zimmerman AR, Lehmann J (2012) Corn growth and ... Crowley D (2010) Effect of biochar amendment on yield and methane and nitrous oxide emissions from ... Li LQ, Zheng JW, Zhang XH (2012b) Effect of biochar amendment on maize yield and ...
Cited by 109

11.4 Search Terms - Energy efficiency of "corn ethanol"

The search terms and top results are presented below. Papers that aggregated primary data are discussed in the main body of the report.

8,310 results

The top papers are identified below. In many cases the data in the papers was much older than the published date of the report and thus of little current value.

Well-to-wheels **energy** use and greenhouse gas emissions of **ethanol** from **corn**, sugarcane and cellulosic biomass for US use
M Wang, J Han, JB Dunn, H Cai… - Environmental …, 2012 - iopscience.iop.org

... Well-to-wheels **energy** use and greenhouse gas emissions of **ethanol** from **corn**, sugarcane and cellulosic biomass for US use. **... Corn ethanol** production. **Ethanol** yield: l/tonne of **corn**, 425, 412, 439, Triangular a. **Ethanol** plant **energy** use: MJ/l of **ethanol**, 7.49, 6.10, 8.87, Normal a **...**
Cited by 133

[**Energy** and greenhouse gas emission effects of **corn** and cellulosic **ethanol** with technology improvements and land use changes]
MQ Wang, J Han, Z Haq, WE Tyner, M Wu… - Biomass and …, 2011 - Elsevier
... Energy use is the second largest cost component (after **corn** feed cost) in **ethanol** plant operation. **...**During that period, engineering firms and other third parties began to market and introduce **energy**-**efficient** technologies and processes into **ethanol** plants [40] and [41]. **...**
Cited by 105

[2008 National dry mill **corn ethanol** survey]
S Mueller - Biotechnology letters, 2010 - Springer
... once 0.633 kg DDGS and 0.257 kg WDGS as well as 0.006 l of **corn** oil. **...** plants is not due to chance variation, and can be attributed to more **efficient** technologies **...** Since the older plant group also shows significant reductions, one must conclude that **energy efficiency** retrofits were **...**
Cited by 34

[Anaerobic digestion of thin stillage for **energy** recovery and water reuse in **corn-ethanol** plants]
A Alkan-Ozkaynak, KG Karthikeyan - Bioresource technology, 2011 - Elsevier
... Anaerobic digestion of treated-thin stillage can be expected to improve the water and **energy efficiencies** of dry grind **corn**-**ethanol** plants. Highlights. **...** Our treatment train can improve **energy**/water use **efficiency** in **ethanol** plants. Keywords. **...**
Cited by 33

[**New perspectives on the** energy **return on (**energy**) investment (EROI) of** corn ethanol]
DJ Murphy, CAS Hall, B Powers - Environment, development and …, 2011 - Springer
... In this analysis, we adopt the boundaries used by Patzek (2004) so that our results agree with the principles of **conservation** of mass/**energy**. 1.4 Natural gradients of corn and **corn ethanol** production. **...** Farrell et al. (2006).
Corn **energy** content. **...** Biorefinery **efficiency** for **corn ethanol**. **...**
Cited by 52

[Year in review—EROI or **energy** return on (**energy**) invested]
DJ Murphy, CAS Hall - Annals of the New York Academy of …, 2010 - Wiley Online Library
... One side argues that as economies become wealthy they use less **energy** per dollar output, ie, become more **efficient**. **...** GDP has been continuously and progressively overestimated, and there may have been little or no increase in the **efficiency** with which **energy** has been **...**
Cited by 304

11.5 Search Terms - Energy intensity of "corn ethanol"

This search returned 6,870 results. The top papers are identified below.

[Well-to-wheels **energy** use and greenhouse gas emissions of **ethanol** from **corn**, sugarcane and cellulosic biomass for US use]
M Wang, J Han, JB Dunn, H Cai… - Environmental …, 2012 - iopscience.iop.org

... In particular, based on a consistent and systematic model platform, we estimate life-cycle **energy consumption** and GHG emissions from using **ethanol** produced from five feedstocks: **corn**, sugarcane, **corn** stover, switchgrass and miscanthus. **...**
Cited by 133

Energy and greenhouse gas emission effects of **corn** and cellulosic **ethanol** with technology improvements and land use changes
MQ Wang, J Han, Z Haq, WE Tyner, M Wu… - Biomass and …, 2011 - Elsevier
... Fourth, we collected and analyzed US farming data on both chemicals and **energy** use to develop historical trends of US farming chemical and **energy** use **intensity** [33]. **...** US **Consumption** level a, 0.778, 0.304, 0.022, **...** 3.4. Chemicals and **energy** use **intensities** of **corn** farming. **...**
Cited by 105

Optimization of **energy** and water **consumption** in **corn** based **ethanol** plants
E Ahmetović, M Martín… - Industrial & Engineering …, 2010 - ACS Publications
In this paper we study the simultaneous **energy** and water **consumption** in the conceptual design of **corn**-based **ethanol** plants. A major goal is to reduce the freshwater **consumption** and wastewater discharge. We consider the **corn**-based **ethanol** plant reported in **...**
Cited by 76

Year in review—EROI or **energy** return on (**energy**) invested
DJ Murphy, CAS Hall - Annals of the New York Academy of …, 2010 - Wiley Online Library
... and efficiency means output over input, yet the units are given as **intensity**, ie, MJ **...** if the economy is to function, and only after that are discretionary investments or **consumption** possible **...** can grow indefinitely, but rather, in the face of declining EROIs and fossil **energy** supplies, can **...**
Cited by 304

Nonrenewable **energy** cost of **corn-ethanol** in China
Q Yang, GQ Chen - **Energy** Policy, 2012 - Elsevier
... NEIED is proposed to identify the nonrenewability of believed renewable **energies**. Significant cases could be identified for different ranges of NEIED values. **...** Tracing back to the primary nonrenewable **energy consumption**, the nonrenewable **energy**-**intensity** coefficients for **...**
Cited by 29

11.6 Search Terms - Benchmarking of "corn ethanol"

This search term returned 1,130 results. The most relevant papers are shown below.

Algae biodiesel has potential despite inconclusive results to date
X Liu, AF Clarens, LM Colosi - Bioresource technology, 2012 - Elsevier
... results, and, more importantly, enables direct comparison between algae bioenergy and selected **benchmarks**. **...** exhibits GHG emissions that are highly consistent with both **benchmark** biofuels **...** Notably, this represents the first conclusive **benchmarking** of algae biofuels relative to **...**
Cited by 78

The impact of **ethanol** and **ethanol** subsidies on **corn** prices: revisiting history
BA Babcock, JF Fabiosa - 2011 - works.bepress.com
... Using 2004 **corn** prices of $2.06 per bushel as a **benchmark**, we can calculate how much of the **corn** price changes since 2004 can be attributed to **ethanol** subsidies, to market-based expansion of **ethanol**, and to all other supply and demand forces at work in the **corn** market. **...**
Cited by 36

Optimization of energy and water consumption in **corn**-based **ethanol** plants
E Ahmetović, M Martín… - Industrial & Engineering …, 2010 - ACS Publications
... 3 **Corn**-Based **Ethanol** Production Process. **...** In spite of bioethanol's environmental benefits like lower emissions, the volume of production of **corn ethanol** to meet the US policies(43) has raised questions regarding its technological feasibility as an alternative fuel. **...**
Cited by 76

A comparison of commercial **ethanol** production systems from Brazilian sugarcane and US **corn**
HL Chum, E Warner, JEA Seabra… - Biofuels, bioproducts …, 2014 - Wiley Online Library

... Sugarcane self-**benchmarking** systems showed RER values of 7.0 in 2002 to 9.4 in **...** see Section 1 of the supplemental information for more details) to **benchmark** these aspects **...** Within these boundaries, GHG emission reduction and energy production **benchmarks** are still subject **...**
Cited by 22

Energy and water optimization in biofuel plants
IE Grossmann, M Martín - Chinese Journal of Chemical Engineering, 2010 - Elsevier
... http://www.transportation.anl.gov/pdfs/TA/58.pdf. 37; M. Wang, M. Wu, H. Huo; "Life-cycle energy and greenhouse gas emission impacts of different **corn ethanol** plant types". Environ. **...** 40; Minnesota Technical Assistance Program, MTAP; "**Ethanol benchmarking** and best practices. **...**
Cited by 49

11.7 Search Terms - Energy benchmarking of "corn ethanol"

This term returned 1,110 papers published since 2010, only twenty fewer than the more general benchmarking term indicating that most benchmarking exercises considered energy.. The most relevant papers are shown below.

2008 **Energy** Balance for the **Corn-Ethanol** Industry
H Shapouri - 2011 - books.google.com
2008 **Energy** Balance for the **Corn-Ethanol** Industry Abstract The Agricultural Resource Management Survey of **corn** growers for the year 2005 and the 2008 survey of dry mill **ethanol** plants are used to estimate the net **energy** balance of **corn ethanol**. **...**
Cited by 39

Optimization of **energy** and water consumption in **corn**-based **ethanol** plants
E Ahmetović, M Martín… - Industrial & Engineering …, 2010 - ACS Publications
... Optimization of **Energy** and Water Consumption in **Corn**-Based **Ethanol** Plants. **...** 4 Review of **Energy** Optimization in **Corn**-Based **Ethanol** Plant. Given the dry milling **ethanol** process in Figure 2, Karuppiah et al. (2008)(40) optimized **...**
Cited by 76

Algae biodiesel has potential despite inconclusive results to date
X Liu, AF Clarens, LM Colosi - Bioresource technology, 2012 - Elsevier
... baseline algae case exhibits GHG emissions that are highly consistent with both **benchmark** biofuels. Notably, this represents the first conclusive **benchmarking** of algae biofuels relative to their terrestrial **...** Smaller green circles depict net **energy** ratios and greenhouse gas (GHG **...**
Cited by 78

Energy and water optimization in biofuel plants

IE Grossmann, M Martín - Chinese Journal of Chemical Engineering, 2010 - Elsevier
... 37; M. Wang, M. Wu, H. Huo; "Life-cycle **energy** and greenhouse gas emission impacts of different **corn ethanol** plant types". Environ. Res. Lett., 2 (2007), pp. 1–13. **...** 40; Minnesota Technical Assistance Program, MTAP; "**Ethanol benchmarking** and best practices. **...**
Cited by 49

11.8 Search Terms - kWh/gallon of corn ethanol

Looking for just the term kWh/gallon of corn ethanol to investigate the electric power use produces only 9 results. The most relevant papers are shown below.

2008 Energy Balance for the **Corn-Ethanol** Industry
H Shapouri - 2011 - books.google.com
... Page 2. 2008 Energy Balance for the **Corn**-**Ethanol** Industry. The Agricultural Resource Management Survey of **corn** growers for the year 2005 and the 2008 survey of dry mill **ethanol** plants are used to estimate the net energy balance of **corn ethanol**. **...**
Cited by 39

Sugarcane as an energy source
MRLV Leal, AS Walter, JEA Seabra - Biomass Conversion and Biorefinery, 2013 - Springer
... The works of NREL [28, 29] have suggested values for **ethanol** yields for **corn** stover as feed- stock of 374 l/tonne stover (db) [28] to 330 l/tonne stover (db) [29]; in the latter reference, the surplus electricity is estimated as 1.8 **kWh**/**gallon ethanol** or 157 kWh/tonne stover (db). **...**
Cited by 17

Land-use and alternative bioenergy pathways for waste biomass
JE Campbell, E Block - Environmental science & technology, 2010 - ACS Publications
... Life-cycle components included emissions from building the cellulosic refinery (29 g $CO_{2\text{-}e}$/l **ethanol**) and emissions offsets from electricity coproducts from the lignin component of the waste (0.57 **kWh**/**gallon ethanol**) (25). **...**
Cited by 20

A Variable Cost Function for **Corn Ethanol** Plants in the Midwest
JP Sesmero, RK Perrin… - Canadian Journal of …, 2015 - Wiley Online Library
Page 1. A Variable Cost Function for **Corn Ethanol** Plants in the Midwest Juan P. Sesmero, Richard K. Perrin and Lilyan E. Fulginiti **...** This study estimates a variable cost function for **corn ethanol** plants, using data from a unique survey of Midwest plants. **...**

11.9 Search Terms - BTU/gallon of "corn ethanol"

Looking for just the term BTU/gallon of corn ethanol produces 43 results. The most relevant papers are shown below.

2008 Energy Balance for the **Corn-Ethanol** Industry
H Shapouri - 2011 - books.google.com
... Replace 50% Biomass power, Replace 100% w/**Corn** ASPEN DDG credit Survey DDG credit of Natural Gas (NG) Stover of NG & elec w/ **Corn** Stover in **BTU** / **gallon Corn** Production 9,811 9,811 9,811 9,811 **Corn** Transport 1,430 1,430 1,430 1,430 **Ethanol** Conversion 40,019 1 **...**
Cited by 39

Detailed report: 2008 National dry mill **corn ethanol** survey
S Mueller - Energy Resources Center, University of Illinois at …, 2010 - erc.uic.edu

... but produces 5.3% more **ethanol** per bushel. On average, a dry-mill **corn ethanol** plant in 2008 • utilizes 25,859 **Btu**/**gallon** (LHV, anhydrous **ethanol**) of thermal energy and 0.74 kWh of electricity per anhydrous gallon of **ethanol ...**
Cited by 11

Sustainability study of hydrogen pathways for fuel cell vehicle applications
JJ Hwang - Renewable and Sustainable Energy Reviews, 2013 - Elsevier
... Ethanol production energy use: dry mill, 26,856 **Btu**/**gallon**. **Ethanol** production energy use: wet mill, 47,409 **Btu**/**gallon**. **Corn ethanol**, share of **ethanol** plant type, dry milling plant, 88.6%. **Corn ethanol**, share of **ethanol** plant type, wet milling plant, 11.4%. **...**
Cited by 38

Biofuel economics in a setting of multiple objectives and unintended consequences
WK Jaeger, TM Egelkraut - Renewable and Sustainable Energy Reviews, 2011 - Elsevier
... Mandated US **corn ethanol** production for 2025 reduces US petroleum input use by 1.75% and would have negligible net effects on CO_2 emissions; and although EU imports of Brazilian **ethanol** may look better given the high costs of other alternatives, this option is equivalent **...**
Cited by 44

An engineering and economic evaluation of quick germ–quick fiber process for dry-grind **ethanol** facilities: Analysis
LF Rodríguez, C Li, M Khanna, AD Spaulding… - Bioresource …, 2010 - Elsevier
... although the QQ process incorporates the wet milling front end, it uses the same amount of water for each gallon **ethanol** produced as the **...** This is due to the fact that the water required for **corn** soaking and germ/fiber washing can be met in both cases by that **... Btu**/**gallon**, **Btu**/**gallon**. **...**
Cited by 11

12. Appendix 2 – Petroleum Literature Search

12.1 Search Terms - "energy consumption" "crude oil production" -algae -ethanol – biodiesel

424 Results. The top 20 results are shown below.

International energy outlook
A Sieminski - Energy Information Administration (EIA), 2014 - 199.36.140.204
... 3 world **energy consumption**, 1990-2040 quadrillion Btu **...** Administration Note: Petroleum production includes crude oil, natural gas liquids, condensates, refinery processing gain, and other liquids, including biofuels; barrels per **...** estimated unplanned **crude oil production** outages **...**
Cited by 45

Energy and renewable energy scenario of Pakistan
MA Sheikh - Renewable and Sustainable Energy Reviews, 2010 - Elsevier
... 4. **Crude oil production** per day. **...** The final **energy consumption** by sector during year 2007–2008 was 39.41 MTOE, Fig. **...** These types include solar (PV and thermal), wind, biogas, microhydel/canal fall, **biodiesel** production, biomass/waste to energy production, geothermal, tidal **...**
Cited by 106

Are fluctuations in energy variables permanent or transitory? A survey of the literature on the integration properties of energy consumption and production
R Smyth - Applied Energy, 2013 - Elsevier
... [16], OPEC countries, 1973:1–2008:10 (monthly data), **Crude oil production**, Fractional integration **...** and Aslan [23], Turkey, Sectors, 1970–2006 (annual data), **Energy consumption** per capita, **...** monthly data over different periods, Production of renewable energy, biofuels and biomass **...**
Cited by 54

The end of Peak Oil? Why this topic is still relevant despite recent denials
I Chapman - Energy Policy, 2014 - Elsevier
Up until recently Peak Oil was a major discussion point crossing from academic research into mainstream journalism, yet it now attracts far less interest. This.
Cited by 76

Global energy security and the implications for the EU
F Umbach - Energy Policy, 2010 - Elsevier
... as the world's largest oil producer and exporter needs to increase its **crude oil production** from the **...** as the increase in the share of renewable energies in the overall EU **energy consumption** by 2020 **...** with the increasing critical global debate on the first generation of biofuels as a **...**
Cited by 189

Open-source LCA tool for estimating greenhouse gas emissions from crude oil production using field characteristics
HM El-Houjeiri, AR Brandt, JE Duffy - Environmental science & …, 2013 - ACS Publications
... For example, one can compare palm oil **biodiesel** to oil-sands-derived **...** OPGEE calculates the energy use and emissions from **crude oil production** using engineering fundamentals **...** process stage calculations and compile them into summed **energy consumption** (including energy **...**
Cited by 21

Evidence of long memory behavior in US renewable energy consumption
CP Barros, LA Gil-Alana, JE Payne - Energy Policy, 2012 - Elsevier
... and Security Act of 2007, created renewable energy production tax credits, federal income tax credits for renewable energy systems, customer net metering services, and financial incentives for the expansion of biofuels to stimulate renewable **energy consumption**. **...**
Cited by 33

China′ s energy security: Oil and gas
K Wu - Energy Policy, 2014 - Elsevier
... doubt that the share of natural gas in China′s overall primary **energy consumption** will continue **...** of other forms of renewable energy such as wind power, solar power, biofuels (O'Kray **...** Over the next five to ten years, China′s **crude oil production** is expected to increase moderately **...**
Cited by 23

Environmental assessment of energy production based on long term commercial willow plantations in Sweden
S González-García, B Mola-Yudego, I Dimitriou… - Science of the total …, 2012 - Elsevier
The present paper analyzed the environmental assessment of short rotation willow plantations in Sweden based on the standard framework of Life Cycle Assessment.
Cited by 37

US disaggregated renewable energy consumption: persistence and long memory behavior
CP Barros, LA Gil-Alana, JE Payne - Energy Economics, 2013 - Elsevier
... OPEC and non-OPEC countries to reveal threshold effects in **crude oil production** over two **...** on the previous research with respect to US renewable **energy consumption**, we extend **...** the various components (hydropower, geothermal, solar, wind, wood, waste, and biofuels) of US **...**
Cited by 15

Understanding renewable energy systems
V Quaschning - 2016 - books.google.com
'What it costs to boil water' from 1994 Energy conversion chain, losses and carbon dioxide emissions from boiling water Annual global **crude oil production** Global primary **energy consumption** in 2011 by **...**
Cited by 290

IEA World Energy Outlook 2010—A comment
H Khatib - Energy policy, 2011 - Elsevier
... annual rate of 2.2%, compared to 1.2% in case of primary **energy consumption**, thus indicating **...** demand continues to grow steadily, reaching about 99 mb/d (excluding biofuels) by 2035 **...** This means that conventional **crude oil production**, as we know it, has peaked at 70 mb/d in **...**
Cited by 12

Thailand's energy security indicators
J Martchamadol, S Kumar - Renewable and Sustainable Energy Reviews, 2012 - Elsevier
... The renewable energy roadmap (15 years plan during 2008–2022) launched in January 2009 has renewable energy target at the end of 2022 to be 14% of the final **energy consumption** (13.7 Mtoe) for heat, power and biofuels consumption. **...**
Cited by 35

Are shocks to commodity prices persistent?
PK Narayan, R Liu - Applied energy, 2011 - Elsevier

... [23], who consider **biodiesel** production from crude rice bran oil; (g) Narayan and Narayan [24], who examine the effect of commodity price on Vietnam's stock market; and (h) Lee and Lee [25], who consider the efficient market hypothesis for commodity prices. **...**
Cited by 23

Degrowth, expensive oil, and the new economics of energy
S Alexander - Available at SSRN 2153342, 2012 - papers.ssrn.com
... The **biofuel** category also includes wind, solar, and other new renewables. **...** findings] provide clear evidence of the importance of the quantity of **energy consumption** for GDP **... Crude oil production** seems to have reached an undulating plateau, and growth in overall oil supplies is **...**
Cited by 8

Oil palm expansion in Riau province, Indonesia: Serving people, planet, profit?
A Susanti, PPM Burgers - 2011 - dspace.library.uu.nl
... gas and coal) have been the main energy sources, accounting for about 80% of the world's **energy consumption** (World Bank **...** The world's **crude oil production** and consumption **...** from 223 to 743 kHa per Mtoe, and Edwards et al.'s evaluation of all EU **biodiesel** scenarios shows **...**
Cited by 18

Environmental impact assessment of three coal-based electricity generation scenarios in China
X Cui, J Hong, M Gao - Energy, 2012 - Elsevier
... use of hydropower, nuclear power, and other sources (eg, **biofuel** and wind **...** All materials, waste, emissions, and **energy consumption** levels are based on this functional **...** scenario, the direct emissions from electricity production, road transport, **crude oil production**, coal production **...**
Cited by 38

Oil and the world economy: some possible futures
M Kumhof, D Muir - … of the Royal Society of London …, 2014 - rsta.royalsocietypublishing.org
... Figure 1. World **crude oil production** (in million barrels per day). (Online version in colour.). This paper attempts to analyse the implications of downward shifts in the growth rate of world oil production for the world economy. 1 **...**
Cited by 36

Technological feasibility and costs of achieving a 50% reduction of global GHG emissions by 2050: mid-and long-term perspectives
O Akashi, T Hanaoka - Sustainability Science, 2012 - Springer
... The model estimates **energy consumption** and GHG emissions (eg, CO 2 , CH 4 , N 2 O, HFC, PFC **...** Efficient aircraft (eg, engine improvement, weight reduction, drag reduction), **biofuel**. **...** eg, use of instrument air, use of low bleed pneumatic devices), **crude oil production** (eg, flaring **...**
Cited by 29

Affordability of electric vehicles for a sustainable transport system: An economic and environmental analysis
HK Tseng, JS Wu, X Liu - Energy policy, 2013 - Elsevier
... Other estimates suggest that the conventional **crude**-**oil production** could be terminated by 2090 in the US, and the world's oil production will be **...** A life-cycle cost analysis is used to determine the lifetime total costs of ownership, **energy consumption**, and emission abatement. **...**
Cited by 26

12.2 Search Terms - "EROEI" "crude oil production" -algae -ethanol – biodiesel

This search returned 45 results but they were mostly very general in nature.

Peak oil and energy independence: Myth and reality
JW Murray, J Hansen - EOS, Transactions American …, 2013 - Wiley Online Library
... oil includes deep- water oil, tar sands, tight oil (often improperly called oil shale), heavy oil, biofuels, and synthetic **...** rates, the debate about "peak oil" comes down to the prospects for production rate from low- **EROI**—and thus **...** (b) Since 2005, world **crude oil production** has been **...**

Cited by 14

Former BP geologist: peak oil is here and it will 'break economies'
N Ahmed - 2013 - globalwarming-sowhat.com
... **Crude oil production** is heavily concentrated in a small number of countries, and a small number of giant fields, with approximately 100 fields producing 1/2 of global **...** For the US, **EROI** of oil and gas production is 11 and declining; and for unconventional oil and biofuels, it is **...**
Cited by 3

Climate change in the face of peak oil: An unconventional view
International Issues & Slovak Foreign Policy Affairs, 2011 - ceeol.com
... In fact, IEA announced in its last World Energy Outlook, that peak in **crude oil production** reached in 2006 will **...** Oil, declining **EROEI** and the problem with alternatives **...** 35 CAS Hall, R. Powers and W. Schoenberg, "Peak oil, **EROI**, investments and the economy in an uncertain **...**
Cited by 1

When Should We Expect the Peak?
RW Bentley - Introduction to Peak Oil, 2016 - Springer
... itself results from summing a URR of 2200 Gb for 'conventional' oil (**crude oil production** including condensate **...** assuming these to be small over any reasonable timeframe; nor from **biofuel** as not **...** But the intrinsic costs due to relatively low **EROI** ratios (for GTLs, CTLs, kerogen oil **...**

Energy shift: decline of easy oil and restructuring of geo-politics

OR Inderwildi, DA King - Frontiers in Energy, 2016 - Springer
... 2 **Crude oil production** as a function of Brent crude oil price, 1998–2013 [7] **...** Murphy and Hall gauge that shale oil, for instance, has an **EROI** of as little as 5 **...** highly polluting resources such as coal are replaced by renew- ables, energy efficiency measures, and advanced biofuels. **...**

The impact of global climate change and energy scarcity on Mississippi delta restoration
JW Day, M Moerschbaecher - Perspectives on the Restoration of the …, 2014 - Springer
... Indeed, global conventional **crude oil production** appears to have already peaked, and exploration attention is currently **...** The **EROI** for non-conventional sources of oil (oil shale and oil sands) and **...** for other unconventional oil sources such as natural gas plant liquids and biofuels. **...**
Cited by 2

Oil and the world economy: some possible futures
M Kumhof, D Muir - … of the Royal Society of London …, 2014 - rsta.royalsocietypublishing.org
... Figure 1. World **crude oil production** (in million barrels per day). (Online version in colour.). This paper attempts to analyse the implications of downward shifts in the growth rate of world oil production for the world economy. 1 **...**
Cited by 36

Emergy analysis of emerging methods of fossil fuel production
ET Campbell - Ecological Modelling, 2015 - Elsevier
... (2011), measured by **EROI**, energy return **...** In situ Production of Syncrude from Oil Sands, Mining Production of Syncrude from Oil Sands, Tight **Crude Oil Production**, USGS EUR, Tight **Crude Oil Production**, EIA EUR, Marcellus Wet Gas EIA EUR estimate, Marcellus wet gas USGS **...**
Cited by 2

The future of oil: unconventional fossil fuels
KJ Chew - … Transactions of the Royal Society of …, 2014 - rsta.royalsocietypublishing.org
... here, but is dealt with elsewhere in this Theme Issue, comprises gas and liquids manufactured from coal-, gas- or organic-rich shales and non-geological biofuels [1,2]. **...** US **crude oil production**, 1954–2012, by source of production. **...** Energy return on investment (**EROI**): the ratio of **...**
Cited by 21

Shale Fuels: The Solution to the Energy Conundrum?
V Di Nino, I Faiella - European Energy and Climate Security, 2016 - Springer
... Oil production does not include biofuels and refinement efficiency gains. **...** Considering the wellhead **EROI**, the **crude oil production** pattern in the US will slowly decline from 2016, in contrast with the sustained growth assumed in the EIA projections (see Fig. 3). Fig. 3 **...**

General optimization model for the energy planning of industries including renewable energy: A case study on oil sands

M Elsholkami, A Elkamel - AIChE Journal, 2016 - Wiley Online Library
... The **EROI** has a significant impact on the long term viability of oil sands operations, and it is affected by several factors which **...** of energy is required for these operations, which makes the Canadian oil sands one of the most energy intensive crude oil production industries in the ...

The fossil fuels war
JB Foster - Monthly Review, 2013 - search.proquest.com
... accounting for about 20 percent.26 As the energy return on energy investment (**EROEI**) of fossil **...** when he declared on March 7, 2013, that renewables such as "wind, solar, biofuels" would be **...** Washington has used its influence in Iraq to get it to boost its **crude oil production**.34. **...**
Cited by 4

European Union's energy policy from the sustainability perspective
H MANTEUFFEL, M BUKOWSKI - 2012 - ees.uni.opole.pl
... That is why their **EROEI** (Energy Returned on Energy Invested) index is very low, about 3:1 (sometimes even **...** primary energy consumption in Europe and 10% of biofuels share in the transportation fuels in ... Table 11.5 World Crude Oil Production, 1960-2007. Available at:. ...

Earth's Limits: Why Growth Won't Return
K Deffeyes - richardheinberg.com
... 2010 World Energy Outlook, the IEA announced that total annual global **crude oil production** will probably **...** and that total volumes of liquid fuels (including crude oil, biofuels, synthetic oil **...** the amount of energy returned on the energy that's invested in producing energy (**EROEI**). **...**

Technological Innovation as a Factor of Demand for Energy Sources in Automotive Industry
T Mitrova, V Kulagin, D Grushevenko, E Grushevenko - Форсайт, 2015 - cyberleninka.ru
... their direct substitutes by type — petrol (bioethanol, GTL and CTL petrol), diesel (**biodiesel**, GTL and **...** Hook M. (2009) Depletion and Decline Curve Analysis in **Crude Oil Production**, Uppsala: Uppsala University. **...** Z., Dong X., Xu B., Li R., Yin Q., Song C. (2015) **EROI** Analysis for **...**

Cited by 2

Global oil risks in the early 21st century
D Fantazzini, M Höök, A Angelantoni - Energy Policy, 2011 - Elsevier
... The energy obtained from an extraction process divided by the energy expended during the process is the Energy Return on Energy Invested (**EROEI**). **...** Even if there is sufficient capital, substitution has thus far operated with high and even increasing **EROEI** fuel sources. **...**
Cited by 54

The end of Peak Oil? Why this topic is still relevant despite recent denials
I Chapman - Energy Policy, 2014 - Elsevier
Up until recently Peak Oil was a major discussion point crossing from academic research into mainstream journalism, yet it now attracts far less interest. This.
Cited by 76

Views on peak oil and its relation to climate change policy
A Verbruggen, M Al Marchohi - Energy Policy, 2010 - Elsevier
... Carbon intensities of fuels are related to their **EROEI**, 4 being the ratio of MJ energy output to MJ energy input for generating the output (Hall et al., 2008). The average **EROEI** for finding and producing US domestic oil has declined **...**
Cited by 76

The making of Scandinavian ecosocialism
JB Foster - The Politics of Ecosocialism: Transforming Welfare, 2015 - books.google.com
... Rather the peak- ing of conventional **crude oil production** is leading to the exploitation of Alberta's tar **...** are far from cheap and have a much lower energy return on energy invested ratio (**EROI**). **...** energies and materials see separate entry; return on energy investment (**EROEI**) 56–7 **...**
Related articlesCiteSave

Current Commentary: Thorium-based nuclear power
CJ Rhodes - Science progress, 2013 - search.proquest.com
... to any other new technology, on the grand scale, including hydrogen and biofuels, with attendant **...**and most immediate, consequence of a decline in world conventional **crude oil production**, peak oil **...** if they were sought with sufficient assiduousness, noting that the **EROEI** would fall **...**
Cited by 5

12.3 SEARCH TERMS – OPGEE "CRUDE OIL"

The OPGEE model has been developed by Adam Brandt to estimate energy use and GHG emissions associated with various crude oil fields. There were 43 papers returned with these search terms. The top 20 are listed below.

Open-source LCA tool for estimating greenhouse gas emissions from crude oil production using field characteristics
HM El-Houjeiri, AR Brandt, JE Duffy - Environmental science & …, 2013 - ACS Publications
... This functional unit is held constant across different production processes included in **OPGEE**, and the energy content of **crude oil** at the refinery gate is calculated based on API gravity (no account of effects of other **crude oil** characteristics such as sulfur content). **...**
Cited by 21

Energy intensity and greenhouse gas emissions from crude oil production in the Eagle Ford Region: Input data and analysis methods
A Ghandi, S Yeh, AR Brandt, K Vafi, H Cai… - UC Davis Inst. of …, 2015 - researchgate.net

... in the Eagle Ford Shale in South Texas from 2010 through 2013 and calculates energy consumption and greenhouse gas (GHG) emissions associated with the **crude oil** and NG extraction using the Oil Production Greenhouse Gas Emissions Estimator (**OPGEE**) model. **...**
Cited by 5

Reproducibility of LCA models of crude oil production
K Vafi, AR Brandt - Environmental science & technology, 2014 - ACS Publications
... of total hydrocarbon produced). Unlike other WTR studies, the **OPGEE** comparison to NETL does not include **crude oil** transportation emissions, so the functional unit is 1 MJ of **crude oil** produced and processed for transport. **...**
Cited by 5

Energy consumption and greenhouse gas emissions in the recovery and extraction of crude bitumen from Canada's oil sands
B Nimana, C Canter, A Kumar - Applied Energy, 2015 - Elsevier
... for 52% of the total crude bitumen production remaining from surface mining [8]. The bitumen produced from surface mining and SAGD is mixed with a diluent (naphtha or natural gas based condensate) for transportation to an upgrader (to produce synthetic **crude oil** [SCO], a **...**
Cited by 8

Uncertainty of Oil Field GHG Emissions Resulting from Information Gaps: A Monte Carlo Approach
K Vafi, AR Brandt - Environmental science & technology, 2014 - ACS Publications
... fuel sectors and in other sectors, as has been shown clearly in the biofuels literature.(16, 17) This study focuses solely on the first source of uncertainty, as we judge it to be among the largest sources of uncertainty in **crude oil** modeling. Future analysis of the **OPGEE** model will **...**
Cited by 7

Oil Production Greenhouse Gas Emissions Estimator OPGEE v1. 0
HM El-Houjeiri, AR Brandt - Work, 2012 - pangea.stanford.edu
... 15 3.2 Default land use GHG emissions from field drilling and development in **OPGEE** for conventional oil operations [g CO_2 eq./MJ of **crude oil** produced]. Data from Yeh et al. (2010). . . . 35 3.1 Default inputs for drilling calculations. . . . . **...**
Cited by 1

Life cycle energy and greenhouse gas emissions from transportation of Canadian oil sands to future markets
T Tarnoczi - Energy policy, 2013 - Elsevier
... Oil sands transportation diversification is important for preventing discounted crude pricing. Current life cycle assessment (LCA) models that assess greenhouse gas (GHG) emissions from **crude oil** transportation are linearly-scale and fail to account for project specific details. **...**
Cited by 7

Energy Return on Investment (EROI) for Forty Global Oilfields Using a Detailed Engineering-Based Model of Oil Production
AR Brandt, Y Sun, S Bharadwaj, D Livingston, E Tan… - PloS one, 2015 - journals.plos.org
... We generated a global range of **crude oil** operations by creating a dataset with 40 global oil fields [26]. This dataset allows for input of up to 60 parameters for each oil field, as allowed in the **OPGEE** bulk assessment tool. These **...**
Cited by 4

Uncertainty in Regional-Average Petroleum GHG Intensities: Countering Information Gaps with Targeted Data Gathering
AR Brandt, Y Sun, K Vafi - Environmental science & technology, 2014 - ACS Publications
... are created. Each basket includes 20 of the 30 modeled **crude oil** fields. The first basket, called the matched basket, is selected so that its production-weighted true CI is approximately equal to the **OPGEE** default CI. The matched **...**
Cited by 6

Well-to-wheels greenhouse gas emissions of Canadian oil sands products: Implications for US petroleum fuels
H Cai, AR Brandt, S Yeh, JG Englander… - … science & technology, 2015 - ACS Publications
... Four major oil sands production pathways were examined, including bitumen and synthetic **crude oil** (SCO) from both surface mining and in situ projects. **...** This range can be compared to ~4.4 g CO_2 e/MJ for US conventional **crude oil** recovery. **...**
Cited by 14

Use of Statistical Indicators to Measure Crude Oil and Natural Gas Reserves and Production.
C Lazăr, M Lazăr - Economic Insights-Trends & Challenges, 2014 - upg-bulletin-se.ro
... 7 Houjeiri, H., Brandt, A., Oil Production Greenhouse Emissions Estimator, **OPGEE** v1.0, User guide & Technical documentation, Stanford University, 2012, p.33 Page 7. Use of Statistical Indicators to Measure **Crude Oil** and Natural Gas Reserves and Production 51 **...**

Net energy analysis of Bakken crude oil production using a well-level engineering-based model
AR Brandt, T Yeskoo, K Vafi - Energy, 2015 - Elsevier
... 2.3.1. **Crude oil** energy intensity modeling (**OPGEE** and GHGFrac). Drilling energy calculated in **OPGEE** model is replaced with results from GHG frack. **...** Each **crude oil** energy density is assigned based on API gravity as in the **OPGEE** model [45]. **...**
Cited by 2

Oil Production Greenhouse Gas Emissions Estimator OPGEE v1. 1 Draft E
M Hassan, K Vafi, J Duffy, S McNally, AR Brandt - 2014 - pangea.stanford.edu
... 15 4.1 Land use GHG emissions for 30 year analysis period from field drilling and development in **OPGEE** for conventional oil operations [g CO2 eq./MJ of **crude oil** produced]. Data from Yeh et al. (2010). . . . **...**

Reference: Comments on Petroleum Refining Emissions
K Sideco - 2014 - Citeseer
... Then add a column in CA GREET for California **Crude Oil** Production, which flows to CA CARBOB and ULSD production. Table 3. Example of CA **Crude Oil** Inputs that Result in the Same CI as **OPGEE** Predictions. Upstream Emissions in Refining **...**

OPGEE v1. 1 DRAFT C
M Hassan, K Vafi, J Duffy, S McNally, AR Brandta - 2014 - Citeseer
... 16 4.1 Land use GHG emissions for 30 year analysis period from field drilling and development in **OPGEE** for conventional oil operations [g CO_2 eq./MJ of **crude oil** produced]. Data from Yeh et al. (2010). . . . **...**

CO_2 Life-Cycle Assessment of the Production of Algae-Based Liquid Fuel Compared to Crude Oil to Diesel
JL Manganaro, A Lawal - Energy & Fuels, 2016 - ACS Publications
... CO 2 Life-Cycle Assessment of the Production of Algae-Based Liquid Fuel Compared to **Crude Oil** to Diesel. **...**

OPGEE v1. 1 DRAFT A
HM El-Houjeiri, S McNally, AR Brandt - Work, 2013 - pangea.stanford.edu
... 14 3.1 Land use GHG emissions for 30 year analysis period from field drilling and development in **OPGEE** for conventional oil operations [g CO_2 eq./MJ of **crude oil** produced]. Data from Yeh et al. (2010). . . . **...**

Embodied energy and GHG emissions from material use in conventional and unconventional oil and gas operations
AR Brandt - Environmental science & technology, 2015 - ACS Publications
... oilfield equipment consumes ~0.014 MJ of primary energy per MJ of oil produced, and results in ~1.3 g CO_2 -eq GHG emissions per MJ (lower heating value) of **crude oil** produced, an increase of 15% relative to upstream emissions assessed in earlier **OPGEE** model versions **...**

Energy intensity and greenhouse gas emissions from tight oil production in the Bakken formation
AR Brandt, T Yeskoo, MS McNally, K Vafi, S Yeh… - Energy & …, 2016 - ACS Publications
... Laboratory US **crude oil** baseline, which includes imported **crude oil**.(7) A study by IHS CERA, using the Oil Production Greenhouse Gas Emissions Estimator (**OPGEE**) model of Stanford University, found that Bakken **crude oil** emits 9.1 g CO_2 eq/MJ of **crude oil** produced.(8, 9 **...**

Biofuel Bins
K Sideco - 2014 - Citeseer
... ARB has examined the emissions from **crude oil** sources using the **OPGEE** model. The model provides a more accurate assessment of **crude oil** production based on oil field parameters. **...** 9 | cycle energy for **crude oil** production which is calculated in GREET or **OPGEE**. **...**

12.4 Search Terms "crude oil production" "methane emissions"

There were 251 results for this search. The most relevant papers are listed below.

Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum
A Burnham, J Han, CE Clark, M Wang… - … science & technology, 2011 - ACS Publications
... It has been debated whether the fugitive **methane emissions** during natural gas production and transmission outweigh the lower carbon dioxide emissions during combustion when compared to coal and petroleum. Using the **...**
Cited by 303

Remote sensing of fugitive **methane emissions** from oil and gas production in North American tight geologic formations
O Schneising, JP Burrows, RR Dickerson… - Earth's …, 2014 - Wiley Online Library
... The latest estimate of **methane emissions** from natural gas systems reported by the US Environmental Protection Agency (EPA) is 6343 kt in **...** estimate of methane released to the atmosphere by petroleum systems corresponds to 0.7% of the US **crude oil production** (0.5%– **...**
Cited by 55

Addressing the environmental risks from shale gas development
M Zoback, S Kitasei, B Copithorne - 2010 - blogs.worldwatch.org
... five most productive US shale gas fields – the Barnett, Haynesville, Fayetteville, Woodford, and Marcellus shales – were producing some 8.3 billion cubic feet a day, the

equivalent of nearly 1.6 million barrels of oil a day, or 30 percent of total US **crude oil production** during 2009 **...**
Cited by 150

Canadian oil sands: Life-cycle assessments of greenhouse gas emissions
RK Lattanzio - Current Politics and Economics of the United …, 2015 - search.proquest.com
... Canadian oil sands account for about 56% of Canada's total **crude oil production**, and that number is expected to rise from its **...** Further, **methane emissions** from fugitive leaks throughout the oil sands production process can potentially contribute up to 1% of GHG emissions.25 **...**
Cited by 27

Methane emissions of energy activities in China 1980–2007
B Zhang, GQ Chen, JS Li, L Tao - Renewable and Sustainable Energy …, 2014 - Elsevier
... is the largest coal production and consumption country, large coal supply has resulted in a high growth rate of coalbed **methane emissions**, without an **...** [30], the emission sources in oil and natural gas systems considered in this study include: **crude oil production** (onshore and **...**
Cited by 22

The role of toxicological science in meeting the challenges and opportunities of hydraulic fracturing
BD Goldstein, BW Brooks, SD Cohen… - Toxicological …, 2014 - Soc Toxicology
... Methane emissions during the flowback period immediately following hydraulic fracturing ranged from 0.01 to 17 Mg **...** Divine and Hartman (2000) in a large cohort study of **crude oil production** and pipeline workers found slight increases for cancer of the prostate, brain and central **...**
Cited by 51

Historical trends in greenhouse gas emissions of the Alberta oil sands (1970–2010)
JG Englander, S Bharadwaj… - Environmental Research …, 2013 - iopscience.iop.org
... crude oil (Brandt et al 2013). In addition, oil sands extraction results in secondary emissions sources such as fugitive emissions, land-use impacts, and **methane emissions** from tailings ponds. Regulations such as the California **...**
Cited by 13

Comparative life cycle assessment of margarine and butter consumed in the UK, Germany and France
K Nilsson, A Flysjö, J Davis, S Sim, N Unger… - The International Journal …, 2010 - Springer
... 59.5. Nitrogen obtained from other sources [kg-N/ha/year]. 26.36. 26.36. Oil extraction. Crop input to crushing mill [kg]. 2,500. 2,500. 4,545. 4,545. **Crude oil production** [kg]. 1,000. 1,000. 1,000. 1,000. Meal production [kg]. 1,500. 1,500. Palm kernel production (contains 50% oil) [kg **...**
Cited by 41

Life cycle water consumption for shale gas and conventional natural gas
CE Clark, RM Horner, CB Harto - Environmental science & …, 2013 - ACS Publications
Cited by 63

Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe
S González-García, CM Gasol, X Gabarrell… - Renewable Energy, 2010 - Elsevier
Liquid biofuels provide one of the few options for fossil fuel substitution in the short to medium-term and they are strongly being promoted by the European Uni.
Cited by 78

Energy intensity and greenhouse gas emissions from **crude oil production** in the Eagle Ford Region: Input data and analysis methods
A Ghandi, S Yeh, AR Brandt, K Vafi, H Cai… - UC Davis Inst. of …, 2015 - researchgate.net
Page 1. Energy Intensity and Greenhouse Gas Emissions from **Crude Oil Production** in the Eagle Ford Region: Input Data and Analysis Methods Abbas Ghandi 1 , Sonia Yeh 1 , Adam R. Brandt 2 , Kourosh Vafi 2 , Hao Cai 3 **...**
Cited by 5

Comparing the heat of combustion of fossil fuels to the heat accumulated by their lifecycle greenhouse gases
R Sathre - Fuel, 2014 - Elsevier
... US underground bituminous coal mining, and result from energy used for commissioning and operating the mine, mine **methane emissions**, and transport **...** Allocation of emissions from **crude oil production** and transport among the diverse refinery products is done on the basis of **...**
Cited by 14

Spatially explicit **methane emissions** from petroleum production and the natural gas system in California
S Jeong, D Millstein, ML Fischer - Environmental science & …, 2014 - ACS Publications
... Spatially Explicit **Methane Emissions** from Petroleum Production and the Natural Gas System in California. **...**
Cited by 12

Beyond oil and gas: the methanol economy
GA Olah, A Goeppert, GKS Prakash - 2011 - books.google.com
Page 1. Ceorge A. Olah, Alain Coeppert, ^ WILEY VCH and CK Surya Prakash Beyond Oil and Gas: The Methanol Economy Second Updated and Enlarged Edition Page 2. George A. Olah, Alain Goeppert, and GK Surya Prakash Beyond Oil and Gas: The Methanol Economy **...**
Cited by 396

An overview of unconventional oil and natural gas: resources and federal actions
M Ratner, M Tiemann - Congressional Research Service, 2014 - baraka.consulting
... since. Between January 2008 and May 2014, US monthly **crude oil production** rose by 3.2 million barrels per day, with about 85% of the increase coming from shale and related tight oil formations in Texas and North Dakota. **...**
Cited by 27

Quantifying sources of methane using light alkanes in the Los Angeles basin, California
J Peischl, TB Ryerson, J Brioude… - Journal of …, 2013 - Wiley Online Library
Our site uses cookies to improve your experience. You can find out more about our use of cookies in About Cookies, including instructions on how to turn off cookies if you wish to do so. By continuing to browse this site you agree **...**
Cited by 88

Understanding renewable energy systems
V Quaschning - 2016 - books.google.com
'What it costs to boil water' from 1994 Energy conversion chain, losses and carbon dioxide emissions from boiling water Annual global **crude oil production** Global primary **...**
Cited by 290

Life cycle assessment of milk produced in two smallholder dairy systems in the highlands and the coast of Peru
K Bartl, CA Gómez, T Nemecek - Journal of Cleaner Production, 2011 - Elsevier

... Based on the results of this study, strategies in order to reduce the environmental burden of milk production should focus on an increase of production levels and a reduction of **methane emissions** from enteric fermentation in the highlands and a modification of the concentrate **...**
Cited by 42

Aircraft-based estimate of total **methane emissions** from the Barnett shale region
A Karion, C Sweeney, EA Kort… - … science & technology, 2015 - ACS Publications
... Aircraft-Based Estimate of Total **Methane Emissions** from the Barnett Shale Region. **...** Some liquid (condensate and oil) production occurs in the Barnett as well, totaling approximately 49 000 barrels (bbl) day –1 , approximately 0.6% of US **crude oil production**.(27, 28) The Barnett **...**
Cited by 22

Life cycle assessment integrated with thermodynamic analysis of bio-fuel options for solid oxide fuel cells
J Lin, CW Babbitt, TA Trabold - Bioresource technology, 2013 - Elsevier
... Characterization, Greenhouse gas emission from CO 2 and **methane emissions** (kg CO 2 -eq/kWh), energy consumption from **...** onshore production, offshore production, and advanced onshore steam-injection) are considered both for domestic **crude oil production** and foreign **...**
Cited by 16

12.5 Search Terms "crude oil production" "fugitive emissions"

For this search fugitive emissions replaced methane emissions. The results are similar to the previous search.

Life-cycle greenhouse gas emissions of shale gas, natural gas, coal, and petroleum
A Burnham, J Han, CE Clark, M Wang… - … science & technology, 2011 - ACS Publications
... sources such as leaks. This article documents the **fugitive emissions** from leaks and venting for each pathway, however combustion emissions are included as part of the results to examine the life-cycle emissions. Figure 1 shows **...**
Cited by 303

Open-source LCA tool for estimating greenhouse gas emissions from **crude oil production** using field characteristics
HM El-Houjeiri, AR Brandt, JE Duffy - Environmental science & …, 2013 - ACS Publications
... OPGEE calculates the energy use and emissions from **crude oil production** using engineering fundamentals of petroleum production and processing. **...** (v) Maintenance, Venting and **fugitive emissions** associated with maintenance (eg, compressor blowdowns, well workovers and **...**
Cited by 21

Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations
O Schneising, JP Burrows, RR Dickerson… - Earth's …, 2014 - Wiley Online Library
... content, calling immediate climate benefit into question and indicating that current inventories likely underestimate the **fugitive emissions** from Bakken **...** of methane released to the atmosphere by petroleum systems corresponds to 0.7% of the US **crude oil production** (0.5%–1.7 **...**
Cited by 55

Energy return on investment (EROI) of oil shale
CJ Cleveland, PA O'Connor - Sustainability, 2011 - mdpi.com

... By way of comparison, global **crude oil production** in 2005 averaged 84.6 million barrels per day **...** 13] conservatively estimates that the resulting greenhouse gas emissions are about 50–75% higher than those of conventional oil, and that is without considering **fugitive emissions**. **...**
Cited by 56

Canadian oil sands: Life-cycle assessments of greenhouse gas emissions
RK Lattanzio - Current Politics and Economics of the United …, 2015 - search.proquest.com
... Due to the complex nature of **crude oil production** systems and resource reservoirs, studies often use ratios to describe the fraction of the **...** Further, assumptions regarding venting or flaring of associated gas, and **fugitive emissions** from produced water, may further impact GHG **...**
Cited by 27

Upstream greenhouse gas (GHG) emissions from Canadian oil sands as a feedstock for European refineries
AR Brandt - 2011 - insideclimatenews.com
... SAGD). 3. Differences in the fuel mix assumed to be consumed during oil sands extraction and upgrading. 4. Treatment of secondary non-combustion emissions sources, such as venting, flaring and **fugitive emissions**. 5. Treatment **...**
Cited by 35

Historical trends in greenhouse gas emissions of the Alberta oil sands (1970–2010)
JG Englander, S Bharadwaj… - Environmental Research …, 2013 - iopscience.iop.org
... In situ projects have benefitted from substantial reductions in **fugitive emissions** from bitumen batteries. **...** In addition, oil sands extraction results in secondary emissions sources such as **fugitive emissions**, land-use impacts, and methane emissions from tailings ponds. **...**
Cited by 13

Methane emissions of energy activities in China 1980–2007
B Zhang, GQ Chen, JS Li, L Tao - Renewable and Sustainable Energy …, 2014 - Elsevier
... Based on the data availability and the calculation results for the year of 2006 by Liu et al. [30], the emission sources in oil and natural gas systems considered in this study include: **crude oil production** (onshore and **fugitive emissions**, venting, flaring), crude oil transportation (by **...**
Cited by 22

Energy intensity and greenhouse gas emissions from **crude oil production** in the Eagle Ford Region: Input data and analysis methods
A Ghandi, S Yeh, AR Brandt, K Vafi, H Cai… - UC Davis Inst. of …, 2015 - researchgate.net
Page 1. Energy Intensity and Greenhouse Gas Emissions from **Crude Oil Production** in the Eagle Ford Region: Input Data and Analysis Methods **...** 59 43 CO2 and CH4 emissions from gas flaring and **fugitive emissions** ..... 60 Page 6. vi LIST OF TABLES (Cont.) **...**
Cited by 5

Model to investigate energy and greenhouse gas emissions implications of refining petroleum: impacts of crude quality and refinery configuration
JP Abella, JA Bergerson - Environmental science & technology, 2012 - ACS Publications
Cited by 23

Technological feasibility and costs of achieving a 50% reduction of global GHG emissions by 2050: mid-and long-term perspectives
O Akashi, T Hanaoka - Sustainability Science, 2012 - Springer

... **Fugitive emissions** from fuel production. **...** pipeline injection, degasification for electricity, ventilation for electricity, ventilation oxidizer for heat), natural gas production and distribution (eg, use of instrument air, use of low bleed pneumatic devices), **crude oil production** (eg, flaring in **...**
Cited by 29

Production-based and consumption-based national greenhouse gas inventories: An implication for Estonia
O Gavrilova, R Vilu - Ecological Economics, 2012 - Elsevier
... 20% higher than that for CO_2eq emissions associated with production. 3.1.2. **Fugitive emissions** related to primary fuel production and consumption. The total amount of primary fuel energy produced in Estonia in 2005 was **...**
Cited by 25

Receptor modeling of epiphytic lichens to elucidate the sources and spatial distribution of inorganic air pollution in the Athabasca Oil Sands Region
MS Landis, JP Pancras, JR Graney… - Developments in …, 2012 - books.google.com
... 20 km around the major mining and oil production facilities, which is indicative of ground-level coarse particulate **fugitive emissions** from these **...** Production is expected to be in excess of 3.5 million barrels per day by 2025 (Chapter 2). Synthetic **crude oil production** from bitumen **...**
Cited by 26

Reproducibility of LCA models of **crude oil production**
K Vafi, AR Brandt - Environmental science & technology, 2014 - ACS Publications
... **emissions** of CH 4 from oil production operations vary significantly between operations, even within the same region. Fugitive releases are currently poorly understood.(10-12) For these reasons, many studies have recently attempted to assess different **crude oil production** **...**
Cited by 5

Life cycle energy and greenhouse gas emissions from transportation of Canadian oil sands to future markets
T Tarnoczi - Energy policy, 2013 - Elsevier
... A surge in unconventional **crude oil production**, particularly from light tight oil in the Eagle Ford and Bakken formations, is raising the prospect of US energy independence (EIA, 2013) while at the same time squeezing pipeline capacity for oil **...** 2.2.2. **Fugitive emissions** (Direct). **...**
Cited by 7

Well-to-wheels greenhouse gas emissions of Canadian oil sands products: Implications for US petroleum fuels
H Cai, AR Brandt, S Yeh, JG Englander… - … science & technology, 2015 - ACS Publications
Cited by 15

Spatially explicit methane emissions from petroleum production and the natural gas system in California
S Jeong, D Millstein, ML Fischer - Environmental science & …, 2014 - ACS Publications
Cited by 12

Life cycle assessment integrated with thermodynamic analysis of bio-fuel options for solid oxide fuel cells
J Lin, CW Babbitt, TA Trabold - Bioresource technology, 2013 - Elsevier

... processes (onshore production, offshore production, and advanced onshore steam-injection) are considered both for domestic **crude oil production** and foreign **...** Energy use and **fugitive emissions** from crude oil storage and handling in the transportation processes (eg, crude oil **...**

Analysis of energy use and CO_2 emissions in the US refining sector, with projections for 2025
DS Hirshfeld, JA Kolb - Environmental science & technology, 2012 - ACS Publications
... These include tighter sulfur specifications on gasoline (Tier 3) and marine diesel fuel (MARPOL Annex VI sulfur standards on marine diesel fuel(6)). (Lifecycle analysis including CO 2 emissions from **crude oil production** through refined product use is beyond the scope of this **...**

Greenhouse gas emissions from recovery of various North American conventional crudes
MM Rahman, C Canter, A Kumar - Energy, 2014 - Elsevier
... oil. This is done by dividing the amount of flared, vented, and fugitive volumes by the total **crude oil production** in the state or country. **...** years. For venting and **fugitive emissions**, efficiency and stoichiometric factors are not required. **...**

12.6 Search Terms "oil refining" "energy consumption"

This search is looking for papers on the energy use in the refining sector. The most relevant papers are listed below.

Life cycle energy efficiency and potentials of biodiesel production from palm oil in Thailand
S Papong, T Chom-In, S Noksa-nga, P Malakul - Energy Policy, 2010 - Elsevier
... The **energy consumption** in the transportation stage, which includes: (1) fertilizer transport from overseas to the port of Thailand, transport to the **...** Thailand, transport to the dealer, and transport to the biodiesel plants; and, (5) palm stearin transport from the palm **oil refining** plant to **...**

A review analyzing the industrial biodiesel production practice starting from vegetable **oil refining**
G Santori, G Di Nicola, M Moglie, F Polonara - Applied energy, 2012 - Elsevier
... Cover image Cover image. A review analyzing the industrial biodiesel production practice starting from vegetable **oil refining**. **...** Keywords. Biodiesel; Production process; Industrial practice; Vegetable **oil refining**; Biodiesel refining; Transesterification. 1. Introduction. **...**

Energy consumption and CO_2 emission impacts of vehicle electrification in three developed regions of China
Y Wu, Z Yang, B Lin, H Liu, R Wang, B Zhou, J Hao - Energy Policy, 2012 - Elsevier
... Energy consumption and CO 2 emission impacts of vehicle electrification in three developed regions of China. **...** In this study, we used the GREET1.8d model as a platform to calculate the WTW **energy consumption** and CO2 emissions of HEV, PHEV, EV and conventional ICEV. **...**

The water–energy nexus in Middle East and North Africa
A Siddiqi, LD Anadon - Energy policy, 2011 - Elsevier

... In order to understand the mutual dependencies of water and energy systems in MENA, we quantified the water consumption in energy production and **energy consumption** in water systems in those cases where data was available. 4.1. **... Oil refining** (gal/MMBtu), 7.2, 13.4, 10.3. **...**
Cited by 162

Hydrogen production from biomass gasification in the **oil refining** industry–a system analysis
D Johansson, PÅ Franck, T Berntsson - Energy, 2012 - Elsevier
... oil refining industry to act towards CO 2 mitigation measures. Although energy efficiency in the refining process has improved significantly over the last decades, continuing growth in diesel demand, and demand for cleaner fuels, have resulted in higher total **energy consumption ...**
Cited by 36

Zeolites as catalysts in **oil refining**
A Primo, H Garcia - Chemical Society Reviews, 2014 - pubs.rsc.org
... In the initial times of the automotive industry the light naphtha fraction of the crude **oil refining** was used directly as gasoline ("light straight run **...** oil and natural gas are still very high, it is clear that the present situation, in which about 80% of the total **energy consumption** in 2013 **...**
Cited by 70

Fish oil replacement and alternative lipid sources in aquaculture feeds
GM Turchini, WK Ng, DR Tocher - 2010 - books.google.com
Page 1. Fish Oil Replacement and Alternative Lipid Sources in Aquaculture Feeds --*|| _. Edited by Giovanni M. Turchini-Wing-Keong Ng Douglas R. Tocher CRC PreSS Taylor & Francis Group Page 2. Fish **...**
Cited by 85

Greenhouse gas emissions and energy balance of palm oil biofuel
SP De Souza, S Pacca, MT De Avila, JLB Borges - Renewable Energy, 2010 - Elsevier
... Shells and fibers are usually used as fuel in cogeneration schemes. Thus, palm **oil refining** is self sufficient with respect to **energy consumption**, and the use of fossil inputs and their respective GHG emissions is negligible [20] and [21]. **...**
Cited by 103

Energy intensity and greenhouse gas emissions from thermal enhanced oil recovery
AR Brandt, S Unnasch - Energy & Fuels, 2010 - ACS Publications
... The normalized **energy consumption** ratio for steam produc- tion,Rsteam (MJ consumed/MJ of incremental crude oil produced), is therefore equal to **...** as an energy input, using an estimate of 20 kWh/bbl of oil produced.22 GHG emissions from crude **oil refining** depend upon the **...**
Cited by 37

The energy efficiency of crude **oil refining** in Brazil: A Brazilian refinery plant case
RS De Lima, R Schaeffer - Energy, 2011 - Elsevier
... This article evaluates energy efficiency in Brazilian crude **oil refining** in comparison with the crude **oil refining** in the United States between 1930 and 2008. It aims to show that increased refinery complexity reduces the **energy consumption** of products of high value added. **...**
Cited by 13

The long-term forecast of Taiwan's energy supply and demand: LEAP model application
Y Huang, YJ Bor, CY Peng - Energy policy, 2011 - Elsevier

... 2. Sector total shares plus non-**energy consumption** adds to approximately 100%. **...** The energy conversion system is divided into modules for transmission and distribution losses, electric power generation, **oil refining**, coal transformation (coking), and gasworks. **...**
Cited by 93

Oil depletion and the energy efficiency of oil production: The case of California
AR Brandt - Sustainability, 2011 - mdpi.com
... No data were found on the time-varying efficiency of **oil refining**. In the absence of data, the model assume refinery **energy consumption** per unit of energetic throughput decreased by 2.5% per 10 year period in the Low case and 5% per 10 year period in the High case. **...**
Cited by 39

Waste cooking oil as an energy resource: Review of Chinese policies
H Zhang, Q Wang, SR Mortimer - Renewable and sustainable energy …, 2012 - Elsevier
... 4.1. Analysis on basic policy tools. Table 2 presents basic policy tools of waste cooking **oil refining** biofuel. The numbers **...** realized. Currently, the proportion of biomass in **energy consumption** structure in Brazil exceeds 30%. Likewise **...**
Cited by 31

Assessment of a dry and a wet route for the production of biofuels from microalgae: energy balance analysis
L Xu, DWFW Brilman, JAM Withag, G Brem… - Bioresource …, 2011 - Elsevier
... Both routes are intended to convert the chemical energy contained in the microalgae into high-value biofuels with minimal fossil **energy consumption**. **...** To improve the overall energy balance, the **energy consumption** of the dewatering has to be reduced. **...**
Cited by 219

Is it environmentally advantageous to use vegetable oil directly as biofuel instead of converting it to biodiesel?
B Esteban, G Baquero, R Puig, JR Riba, A Rius - Biomass and Bioenergy, 2011 - Elsevier
... The production of SVO with respect to BD is much easier because it includes fewer processes and less **energy consumption**. The aim of this study is to compare small-scale SVO production to large-scale BD production. **...** Refining. The **oil refining** process involves several stages. **...**
Cited by 59

Life cycle assessment of an industrial symbiosis based on energy recovery from dried sludge and used oil
Q Liu, P Jiang, J Zhao, B Zhang, H Bian… - Journal of Cleaner …, 2011 - Elsevier
... Abstract. Recovering energy from wastes is a useful strategy for integrated waste and energy management in an eco-industrial park (EIP) and gives promising reduction of wastes, total **energy consumption** and operation cost. **...**
Cited by 37

Camelina-derived jet fuel and diesel: Sustainable advanced biofuels
DR Shonnard, L Williams… - Environmental Progress & …, 2010 - Wiley Online Library
... Crude camelina **oil refining** inputs were obtained from a recent study [14]. **... Energy consumption** for each product over the life cycle is another important characteristic to judge the comparative advantages of camelina biofuels. **...**
Cited by 164

Energy sector vulnerability to climate change: a review
R Schaeffer, AS Szklo, AFP de Lucena, BSMC Borba… - Energy, 2012 - Elsevier
Energy systems can be vulnerable to climate change. This paper summarizes the contribution of their authors to a few strategic studies, research workshops, deve.

Cited by 139

A review on biodiesel production using catalyzed transesterification
DYC Leung, X Wu, MKH Leung - Applied energy, 2010 - Elsevier
Biodiesel is a low-emissions diesel substitute fuel made from renewable resources and waste lipid. The most common way to produce biodiesel is through transeste.
Cited by 1277

Techno-economic analysis of biomass fast pyrolysis to transportation fuels
MM Wright, DE Daugaard, JA Satrio, RC Brown - Fuel, 2010 - Elsevier
... projected to increase by 4.4% per year from 2007 to 2030 compared to 0.5% increase in primary **energy consumption** for end **...** Although bio-oil upgrading employs technology similar to crude **oil refining** equipment, this technology has not been commercially employed to process **...**
Cited by 371

12.7 Search Terms "oil refining" "fugitive emissions"

There were 256 results returns for this search, the most relevant papers are listed below.

Canadian oil sands: Life-cycle assessments of greenhouse gas emissions
RK Lattanzio - Current Politics and Economics of the United …, 2015 - search.proquest.com
... Further, assumptions regarding venting or flaring of associated gas, and **fugitive emissions** from produced water, may further impact GHG emissions intensities. **...** refining (emissions from the crude **oil refining** process and the combustion of co-products),. **...**
Cited by 27

Upstream greenhouse gas (GHG) emissions from Canadian oil sands as a feedstock for European refineries
AR Brandt - 2011 - insideclimatenews.com
... SAGD). 3. Differences in the fuel mix assumed to be consumed during oil sands extraction and upgrading. 4. Treatment of secondary non-combustion emissions sources, such as venting, flaring and **fugitive emissions**. 5. Treatment **...**
Cited by 35

Uncertainty analysis of life cycle greenhouse gas emissions from petroleum-based fuels and impacts on low carbon fuel policies
A Venkatesh, P Jaramillo, WM Griffin… - … science & technology, 2010 - ACS Publications
... The extraction of domestic and imported crude oil releases GHG emissions due to process fuel consumption and **fugitive emissions**. **...** Crude **Oil Refining** Petroleum refineries are massively complex process-based systems that synthesize a number of products while utilizing large **...**
Cited by 69

Economic analysis of greenhouse gas emissions in the Spanish economy
JM Cansino, MA Cardenete, M Ordóñez… - … and Sustainable Energy …, 2012 - Elsevier
... In the case of Spain, energy transformation–mostly through combustion activities–and, to a lesser extent, the **fugitive emissions** from fuel, 2 represent 77.0 percent of the total GHG emissions. **...** 4. **Oil refining**, 0.3261, 0.3153, 0.3008, 0.2430, 0.2149, 0.2092, −35.8. **...**
Cited by 16

Model to investigate energy and greenhouse gas emissions implications of refining petroleum: impacts of crude quality and refinery configuration
JP Abella, JA Bergerson - Environmental science & technology, 2012 - ACS Publications

Cited by 23

Net CO_2 stored in North American EOR projects
JE Faltinson, B Gunter - Journal of Canadian Petroleum Technology, 2013 - onepetro.org
... are deducted. It has been suggested that **fugitive emissions** from downstream **oil refining** and consumption of the transportation products should be deducted from the net CO_2 stored by CO2-EOR projects. This presumes that **...**
Cited by 9

Methane emissions of energy activities in China 1980–2007
B Zhang, GQ Chen, JS Li, L Tao - Renewable and Sustainable Energy …, 2014 - Elsevier
... in oil and natural gas systems considered in this study include: crude oil production (onshore and **fugitive emissions**, venting, flaring), crude oil transportation (by pipelines, tanker or rail), and crude **oil refining** in oil systems; gas production (**fugitive emissions**, flaring), gas **...**
Cited by 22

Evaluation of spatial relationships between health and the environment: the rapid inquiry facility
L Beale, S Hodgson, JJ Abellan… - Environmental …, 2010 - search.proquest.com
... Industries associated with **oil refining** are colocated with these refineries, and several National Priority List hazardous waste sites are found in the vicinity **...** Exposures at Woods Cross, within 2.5 km, are more likely a result of **fugitive emissions** because it sits in the shadow of the **...**
Cited by 34

A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels
S Bengtsson, K Andersson… - Proceedings of the …, 2011 - SAGE Publications
Cited by 63

Life cycle assessment of gasoline in Indonesia
YY Restianti, SH Gheewala - The International Journal of Life Cycle …, 2012 - Springer
... The second largest contributor to GWP is **oil refining** (5%) followed by crude oil extraction (2%). In AP, combustion plays a significant role too with a contribution of 84%, followed by refining with 13% and crude **...** Picard D (2001) **Fugitive emissions** from oil and natural gas activities **...**
Cited by 11

Infrared differential absorption Lidar (DIAL) measurements of hydrocarbon emissions
R Robinson, T Gardiner, F Innocenti… - Journal of …, 2011 - pubs.rsc.org
... industry, alongside vehicle emissions and solvent processes, is one of the most significant contributors to non-methane VOC emissions 28 via processes such as **oil refining** and production of petrochemical materials (eg plastics). Traditionally **fugitive emissions** 29 (emissions **...**
Cited by 19

Methane emissions in India: Sub-regional and sectoral trends
A Garg, B Kankal, PR Shukla - Atmospheric environment, 2011 - Elsevier
... Natural Gas production d, Fugitives, 12.19. Flaring, 8.80E−04. **Oil refining** d, 3.91. **...** 4a–c). It is followed by biomass burning (21%), solid waste disposal (7%), coal mining (5%), **fugitive emissions** from oil and natural gas production and handling (4%) and waste water disposal (1%) **...**
Cited by 19

On the sources of methane to the Los Angeles atmosphere

PO Wennberg, W Mui, D Wunch, EA Kort… - … science & technology, 2012 - ACS Publications
... Thus, at the upper limit (assuming that the only major source of atmospheric C 2 H 6 is **fugitive emissions** from the natural gas infrastructure) these data are consistent with the attribution of most (0.39 ± 0.15 Tg yr –1) of the excess CH 4 in the basin to uncombusted losses from **...**
Cited by 64

Assessment of CO_2 Emissions in the Petroleum Refining in Cameroon.
JG Tamba, D Njomo, ET Mbog - Universal Journal of …, 2011 - search.ebscohost.com
... This is the first CO2 inventory for the petroleum refining category carried out in Cameroon; but we could not include **fugitive emissions**. **...** 2.0 Overview of SONARA: SONARA (Figure 1) is a mixed company specialised in crude **oil refining**. **...**
Cited by 5

Allocating methane emissions to natural gas and oil production from shale formations
D Zavala-Araiza, DT Allen, M Harrison… - ACS Sustainable …, 2015 - ACS Publications
Cited by 12

Analysis of energy use and CO_2 emissions in the US refining sector, with projections for 2025
DS Hirshfeld, JA Kolb - Environmental science & technology, 2012 - ACS Publications
Cited by 8

The improvement of greenhouse gas inventory as a tool for reduction emission uncertainties for operations with oil in the Russian Federation
NE Uvarova, VV Kuzovkin, SG Paramonov… - Climatic change, 2014 - Springer
... As indicated in the National Inventory Report of the Russian Federation, the operations with oil (**fugitive emissions**) are key because of their contribution to the entire emission profile and according to the trend **... Oil refining** was by 20.1 % lower in 2009 compared to 1990. **...**
Cited by 8

Physical sustainability assessment for the China society: exergy-based systems account for resources use and environmental emissions
B Zhang, GQ Chen - Renewable and Sustainable Energy Reviews, 2010 - Elsevier
... There is 5034.5 PJ coal for consumption of **oil refining** and coking (ORC). Unlike the former three items, this consumption also generates raw materials to produce the other energy carriers. Table 2. Use of energy carriers within the Ex-sector (Unit: PJ). **...**
Cited by 50

Spatially explicit methane emissions from petroleum production and the natural gas system in California
S Jeong, D Millstein, ML Fischer - Environmental science & …, 2014 - ACS Publications
Cited by 12

Ambient air quality monitoring in terms of volatile organic compounds (VOCs) occupational health exposure at petroleum refinery
RK Singh, DS Ramteke, HD Juneja… - International Journal …, 2013 - search.proquest.com
... The **fugitive emissions** of Total VOCs were also monitored near major activities inside oil refinery to have first-hand information **... Oil refining** involves physical separation, chemical conversion, treating processes apart from storage and handling of feed stock, intermediates as well **...**
Cited by 4

13. APPENDIX 3 – NATURAL GAS LITERATURE SEARCH

13.1 SEARCH TERMS - "NATURAL GAS" "FUGITIVE EMISSIONS"

The search returned 3,500 results.

Methane and the greenhouse-gas footprint of **natural gas** from shale formations
RW Howarth, R Santoro, A Ingraffea - Climatic Change, 2011 - Springer
... years. Keywords Methane·Greenhouse gases·Global warming·**Natural gas**·Shale gas·Unconventional gas·**Fugitive emissions**·Lifecycle analysis·LCA·Bridge fuel· Transitional fuel·Global warming potential·GWP Electronic supplementary **...**
Cited by 864

Life-cycle greenhouse gas emissions of shale gas, **natural gas**, coal, and petroleum
A Burnham, J Han, CE Clark, M Wang… - … science & technology, 2011 - ACS Publications
... This article documents the **fugitive emissions** from leaks and venting for each pathway, however combustion emissions are included as part **...** For transportation services, we included a passenger car fueled with petroleum gasoline and compressed **natural gas** (CNG) and a bus **...**
Cited by 300

Human health risk assessment of air emissions from development of unconventional **natural gas** resources
LM McKenzie, RZ Witter, LS Newman… - Science of the Total …, 2012 - Elsevier
... Cover image Cover image. Human health risk assessment of air emissions from development of unconventional **natural gas** resources ☆ ☆☆. **...** Highlights. ► We estimate health risks of air emissions from unconventional **natural gas** development. **...**
Cited by 331

A commentary on "The greenhouse-gas footprint of **natural gas** in shale formations" by RW Howarth, R. Santoro, and Anthony Ingraffea
LM Cathles III, L Brown, M Taam, A Hunter - Climatic Change, 2012 - Springer
... Natural gas is widely considered to be an environmentally cleaner fuel than coal because it does not produce detrimental by **...** We argue here that their analysis is seriously flawed in that they significantly overestimate the **fugitive emissions** associated with unconventional gas **...**
Cited by 179

Uncertainty in life cycle greenhouse gas emissions from United States **natural gas** end-uses and its effects on policy
A Venkatesh, P Jaramillo, WM Griffin… - … Science & Technology, 2011 - ACS Publications
... Emissions and Sinks.(27). GHG emissions from processing **natural gas** are due to fuel combustion at processing plants, **fugitive emissions** and from CO 2 that is separated from the gas processed and vented. A log-normal distribution **...**
Cited by 112

Methane leaks from North American **natural gas** systems
AR Brandt, GA Heath, EA Kort, F O'Sullivan… - …, 2014 - science.sciencemag.org
... Methane Leaks from North American **Natural Gas** Systems. **... Natural gas** (NG) is a potential "bridge fuel" during transition to a decarbonized energy system: It emits less carbon dioxide during combustion than other fossil fuels and can be used in many industries. **...**
Cited by 279

Life cycle greenhouse gas emissions of Marcellus shale gas

M Jiang, WM Griffin, C Hendrickson… - Environmental …, 2011 - iopscience.iop.org
... Methane leakage rates throughout the **natural gas** system (excluding the preproduction processes previously discussed) are a major concern and our analysis has an implied **fugitive emissions** rate of 2%, consistent with the EPA **natural gas** industry study (US EPA 1996, 2010). **...**
Cited by 217

Natural gas fugitive emissions rates constrained by global atmospheric methane and ethane
S Schwietzke, WM Griffin, HS Matthews… - … science & technology, 2014 - ACS Publications
The amount of methane emissions released by the **natural gas** (NG) industry is a critical and uncertain value for various industry and policy decisions, such as for determining the climate implications of using NG over coal. Previous studies have estimated **fugitive emissions** rates
Cited by 21

Shale gas production: potential versus actual greenhouse gas emissions
F O'Sullivan, S Paltsev - Environmental Research Letters, 2012 - iopscience.iop.org
... 25 S3: GHG intensity of flowback gas handling methods Knowing how gas produced during flowback is handled is necessary to evaluate the actual **fugitive emissions** from shale well hydraulic fracturing operations. **...** 3 of methane emissions per m 3 of **natural gas** flared (21). **...**
Cited by 105

Modeling the relative GHG emissions of conventional and shale gas production
T Stephenson, JE Valle… - Environmental science & …, 2011 - ACS Publications
... factors from the 2009 API Compendium:(11) 0.17% of the gas is lost to fugitives from onshore production and 0.18% is lost to **fugitive emissions** from gas processing. (The EPA 2011 Inventory Report(8) estimated that total methane emissions from the **natural gas** industry were **...**
Cited by 118

Toward a better understanding and quantification of methane emissions from shale gas development
DR Caulton, PB Shepson, RL Santoro… - Proceedings of the …, 2014 - National Acad Sciences
... This work emphasizes the need for top-down identification and component level and event driven measurements of methane leaks to properly inventory the combined methane emissions of **natural gas** extraction and combustion to better define the impacts of our nation's **...**
Cited by 133

Remote sensing of fugitive methane emissions from oil and gas production in North American tight geologic formations
O Schneising, JP Burrows, RR Dickerson… - Earth's …, 2014 - Wiley Online Library
... In North America, these unconventional domestic sources of **natural gas** and oil provide an opportunity to achieve energy self **...** content, calling immediate climate benefit into question and indicating that current inventories likely underestimate the **fugitive emissions** from Bakken **...**
Cited by 55

Dispersion modeling approach for quantification of methane emission rates from **natural gas** fugitive leaks detected by infrared imaging technique
A Safitri, X Gao, MS Mannan - Journal of Loss Prevention in the Process …, 2011 - Elsevier

... In order to reduce methane emissions from **natural gas** system, EPA had developed a program called Leak Detection and Repair (LDAR), which requires gas producers to regularly monitor any potential **...** 2. Potential use of infrared imaging technique for **fugitive emissions** control. **...**
Cited by 17

The greenhouse impact of unconventional gas for electricity generation
N Hultman, D Rebois, M Scholten… - Environmental Research …, 2011 - iopscience.iop.org
... 2.1. **Fugitive emissions** from **natural gas** production **...** These **fugitive emissions** contain a heavy concentration of methane, which, because of its high radiative forcing, can contribute significantly to the global warming impact of **natural gas** mining operations. **...**
Cited by 100

Coal to gas: the influence of methane leakage
TML Wigley - Climatic change, 2011 - Springer
... Here we consider a scenario where a fraction of coal usage is replaced by **natural gas** (ie, methane, CH 4) over a given time **...** Although these **fugitive emissions** are relatively small, they are important because methane is a far more powerful forcing agent per unit mass than CO 2 **...**
Cited by 115

Greenhouse gas emissions in China 2007: inventory and input–output analysis
GQ Chen, B Zhang - Energy Policy, 2010 - Elsevier
... mineral products, smelting and pressing for ferrous and nonferrous metals; CH 4 from remarkable sources as agricultural activities (manure management, enteric fermentation, rice cultivation, field burning of plant residues), coal mining, oil and **natural gas** leakage, fossil fuel **...**
Cited by 204

Greenwashing gas: Might a 'transition fuel'label legitimize carbon-intensive **natural gas** development?
E Stephenson, A Doukas, K Shaw - Energy Policy, 2012 - Elsevier
... Meanwhile, the only peer-reviewed study that has actually measured landscape-level emissions from a **natural gas** field found **fugitive emissions** in line with higher rather than lower estimates: a joint study by the National Oceanic and Atmospheric Administration (NOAA) and **...**
Cited by 44

Clearing the air: Reducing upstream greenhouse gas emissions from US **natural gas** systems
J Bradbury, M Obeiter, L Draucker… - … DC: World Resources …, 2013 - psb.vermont.gov
... S-2 | Comparing Detailed Estimates of Life Cycle GHG Emissions from Shale Gas and Conventional Onshore **Natural Gas** Sources * Data available from Marcellus only ** “Other Production” and “Other Processing” each include point source and **fugitive emissions** (mostly **...**
Cited by 46

Greenhouse gas emissions and natural resources use by the world economy: ecological input–output modeling
GQ Chen, ZM Chen - Ecological Modelling, 2011 - Elsevier
For the world economy as a biophysical network associated with financial links, an ecological endowment inventory and corresponding ecological input–output mo.
Cited by 76

Gas-to-liquids (GTL): A review of an industry offering several routes for monetizing **natural gas**
DA Wood, C Nwaoha, BF Towler - … of **Natural Gas** Science and Engineering, 2012 - Elsevier
... Volume 9, November 2012, Pages 196–208. Cover image Cover image. Invited review. Gas-to-liquids (GTL): A review of an industry offering several routes for monetizing **natural gas**. **...** 2). 13. Other **natural gas** GTL conversion technologies. 13.1. Gas to methanol (GTM). **...**
Cited by 145

13.2 Search Terms - "CNG Compressor" kWh/kg

Eco-efficiency of H 2 and fuel cell buses
JY Lee, KH Cha, TW Lim, T Hur - international journal of hydrogen energy, 2011 - Elsevier
... Storage/compression, Electricity consumption, Source. **CNG compressor**, 5.70E − 01 (**kWh**/**kg** CNG compression at 250 bar), Yesco, 2007. H 2 compressor, 2.11E + 00 (**kWh**/**kg** H 2 compression at 350 bar), Deokyang Energen, 2006–2007. **...**
Cited by 15

Towards a business model improving financial situation of small to medium
T Kharrasov - biogas-etc.eu
Page 1. CORNELISSEN CONSULTING SERVICES Towards a business model improving financial situation of small to medium size dairy farmers Internship report Timur Kharrasov 8/19/2013 Page 2. 2 Table of Contents Table **...**

Модернизация АГНКС с интегрированием в её состав оборудования для производства СПГ
ГС Горячев, ВП Кульбякин, СЮ Лебедев… - Технические …, 2012 - irbis-nbuv.gov.ua
... The complex capacity is 580 620 kg/h of LNG specific expenditure of energy 0,95 0,97 **kWh**/**kg** LNG. Keywords: Natural gas. Automobile gas filling compressor stations (AGFCS). Compressed natural gas (**CNG**). **Compressor** unit. Heat exchanger. Cooling system. **...**

Förutsättningar och affärsmodeller för avsättning av småskaligt producerad fordonsgas
M Blom - 2016 - stud.epsilon.slu.se
... Anläggningarna producerar rågas med en metanhalt kring 65 %. Den gas som ev. uppgraderas kallas för fordonsgas. Gasen kan mätas antingen i **kWh**, **kg** eller i Nm3 (normalkubikmeter, vilket beskriver volymen gas vid 1 atm och 0 °C). **...**

13.3 Search Terms - "NGV Compressor" kWh/kg

No results since 2010.

13.4 Search Terms - "CNG Compressor" "inlet pressure"

Atlas Copco
A Copco - Atlas Copco, 2012 - greenways2go.com
... compressor range, with "oil-less " technology. 2007 Atlas Copco acquires Greenfield and its complete CNG business. Atlas Copco launches the BBR gas engine driven compressor and broadens its CNG market further. 2009 Atlas Copco launches the variable **inlet pressure ...**
Cited by 5

Research and Implementation of Control Scheme for Tandem Centrifugal Compressors [J]
L Yueqiang - Automation in Petro-Chemical Industry, 2011 - en.cnki.com.cn
... energy consumption.Load balance allows the coordination operation of two compressors,avoids substantial change of **inlet pressure** and outlet **...** Supervision and Inspection, Chengdu 610000, China);Study of assessment and criteria of technical level for **CNG compressor** units[J **...**
Cited by 2

13.5 Search Terms - "real world" CNG heavy duty

The search returns 1,040 results.

Greater focus needed on methane leakage from natural gas infrastructure
RA Alvarez, SW Pacala, JJ Winebrake… - Proceedings of the …, 2012 - National Acad Sciences
... gasoline cars; (B) **CNG heavy-duty** vehicles vs. diesel vehicles; and (C) combined-cycle natural gas plants vs. supercritical coal plants using low-CH_4 coal. The three curves within each frame simulate **real-world** choices, including a single emissions pulse (dotted lines **...**
Cited by 290

Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing
S Zhang, Y Wu, H Liu, R Huang, L Yang, Z Li, L Fu… - Applied Energy, 2014 - Elsevier
... In this study, we collected on-road testing profiles for 75 **heavy-duty** transit buses in Beijing, which cover almost all current major bus technology groups including diesel, **CNG**/LNG, and **...** We obtained average **real-world** fuel consumption and CO_2 emission factors for all tested **...**
Cited by 50

Assessment of on-road emissions of four Euro V diesel and **CNG** waste collection trucks for supporting air-quality improvement initiatives in the city of Milan
G Fontaras, G Martini, U Manfredi, A Marotta… - Science of the total …, 2012 - Elsevier
... it was also shown that the limits imposed by current emission standards are not necessarily reflected in **real world** operation, under **...** Current emission factors reflect adequately **CNG** but need **...** Pollutant emissions; **Heavy duty** vehicles; Emission factors; PEMS; Vehicle simulation. **...**
Cited by 46

The challenge to NOx emission control for **heavy-duty** diesel vehicles in China
Y Wu, SJ Zhang, ML Li, YS Ge, JW Shu… - Atmospheric …, 2012 - atmos-chem-phys.net
... of engines, discuss on-road brake-specific NOx emission factors, and evaluate the **real-world** SCR performance **...** Y. Wu et al.: The challenge to NOx emission control for **heavy-duty** diesel vehicles in China 9371 **...** Table 6. Summary of on-road PEMS test results for **CNG** EEV buses **...**
Cited by 55

Can Euro V **heavy-duty** diesel engines, diesel hybrid and alternative fuel technologies mitigate NOX emissions? New evidence from on-road tests of buses in China
S Zhang, Y Wu, J Hu, R Huang, Y Zhou, X Bao, L Fu… - Applied Energy, 2014 - Elsevier
... Can Euro V **heavy-duty** diesel engines, diesel hybrid and alternative fuel technologies mitigate NO X emissions **...** **CNG** and LNG buses also had lower NO X emission factors **...** Furthermore, **real-world** NO X emission factors for all tested vehicle categories except diesel hybrids were **...**
Cited by 31

On-road pollutant emission and fuel consumption characteristics of buses in Beijing

A Wang, Y Ge, J Tan, M Fu, AN Shah, Y Ding… - Journal of …, 2011 - Elsevier
... The experimental results revealed that NOx and PM emissions from **CNG** buses were decreased by 72.0% and 82.3% respectively, compared with Euro IV diesel buses. **...** References. Andrei, 2001; Andrei P, 2001. **Real world heavy-duty** vehicle emissions modeling. **...**
Cited by 45

Derivation of motor vehicle tailpipe particle emission factors suitable for modelling urban fleet emissions and air quality assessments
DU Keogh, J Kelly, K Mengersen, R Jayaratne… - … Science and Pollution …, 2010 - Springer
... of toxic pollutants from compressed natural gas and low sulfur diesel-fueled **heavy-duty** transit buses **...** C, Westerholm R, Swietlicki E, Gidhagen L, Wideqvist U, Vesely V (2004) **Real-world** traffic emission **...** Bush C, Zupo D (2003) Comparison of Clean Diesel buses to **CNG** Buses. **...**
Cited by 27

The impact of transportation control measures on emission reductions during the 2008 Olympic Games in Beijing, China
Y Zhou, Y Wu, L Yang, L Fu, K He, S Wang, J Hao… - Atmospheric …, 2010 - Elsevier
... system along with downtown travel restrictions, a compressed natural gas (**CNG**) bus program **...** light-**duty** trucks (LDT), **heavy-duty** trucks (HDT), buses and **heavy-duty** vehicles (HDV). **...** The application of these **real-world** emission measurement technologies helped to improve the **...**
Cited by 145

On-road measurement of gas and particle phase pollutant emission factors for individual **heavy-duty** diesel trucks
TR Dallmann, SJ DeMartini… - … science & technology, 2012 - ACS Publications
... On-Road Measurement of Gas and Particle Phase Pollutant Emission Factors for Individual **Heavy-Duty** Diesel Trucks. **...**
Cited by 53

Particle and gaseous emissions from individual diesel and **CNG** buses
ÅM Hallquist, M Jerksjö, H Fallgren… - Atmospheric …, 2013 - atmos-chem-phys.net
... emission levels than re- quired by regulations, and is mostly applicable to **CNG heavy duty** vehicles. **...** NOx, CO and HC) and size-resolved particle emission factors for **CNG** and diesel **...** Euro classes with various after- treatment equipment, ie EGR and SCR, for **real-world** dilu- tion **...**
Cited by 24

Estimating vehicle emissions from road transport, case study: Dublin City
H Achour, JG Carton, AG Olabi - Applied energy, 2011 - Elsevier
... A representative driving cycle reflecting the **real-world** driving conditions is proposed and estimated vehicle emissions were compared with measured results. **...** for newer cars; using alternative fuel systems, such as using liquefied natural gas or biofuels in **heavy-duty** vehicles [**...**
Cited by 36

On-road measurement of regulated pollutants from diesel and **CNG** buses with urea selective catalytic reduction systems
J Guo, Y Ge, L Hao, J Tan, J Li, X Feng - Atmospheric Environment, 2014 - Elsevier
... buses, three Euro-V diesel buses and four Euro-V **CNG** buses, were characterized in **real world** conditions. **...** SCR; Diesel; **CNG**; NO x ; Particulate. **...** Emissions from **heavy-**

duty diesel vehicles significantly contribute to air pollution, especially NO x and particulate matter (Caserini et **...**

[On-road vehicle emission control in Beijing: past, present, and future]
Y Wu, R Wang, Y Zhou, B Lin, L Fu… - … Science & Technology, 2010 - ACS Publications
... vehicles. Instead, the Acceleration Simulation Mode (ASM) test was considered to more closely represent **real**-**world** conditions (especially for NO X) than the two-speed idle test. To **...** thousand units. **Heavy**-**duty** trucks are not all.

Assessment of **heavy-duty** vehicle activities, fuel consumption and exhaust emissions in port areas
G Zamboni, S Malfettani, M André, C Carraro, S Marelli… - Applied energy, 2013 - Elsevier
... 2] and [3], shows a growing contribution from vehicle categories such as **heavy**-**duty** vehicles (HDVs) or powered two-wheelers (PTWs). Passenger cars (PC) still represent the most important category for fleet extension and travelled mileage, but their **real**-**world** emission factors **...**

The development of a simulation tool for monitoring **heavy-duty** vehicle CO 2 emissions and fuel consumption in Europe
G Fontaras, M Rexeis, P Dilara, S Hausberger… - 2013 - papers.sae.org
... Ascertainment of **Real World** Emissions of **Heavy**-**duty** Vehicles **...** Final report available at:http://ec.europa.eu/clima/policies/transport/vehicles/**heavy**/docs/hdv_2011_01_09_en.pdf, 2012 **...** Assessment of on-road emissions of four Euro V diesel and **CNG** waste collection trucks for **...**

Nano-particle emission characteristics of European and worldwide harmonized test cycles for **heavy-duty** diesel engines
CL Myung, J Kim, S Kwon, K Choi, A Ko… - International Journal of …, 2011 - Springer
... combustion engine fuel providing more power and fuel efficiency than gasoline, **CNG** (compressed natural **...** soot mode particle emission from a diesel passenger car in **real world** and laboratory **...** Development of a Worldwide Harmonized **Heavy**-**duty** Engine Emission Test Cycle. **...**

Experimental demonstration of RCCI in **heavy-duty** engines using diesel and natural gas
E Doosje, F Willems, R Baert - 2014 - papers.sae.org
... Summary/Conclusions The potential of diesel-**CNG** RCCI has been investigated on a 6 cylinder **heavy**-**duty** engine. **...** Furthermore, closed-loop combustion control is essential to enable robust performance under **real**-**world** conditions in multi-cylinder engines. References **...**

Effect of a change towards compressed natural gas vehicles on the emissions of the Milan waste collection fleet
C Pastorello, P Dilara, G Martini - Transportation Research Part D: …, 2011 - Elsevier
... is used to calculate emission factors for the AMSA standard vehicle fleet, excluding **CNG** vehicles where **...** 15 km/h and 10 km/h for light-**duty** vehicles and **heavy duty** vehicles, was **...** driving on urban and suburban roads and was also confirmed during the **real**-**world** testing (Martini **...**

On-road emission characteristics of **CNG**-fueled bi-fuel taxis
Z Yao, X Cao, X Shen, Y Zhang, X Wang, K He - Atmospheric Environment, 2014 - Elsevier
... 2011) studied the **real**-**world** emission characteristics of natural gas-gasoline bi-fuel vehicles. Additionally, other studies of **CNG** vehicles have focused on **heavy**-**duty** vehicles, such as transit buses and refuse trucks (Zhang et al., 2014, Lou et al., 2013 and Fontaras et al., 2012). **...**
Cited by 14

Quantifying on-road emissions from gasoline-powered motor vehicles: Accounting for the presence of medium-and **heavy-duty** diesel trucks
TR Dallmann, TW Kirchstetter… - … science & technology, 2013 - ACS Publications
... limited by the small numbers of vehicles that can be tested and by test cycles that do not fully represent **real**-**world** driving conditions **...** 12) Vehicle-chase and plume-capture methods have been used to measure BC and OA emission factors for individual **heavy-duty** diesel vehicles **...**
Cited by 22

14. Appendix 4- Soybean Literature Search

14.1 Search Terms - soybean "direct energy" use "United States"

The top papers are identified below. In many cases the data in the papers was much older than the published date of the report and thus of little current value.

510 values. Changing the term to direct energy use" reduced the returns to 91.

Comparative life cycle environmental impacts of three beef production strategies in the Upper Midwestern United States
N Pelletier, R Pirog, R Rasmussen - Agricultural Systems, 2010 - Elsevier
... In the absence of production strategy-specific on-farm **direct energy** input data, we **...** of gross chemical energy produced relative to the gross energy **consumption** of cattle in **...** EROI measures speak effectively to equally important biotic resource **use efficiency** considerations (from **...**
Cited by 214

Land, irrigation water, greenhouse gas, and reactive nitrogen burdens of meat, eggs, and dairy production in the United States
G Eshel, A Shepon, T Makov… - Proceedings of the …, 2014 - National Acad Sciences
... N 2 O (17, 19⇓–21, 28, 45, 46) from manure management, enteric fermentation, **direct energy consumption**, and fertilizer **...** nutritionists, and that the combined amino acid mass in current wheat, corn, rice, and **soybean** production exceeds **...** 2 A–D by the caloric **use** shown in Fig. **...**
Cited by 93

A comparative study on energy use and cost analysis of potato production under different farming technologies in Hamadan province of Iran
M Zangeneh, M Omid, A Akram - Energy, 2010 - Elsevier
... direct energy. FYM **...** of integrated production managements are recently considered as a means to reduce production costs, to efficiently **use** human labor **...** to determine the energy **efficiency** of plant production such as sugarcane [17] in Morocco, wheat, maize, **soybean**, sugar beet **...**
Cited by 84

Year in review—EROI or energy return on (energy) invested
DJ Murphy, CAS Hall - Annals of the New York Academy of …, 2010 - Wiley Online Library
... 17 However, cost data tend to be for **direct energy used** or produced, but not indirect (eg, that **...** include some energy credit for nonfuel coproducts, such as residual animal feed, eg, **soybean** husks or **...** fuel **consumption** (oil, gas, and coal) was greater than the total annual **use** of all **...**
Cited by 324

Environmental life cycle comparison of algae to other bioenergy feedstocks
AF Clarens, EP Resurreccion, MA White… - … science & technology, 2010 - ACS Publications
... and so three types of wastewater effluents were evaluated for their usefulness as nutrient **sources**. **...** 13% of the **United States**' land area could meet the nation's total annual energy **consumption**. In contrast, **use** of corn would require 41% of the total land area, while switchgrass **...**
Cited by 736

Net energy balance of small-scale on-farm biodiesel production from canola and soybean
SR Fore, P Porter, W Lazarus - Biomass and bioenergy, 2011 - Elsevier

... a Assuming oil content of 18% and crushing **efficiency** of 75%, **soybeans** produce 411 L **... Direct energy use** in crop production included diesel fuel for field operations consisting of fertilizing, chisel **...** Estimates for diesel **use** in the canola and **soybean** crop production process were **...**
Cited by 51

An investigation on energy consumption and sensitivity analysis of soybean production farms
Z Ramedani, S Rafiee, MD Heidari - Energy, 2011 - Elsevier
... barely [12] and sugarcane in Iran [13], wheat and cotton [14] and [15] in Turkey, rice and **soybeans** [16] and **...** For the growth and development, energy demand in agriculture can be divided into **direct energy** (DE) and indirect energy (IDE) [23]. **...** Energy forms in **soybean** production. **...**
Cited by 35

Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use
M Wang, J Han, JB Dunn, H Cai… - Environmental …, 2012 - iopscience.iop.org
... This volume is significant, even when compared to the annual US **consumption** of gasoline, at 760 **...** fertilizer in cornfields, fertilizer production and fossil fuel **use** for farming are significant GHG emission **sources**. **... Direct energy use** for corn farming: MJ, 379, 311, 476, Weibull a. **...**
Cited by 148

Are biofuels the culprit? OPEC, food, and fuel
G Hochman, D Rajagopal, D Zilberman - The American Economic Review, 2010 - JSTOR
... Crude oil dominates **direct energy** costs, while natural gas dominates indirect costs **...** is 5 percent lower in both China and India (Table 2). In 2007, reducing demand in China and India results in corn prices that are 17 percent lower, **soybean** prices that **...** Corn **Soybeans** Rapeseed **...**
Cited by 32

Energy consumption and CO2 emissions analysis of potato production based on different farm size levels in Iran
SH Pishgar-Komleh, M Ghahderijani… - Journal of Cleaner …, 2012 - Elsevier
... d Precision. D 2 d 2 /z 2. DE **direct energy**. e i Error term. FYM Farmyard manure. GHG **...** The aims of this study were to calculate the input–output energy and greenhouse gas emission **use** in potato production, to investigate the **efficiency** of energy **consumption**, to find a **...**
Cited by 69

14.2 SEARCH TERMS – "SOYBEAN CRUSHING" " ENERGY USE"

The top papers are identified below. Only 74 values were returned for the post 2010 period. Many of the papers deal with the lifecycle production of biodiesel, if biodiesel is removed from the search then there were only 13 papers identified. None of the papers were useful.

Environmental life cycle assessment of lignocellulosic conversion to ethanol: A review
AL Borrion, MC McManus, GP Hammond - Renewable and Sustainable …, 2012 - Elsevier
Bioenergy from lignocellulosic biomass offers the potential to provide a significant source of clean, low carbon and secure energy. In recent years, a number of.
Cited by 76

The Overcapacity Problem of China
E Athanasiou - mibes.teilar.gr

... polycrystalline silicon, and wind power energy, as well as some elements of the electrolytic aluminium, shipbuilding and **soybean crushing** industries. **...** consumption for example, consumers are not yet receiving the proper signals about the true cost of **energy use**; although coal **...**

ECONOMICS OF PRODUCTION AND PROCESSING OF SOYBEAN IN INDORE DISTRICT OF MADHYA PRADESH
J TIWARI - 2011 - krishikosh.egranth.ac.in
... checked for quality. The soybeans then are processed to extract the oil and meal. From 100 pounds of soybeans the **soybean crushing** process produces 18 pounds of soybean although coal **...**

J Brock - 2013 - books.google.com
Page 1. Y mm mm mm S mm Tm N w H D E H T F L E W T £1.“ _ . .||. 1 1 H, .EIIIFI.E1'ulléu_!. H Page 2. THE STRUCTURE OF AMERICAN INDUSTRY TWELETH EDITION Page 3. THE STRUCTURE OF AMERICAN INDUSTRY **...**
Cited by 297 Related articles All 2 versions Cite Save

Beyond the USDA
M Gosselin - Institute for Agriculture and Trade Policy, 2010 - Citeseer
... domestic methane recovery initiatives. The voluntary program encourages methane recovery for **energy use** through the use of anaerobic digesters by confined livestock operations. See http://www.epa.gov/agstar/. ePA funding and **...**
Related articles All 9 versions Cite Save More

Environment and food
C Sage - 2011 - books.google.com
Page 1. ENVIRONMENT AND FOOD Colin Sqge - - - - - II Page 2. Environment and Food This timely book provides a thorough introduction to the interrelationship of food and the environment. **...**
Cited by 72

LOCAL FOOD SYSTEMS & SUSTAINABLE DEVELOPMENT: ANALYZING A REGIME CHANGE IN KANE COUNTY, ILLINOIS, USA, THROUGH A TRANSITION …
TL STROM - lumes.lu.se
... By 2007 four US companies controlled 83.5% of the beef-packing industry, 66% of pork packing,and 80% of **soybean crushing** in the nation; two companies sold 58% of US seed corn, and fourcompanies controlled 29% of the global commercial seed market (Hendrickson and **...**

Visualizing and Quantifying a Normative Scenario for Agriculture in Northeast Ohio
EL Kolbe - 2013 - rave.ohiolink.edu
... 4 firms, etc). In 2007, the concentration ratios of the major agricultural industries were: Beef CR4 83.5%; Pork CR4 66%; Broilers CR4 58.5%; **soybean crushing** CR4 80%; corn seed CR2 58.5% (Hendrickson and Heffernan 2007). Aggregation of these industries is asso- **...**
Cited by 1

Time to Get Real: A Food Assessment of Dining at Pomona College
S Meyer - 2010 - scholarship.claremont.edu
... 25 Industry Corporations Market Share Beef packers Tyson, ConAgra, Cargill, Farmland 81 % Corn exports Cargill-Continental Grain, ADM, Zen Noh 81 % **Soybean crushing** ADM, Cargill, Bunge, AGP 80 % Soybean exports Cargill-Continental Grain, ADM, Zen Noh 65 % **...**

Food, Farms, and Community: Exploring Food Systems

L Chase, V Grubinger - 2014 - books.google.com
Page 1. - 5)* - ty onnuni * d EXPLORT NIG-FOOD SYSTEMS Lisa Chase & Vern Grubinger CIn Page 2. • Food, Farms, and Community Page 3. Page 4. • Lisa Chase & Vern Grubinger • Food, Farms, and Community exploring **...**
Cited by 5

And vegetables for all: urban and civic agriculture in Kansas City and visions for the US agrifood system
SS Beach - 2013 - krex.k-state.edu
Page 1. AND VEGETABLES FOR ALL: URBAN AND CIVIC AGRICULTURE IN KANSAS CITY AND VISIONS FOR THE US AGRIFOOD SYSTEM by SARAH S. BEACH BS, Northern Arizona University, 1998 MA, Colorado State University, 2007 **...**

The Changing Politics of Organic Food in North America
LF Clark - 2015 - books.google.com
The Changing Politics of Organic Food in North America.
The Changing Politics of Organic Food in North America Lisa F. Clark Department of Bioresource Policy, Business and Economics, University of **...**

Reconciling the Divide: An Analysis of Farmers' Land Strategies Within the Corporate-Environmental Food Regime
HM Rud - 2013 - ourspace.uregina.ca
... than reducing the use of agricultural chemicals. Alternative producers may also advocate smaller farm sizes, decreased intensity, reduced **energy use**, greater farm and regional self-sufficiency, agricultural diversity, minimally processed foodstuffs, conservation of **...**
Cited by 1

14.3 Search Terms – "Biodiesel production" "energy use"

The top papers are identified below. In many cases the data in the papers was much older than the published date of the report and thus of little current value.

428 values since 2010. Adding the term soybean reduced the papers returned to 270. Changing the period to 2013 to 2016 reduced the number of papers to 131. Only one of the top 30 papers dealt exclusively with energy use in biodiesel production.

Environmental benefits of the integrated production of ethanol and biodiesel
SP Souza, JEA Seabra - Applied energy, 2013 - Elsevier
... It is worth noting that the impact of the **biodiesel plant** in the plant's energy demand is small. **...** accounts for less than 20% of the mass of the **soybean** grain, emissions from **soybean** production were **...** Breakdown of fossil **energy use** (a) and GHG emissions (b) for the Reference Case **...**
Cited by 23

Towards a sustainable approach for development of biodiesel from plant and microalgae
B Singh, A Guldhe, I Rawat, F Bux - Renewable and sustainable Energy …, 2014 - Elsevier
The production of biodiesel can be accomplished using a variety of feedstock sources. Plant and microalgae based feedstocks are prominent and are studied extens.
Cited by 94

Integrated production of sugarcane ethanol and soybean biodiesel: Environmental and economic implications of fossil diesel displacement
SP Souza, JEA Seabra - Energy Conversion and Management, 2014 - Elsevier

... For this reason, an energy-based allocation was applied to split the fossil **energy use** and the **...** the capital expenditures include only the oil extraction plant and the **biodiesel plant**, while the **...** Once the traditional system does not include the **soybean** production, the costs to produce **...**
Cited by 10

Life cycle assessment of dewatering routes for algae derived biodiesel processes
D O'Connell, M Savelski, CS Slater - Clean Technologies and …, 2013 - Springer
... associated with producing glycerine through the typical commercial route from **soybean** oil as **...** to make an accurate estimation of the requirements for a commercial scale **biodiesel plant**. **...** The resulting **energy use** depends on the extent of dewatering and sequence of these **...**
Cited by 20

Life cycle assessment of camelina oil derived biodiesel and jet fuel in the Canadian Prairies
X Li, E Mupondwa - Science of the Total Environment, 2014 - Elsevier
... is in addition to traditional oilseed crops such as canola/rapeseed, **soybean**, and palm **...** to have better performance in decreasing GHG emissions than traditional **soybeans** and canola **...** of all inputs in agricultural production, transportation of seed to the **biodiesel plant**, direct inputs **...**
Cited by 21

Optimization of biodiesel production for self-consumption: considering its environmental impacts
JA Kaercher, RC de Souza Schneider, RA Klamt… - Journal of Cleaner …, 2013 - Elsevier
... It indicated that **soybean** biodiesel has a high pressure on the environment. **...** were identified and as a consequence alternatives for reduction of water, insumes and **energy use** as well **...** of Feedstock – The feedstocks were received and stored in a room next to the **biodiesel plant**. **...**
Cited by 18

Soy biodiesel pathways: global prospects
MF Milazzo, F Spina, P Primerano, JCJ Bart - Renewable and Sustainable …, 2013 - Elsevier
... Soybean, WTI, 1 kg of **soybeans** exported to Europe, **Soybean** production, Latin America, –, –, GHG, LUC, 2011, [63]. **... Soybean**, WTW, 1 t of output, Production of **soybean** and **soy** industrial products, USA, SimaPro 7, ecoinvent, –, AP, CAP, CE, EP, ET, FFD, GWP, HH, ODP, PS, TFE **...**
Cited by 20

Biodiesel: Environmental Friendly Alternative to Petrodiesel
EPC Lai - J Pet Environ Biotechnol, 2014 - omicsonline.org
... The largest **biodiesel plant**, Great Lakes Biodiesel Inc. **...** Direct esterification could reduce the **energy use** but would increase the land use impact. **...** at 16,991 MJ ha-1. Both the net energy gain of 8,374 MJ ha-1 and the fossil energy ratio of 1.97 showed that **soybean** would be a **...**
Cited by 8

Life cycle assessment on microalgal biodiesel production using a hybrid cultivation system
VO Adesanya, E Cadena, SA Scott, AG Smith - Bioresource technology, 2014 - Elsevier
... other hand, biofuels produced from first generation feedstock (rapeseed, **soybean**, sunflower, wheat **...** study, and furthermore, there are many photobioreactor designs with improved **energy use**. **...** making it difficult to model a complete commercial-scale microalgal **biodiesel plant**. **...**
Cited by 21

[Consequential LCA of two alternative systems for biodiesel consumption in Spain, considering uncertainty]
N Escobar, J Ribal, G Clemente, N Sanjuán - Journal of Cleaner Production, 2014 - Elsevier
... but in Spain, which starts with the UCO collection, and the subsequent transport to the **biodiesel plant**. **...** company of the sector (Bionorte, located in Asturias, Spain): collection distances, **energy use**, and origin of **...** from field to mill, by lorry 3.5–16t (tkm/kg oil), **Soybean** oil extraction **...**
Cited by 12

[Chemicals from biomass–managing greenhouse gas emissions in biorefinery production chains–a review]
R Kajaste - Journal of Cleaner Production, 2014 - Elsevier
... Good management practices, minimization of auxiliary **energy use**, optimal machinery use and use of less emitting transport equipment are eligible options also for the management of GHG emissions in feedstock supply **... Soybean**, VOME 1), 17.7%, 4.0, na, Panichelli et al., 2009. **...**
Cited by 36

[Impact of increasing liquid biofuel usage on EU and UK agriculture]
IS Kim, J Binfield, M Patton, L Zhang, J Moss - Food Policy, 2013 - Elsevier
... The model obtains the net return of a representative **biodiesel plant** using the biodiesel price and the weighted vegetable oil prices, based on the assumption that it is economically and technically feasible for a **biodiesel plant** to substitute feedstock (rape oil, **soy** oil, palm oil and **...**
Cited by 13

[Development of biofuels in South Africa: Challenges and opportunities]
A Pradhan, C Mbohwa - Renewable and Sustainable Energy Reviews, 2014 - Elsevier
... Biodiesel (**soybean**), 288, Port Elizabeth, Eastern Cape. **...** The strategy recommended sugarcane and sugar beet as feedstock for ethanol production; and sunflower, canola and **soybeans** for biodiesel production; however it has currently excluded maize and jatropha citing **...**
Cited by 11

[The EU biofuel policy and palm oil: Cutting subsidies or cutting rainforest?]
I Gerasimchuk, PY Koh - … Geneva, Switzerland,(http://www. iisd. org …, 2013 - foeeurope.org
... In 2011 the Finland-based company Neste Oil opened a new **biodiesel plant** in Rotterdam, which **...** oil, compared with just 0.68 metric tonnes for rapeseed and 0.36 tonnes for **soy** (FAOSTAT **...** Further, compared to **soybean** or rapeseed oil, palm oil derives a much larger share of its **...**
Cited by 11

[Sustainable distributed biodiesel manufacturing under uncertainty: An interval-parameter-programming-based approach]
Z Liu, Y Huang - Chemical Engineering Science, 2013 - Elsevier
... Nevertheless, a recent survey shows that many biodiesel plants in different regions are either in idle mode or operated below design capacity, because the production could not be economically justified (American **Soybean** Association (ASA), 2012). **...**
Cited by 5

[A comparison between ethanol and biodiesel production: the brazilian and european experiences]
PFA Shikida, A Finco, BF Cardoso, VA Galante… - Liquid Biofuels: …, 2014 - Springer

... will be limited to 5 %. The intention of the proposal is to introduce three ILUC emission factors (for cereals 12 g CO2 eq/MJ, sugars 13 g, and oil crops 55 g). The high ILUC factor especially for oil crops could disqualify most biodiesel made from rapeseed, **soybeans**, as well as **...**
Cited by 8

Process integration, energy and GHG emission analyses of Jatropha-based biorefinery systems
E Martinez-Hernandez, J Martinez-Herrera… - Biomass Conversion …, 2014 - Springer
... With systematic selection and process integration of co-production routes, fossil **energy use** and global warming impact of biorefineries can be reduced [25–29]. **...** Methanol kg 12.872 2,836 [33] Hydrogen kg 183.2 11,888 [47] **Soy** meal kg 4.13 726 [48] 108 **...** 2.2.3 **Biodiesel plant ...**
Cited by 7

Greenhouse gasses emissions and energy balances of a non-vertically integrated sugar and ethanol supply chain: a case study in Argentina
MM Acreche, AH Valeiro - Energy, 2013 - Elsevier
... Although Argentina has already developed a very competitive **soybean**-based biodiesel production sector, its potential to produce bioethanol is also important. A study [5] estimates that almost 7.7 million hectares could be potentially grown with sugarcane. **...**
Cited by 10

Life cycle assessment of biofuels from an integrated Brazilian algae sugarcane biorefinery
SP Souza, AR Gopal, JEA Seabra - Energy, 2015 - Elsevier
... All glycerin produced from the **biodiesel plant** is consumed as energy and carbon source in the **...**The life cycle fossil **energy use** and GHG emissions of material and energy inputs were **...** In a previous study, we assessed the LCA of a **soybean**-sugarcane biorefinery system in these **...**
Cited by 8

Ecological efficiency in glycerol combustion
CR Coronado, JA Carvalho, CA Quispe… - Applied Thermal …, 2014 - Elsevier
... This study consists of a comparative analysis of pollution from glycerol combustion in a **biodiesel plant**, utilizing boilers to produce thermal energy for the process and an examination of individual CO_2 , SO_2 , NOx **...** Analysis of three types of glycerol fuel derived from **soybean** oil **...**
Cited by 6

14.4 Search Terms – “Nitrogen content” "below ground biomass" soybean

These very specific search terms only returned 2 papers since 2010. Removing the word content increase the number of papers to 33 but no additional useful information was identified.

Interaction of long-term nitrogen fertilizer application, crop rotation, and tillage system on soil carbon and nitrogen dynamics
KA Congreves, DC Hooker, A Hayes, EA Verhallen… - Plant and Soil, 2016 - Springer
... In the years prior to establishment of the experiment, the area produced winter wheat, **soybeans**, corn and alfalfa with a typical fertility program **...** For corn and **soybean**, the conventional tillage sys- tem consisted of moldboard plowing in the fall (20 cm depth) followed by two to **...**
Cite

Assessing the effects of agricultural management on nitrous oxide emissions using flux measurements and the DNDC model
KC Uzoma, W Smith, B Grant, RL Desjardins… - Agriculture, Ecosystems …, 2015 - Elsevier
... on GHG emissions are strongly tied to climate and soil properties such as soil organic carbon (SOC) content, soil **nitrogen content**, and pH **...** the empirical growth curves, which regulate N and water demand, were modified for cool weather cultivars of corn, **soybeans** (Glycine max **...**
Cited by 12

14.5 Search Terms - "Renewable Diesel" "Process Conditions"

3,330 results

Biodiesel and renewable diesel: a comparison
G Knothe - Progress in Energy and Combustion Science, 2010 - Elsevier
... It may be noted that **renewable diesel** is also termed "HVO" (hydrotreated vegetable oil) in **...** Work on the production of hydrocarbon fuels, mainly by a **process** at that time **...** This cracking **procedure** generally yielded a variety of products including gasoline- and petro diesel-like fuels. **...**
Cited by 543

Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae
ED Frank, A Elgowainy, J Han, Z Wang - Mitigation and Adaptation …, 2013 - Springer
... 2 **Processes** included in the algae growth and oil production model. Details are in Frank et al. **...** Marker et al. (2005) reports upgrading vegetable oil to **renewable diesel** by hydroprocessing. **...** 2.6 Biogas production. The CHG **process** for LEA feeds was described in Frank et al. **...**
Cited by 113

Renewable diesel production from the hydrotreating of rapeseed oil with Pt/Zeolite and NiMo/Al2O3 catalysts
R Sotelo-Boyas, Y Liu, T Minowa - Industrial & Engineering …, 2010 - ACS Publications
... et al.(20) Several oil companies have also developed commercial hydrotreating **processes** by considering **...** that hydroprocessing vegetable oil contributes to the production of a **renewable diesel** with a **...** The understanding of the chemistry of the hydrocracking **process** and of the **...**
Cited by 107

Renewable fuels via catalytic hydrodeoxygenation
TV Choudhary, CB Phillips - Applied Catalysis A: General, 2011 - Elsevier
... for upgrading these fractions into chemicals and fuels using block **process** flow diagrams. **...** **Renewable diesel** molecules are indistinguishable in molecular structure from conventional petroleum-derived **...** Fatty-acid methyl esters (FAME) derived from esterification **processes** on the **...**
Cited by 233

Synthesis of renewable diesel range alkanes by hydrodeoxygenation of furans over Ni/Hβ under mild conditions
G Li, N Li, J Yang, L Li, A Wang, X Wang, Y Cong… - Green …, 2014 - pubs.rsc.org
... Synthesis of **renewable diesel** range alkanes by hydrodeoxygenation of furans over Ni/Hβ under mild **conditions ...** 2 O 3 molar ratio of 394 (denoted as Ni/Hβ-(394)) was found, for the first time, to be extremely active and very stable in the HDO **process** under mild **conditions**. **...**
Cited by 38

Comparison between different types of renewable diesel
S Bezergianni, A Dimitriadis - Renewable and Sustainable Energy …, 2013 - Elsevier
... The test **procedure** used for the measurement of copper strip corrosion is the ASTM D130 method. **...** 3. Description of **renewable diesel** studied. **...** The transesterification **process** is simply described as the chemical breaking of fatty acids contained in vegetable oils using alcohol to **...**
Cited by 66

Biodiesel resources and production technologies–A review
BL Salvi, NL Panwar - Renewable and sustainable energy reviews, 2012 - Elsevier
... The **process** decreases the viscosity but maintains the cetane number and heating value. **...** Transesterification **processes** for biodiesel production from oils and fats. Ester formation constitutes one of the most important classes of reactions in value-added **processing** of animal fats **...**
Cited by 105

Second generation diesel fuel from renewable sources
J Mikulec, J Cvengroš, Ľ Joríková, M Banič… - Journal of Cleaner …, 2010 - Elsevier
... Tall oil is obtained as a by-product of the Kraft **process** of wood pulp manufacture. **...** of refined rapeseed oil was final possibility to prepare **renewable diesel**. **...** pressure 3.5–5.5 MPa, LHSV = 1.0 h −1 and ratio H 2 :HC = 500–1000 Nm 3 /m 3 . During the ests **procedure**, the formed **...**
Cited by 85

Process development for hydrothermal liquefaction of algae feedstocks in a continuous-flow reactor
DC Elliott, TR Hart, AJ Schmidt, GG Neuenschwander… - Algal Research, 2013 - Elsevier
... processing products. Figure options. **...** A total of four HTL tests were performed and the produced biocrude products were hydrotreated in 3 of the cases. Three of the aqueous byproduct streams were gasified. The range of **process conditions** tested in the three **processes** is given **...**
Cited by 147

Renewable diesel from algal lipids: an integrated baseline for cost, emissions, and resource potential from a harmonized model
R Davis, D Fishman, ED Frank… - Argonne National …, 2012 - researchgate.net
... extraction of lipids, and conversion via hydroprocessing to produce a **renewable diesel** (RD) blendstock. **...** data exist to support an end to end experimentally-verified **process** engineering model of algal biofuel production without resorting to theoretical **processes**, so the **...**
Cited by 121

Production of renewable diesel by hydroprocessing of soybean oil: effect of catalysts
B Veriansyah, JY Han, SK Kim, SA Hong, YJ Kim… - Fuel, 2012 - Elsevier
... In addition, the production of **renewable diesel** using hydroprocessing can be employed in the existing infrastructure of petroleum refineries, which **...** temperatures of 300–450 °C and a hydrogen pressure of 5 MPa [4]. Under optimal **conditions**, the molar **...** Apparatus and **procedure**. **...**
Cited by 113

Industrial fermentation of renewable diesel fuels
PJ Westfall, TS Gardner - Current opinion in biotechnology, 2011 - Elsevier
... Table 2. Production **processes** for **Renewable Diesel**. Diesel molecule, Common Name, Trade Name, Feedstock, Fermentation route, Fermentation Product, Chemical **Process**/finishing, Companies. Fermentation **processes**. **...**
Cited by 40

A commercially-viable, one-step process for production of green diesel from soybean oil on Pt/SAPO-11
M Herskowitz, MV Landau, Y Reizner, D Berger - Fuel, 2013 - Elsevier
... As a result, a superior **renewable diesel** called Isodiesel (Scheme 1) was produced from animal and **...** It was sufficient to modify the synthetic **procedure** proposed in [23] in order to combine **...** the reactor packed with SiC with soybean oil at the operating **process condition** (30 bar **...**
Cited by 30

Biomass as renewable feedstock in standard refinery units. Feasibility, opportunities and challenges
JA Melero, J Iglesias, A Garcia - Energy & environmental science, 2012 - pubs.rsc.org
... one promising alternative for the production of biofuels is the co-**processing** of biomass in **...** by dehydration of C 5 sugars like xylose in a well-developed industrial **process**. **...** and highly toxic and suffers from serious drawbacks concerning homogeneous catalytic **processes**, such as **...**
Cited by 163

Hydroconversion of sunflower oil on Pd/SAPO-31 catalyst
OV Kikhtyanin, AE Rubanov, AB Ayupov, GV Echevsky - Fuel, 2010 - Elsevier
... 4]. Vegetable oils (sunflower, soya, palm, etc.) are considered to be possible raw materials for the manufacture of **renewable diesel** fuel **...** n-paraffin-rich product obtained from vegetable oils, having a high yield (>80%) over an expediently selected catalyst and **process conditions**. **...**
Cited by 94

Synthesis of renewable diesel with hydroxyacetone and 2-methyl-furan
G Li, N Li, S Li, A Wang, Y Cong, X Wang… - Chemical …, 2013 - pubs.rsc.org
... K for 6 h. Both 1b and 1c can be used as precursors for synthesis of **renewable diesel** or jet **...** Under solvent-free **conditions**, 79.1% yield of HAA products was obtained over Nafion-212 resin **...** and higher carbon yield of diesel or jet fuel range alkanes in the HDO **process**, which can **...**
Cited by 51

Biomass to olefins: Cracking of renewable naphtha
SP Pyl, CM Schietekat, MF Reyniers, R Abhari… - Chemical engineering …, 2011 - Elsevier
... containing mainly C15–C18 n-paraffins was hydrocracked in order to produce **renewable diesel** or jet **...** For the coking experiments identical **process conditions** are used in the runs performed with (100 **...** the **conditions** specified in Table 3. At the start of the **procedure**, the cracking **...**
Cited by 40

… investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition
MEA Fahd, Y Wenming, PS Lee, SK Chou, CR Yap - Applied Energy, 2013 - Elsevier
... Engine experiments of five different **renewable diesel** fuels including 10% emulsion diesel has been **...** also found that peak combustion pressure, especially at high speed **conditions**, are close **...** by the improved air–fuel mixing mechanism and enhance combustion **process** due to **...**
Cited by 69

Properties and performance of levulinate esters as diesel blend components
E Christensen, A Williams, S Paul, S Burton… - Energy & …, 2011 - ACS Publications
... compounds used in a number of large-volume chemical markets.(3) The **processing conditions** of one proposed method of high-temperature acid hydrolysis, the Biofine **process**,(4, 5 **...** the heavy duty diesel transient (HDDT) cycle in accordance with the federal test **procedure**. **...**
Cited by 66

Hydroprocessing of crude palm oil at pilot plant scale
A Guzman, JE Torres, LP Prada, ML Nunez - Catalysis today, 2010 - Elsevier
... The catalyst was previously activated by a standard **procedure** using straight-run gas oil **...** In terms of **process** profitability that would imply higher hydrogen consumption as reaction pressure is **...**of crude palm oil has resulted in a highly paraffinic **renewable diesel** (Biocetano) with **...**
Cited by 95

14.6 Search Terms - "Renewable Diesel" LCA

586 results

Renewable diesel from algal lipids: an integrated baseline for cost, emissions, and resource potential from a harmonized model
R Davis, D Fishman, ED Frank… - Argonne National …, 2012 - researchgate.net
... analysis (TEA), and life-cycle analysis (**LCA**) models. The baseline attempts to represent a plausible near-term production scenario with freshwater microalgae growth, extraction of lipids, and conversion via hydroprocessing to produce a **renewable diesel** (RD) blendstock. **...**
Cited by 121

Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae
ED Frank, A Elgowainy, J Han, Z Wang - Mitigation and Adaptation …, 2013 - Springer
... is extracted and converted to biodiesel (BD) by transesterification or in which algal lipids are extracted and converted to a **renewable diesel** (RD) blend stock **...** As mentioned, previous work showed that electricity produced from LEA strongly affects life cycle analysis (**LCA**) results. **...**
Cited by 113

Renewable fuels via catalytic hydrodeoxygenation
TV Choudhary, CB Phillips - Applied Catalysis A: General, 2011 - Elsevier
... the resulting straight-chain, renewable hydrocarbon fuel product (R′H 3) is referred to as "**renewable diesel**" in the marketplace. **Renewable diesel** molecules are indistinguishable in molecular structure from conventional petroleum-derived diesel molecules. **...**
Cited by 233

Development of emission parameters and net energy ratio for renewable diesel from Canola and Camelina
P Miller, A Kumar - Energy, 2013 - Elsevier
... unit used in this study is 1 MJ of energy in the **renewable diesel** produced (higher **...** products, allocation methods, and land-use changes) that could significantly impact the **LCA** results **...** Although HDRD and meal are the two products typically considered for HDRD **LCAs**, straw and **...**
Cited by 19

Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing
DD Hsu - Biomass and bioenergy, 2012 - Elsevier
... Data are also reported for 1 MJ of fuel produced to facilitate comparisons with other **LCAs**. **...** mass density and the lower heating value of diesel fuel affect the **LCA** results through the **...** mass density and lower heating value are varied based on ranges for **Renewable Diesel** I (super **...**
Cited by 64

Environmental sustainability of emerging algal biofuels: a comparative life cycle evaluation of algal biodiesel and renewable diesel
GG Zaimes, V Khanna - Environmental Progress & Sustainable …, 2013 - Wiley Online Library
... SYSTEM DESCRIPTION, METHODOLOGY, AND DATA SOURCES. Model Overview. This study is a comparative **LCA** of **Renewable Diesel** (RD) II and Biodiesel (BD) derived from algae cultivated in Open Raceway Ponds (ORP). **...**
Cited by 24

Integrating LCA and thermodynamic analysis for sustainability assessment of algal biofuels: comparison of renewable diesel vs. biodiesel
MG Borkowski, GG Zaimes… - Sustainable Systems and …, 2012 - ieeexplore.ieee.org
Abstract: Advanced biofuels are attracting intense interest from government, industry and researchers as potential substitutes for petroleum gasoline and diesel transportation fuels. Microalgae's advantages as a biofuel feedstock are due particularly to their rapid growth
Cited by 6

Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context
M Wang, H Huo, S Arora - Energy Policy, 2011 - Elsevier
... Soybeans, **Renewable diesel**, Fuel gas and heavy oils, Energy sources for plant internal use; or energy products for sale. **...** This method is widely used in **LCAs** of consumer products and in some generic **LCA** models. Sheehan et al. **...**
Cited by 164

Camelina-derived jet fuel and diesel: Sustainable advanced biofuels
DR Shonnard, L Williams… - Environmental Progress & …, 2010 - Wiley Online Library
... cycle greenhouse gas (GHG) emissions and energy demand for both HRJ and **renewable diesel** (green diesel **...** For the purposes of GHG **LCAs** camelina, HRJ and GD would be considered the **...** The goal of this **LCA** is to determine the GHG emissions, cumulative energy demand **...**
Cited by 176

Carbon footprint of renewable diesel from palm oil, jatropha oil and rapeseed oil
V Uusitalo, S Väisänen, J Havukainen, M Havukainen… - Renewable Energy, 2014 - Elsevier
... Fig. 1. Locations of potential cultivation areas for **renewable diesel** feedstock [17], [19] and [20]. **...** 2.2. Life-cycle assessment. The life-cycle assessment (**LCA**) method may be used to estimate the environmental effect of emissions. **...**
Cited by 20

Camelina (Camelina sativa L.) oil as a biofuels feedstock: Golden opportunity or false hope?
BR Moser - Lipid technology, 2010 - Wiley Online Library
... A recent life-cycle analysis (**LCA**) study concluded that the life cycle greenhouse gas emissions, cumulative energy demand, and fossil energy demand of camelina-derived biodiesel and **renewable diesel** and jet fuels was significantly lower than for the corresponding **...**
Cited by 87

Life cycle assessment of gasoline and diesel produced via fast pyrolysis and hydroprocessing
DD Hsu - Contract, 2011 - Citeseer
... Data are also reported for 1 MJ of fuel produced to facilitate comparisons with other **LCAs**. **...** mass density and the lower heating value of diesel fuel affect the **LCA** results through the **...** mass density and lower heating value are varied based on ranges for **Renewable Diesel** I (super **...**
Cited by 30

Assessment of fuel-cycle energy use and greenhouse gas emissions for Fischer− Tropsch diesel from coal and cellulosic biomass
X Xie, M Wang, J Han - Environmental science & technology, 2011 - ACS Publications
... coal-to-liquids (CTL) processes has become a major diffusion barrier for coal-derived FTD use.(5) Life-cycle analyses (**LCAs**) of FTD **...** to address coproduct issues in biofuel **LCA**, and Huo et al.(12) applied several coproduct methods in **LCA** of biodiesel and **renewable diesel**. **...**
Cited by 30

Well-to-Tank environmental analysis of a renewable diesel fuel from vegetable oil through co-processing in a hydrotreatment unit
D Garraín, I Herrera, Y Lechón, C Lago - Biomass and Bioenergy, 2014 - Elsevier
... Abstract. A Life Cycle Assessment (**LCA**) study of HidroBioDiésel (HBD) was carried out. This partly **renewable diesel** fuel is obtained from the co-processing of soybean vegetable oil with conventional fossil fuel in hydrotreating facilities of crude oil refineries. **...**
Cited by 7

Infrastructure associated emissions for renewable diesel production from microalgae
CE Canter, R Davis, M Urgun-Demirtas, ED Frank - Algal Research, 2014 - Elsevier
... Abstract. Greenhouse gas (GHG) emissions for microalgae biofuel infrastructure are sometimes neglected during a life-cycle analysis (**LCA**). Construction materials were found for a baseline facility designed to produce **renewable diesel** in the United States. **...**
Cited by 10

Renewable diesel fuel from processing of vegetable oil in hydrotreatment units: Theoretical compliance with european directive 2009/28/EC and ongoing …
G Daniel, H Israel, L Carmen, L Yolanda… - Smart Grid and …, 2010 - file.scirp.org
... reduce environmental impacts. For this evaluation, life cycle assessment (**LCA**) methodology was the approach chosen to calculate the GHG emissions profile associated with the production of this new **renewable diesel** fuel. **...**
Cited by 6

The potentials and challenges of algae based biofuels: a review of the techno-economic, life cycle, and resource assessment modeling
JC Quinn, R Davis - Bioresource technology, 2015 - Elsevier
... Challenges associated with the economical delivery and utilization of gaseous carbon dioxide has typically been ignored in TEA and **LCA** studies. A large number of TEAs and **LCAs** assume the co-location of production facilities with industrial waste carbon dioxide without **...**
Cited by 72

A life cycle assessment of pennycress (Thlaspi arvense L.)-derived jet fuel and diesel
J Fan, DR Shonnard, TN Kalnes, PB Johnsen… - biomass and …, 2013 - Elsevier
... Life cycle assessment (**LCA**) studies have been conducted to estimate the life cycle GHG emissions from **renewable diesel** and aviation fuels [38], [39] and [40], but pennycress is a relatively new biomass feedstock which has not been thoroughly investigated yet. **...**
Cited by 32

Methane and nitrous oxide emissions affect the life-cycle analysis of algal biofuels
ED Frank, J Han, I Palou-Rivera… - Environmental …, 2012 - iopscience.iop.org
... GREET is a publicly available **LCA** tool that investigates numerous fuel and vehicle cycles (Wang 1999a, 1999b, GREET 2011). **...** Figure 1. System definition for the algae production pathway. BD—biodiesel; RD—**renewable diesel**; RG—renewable gasoline. **...**
Cited by 49

Evaluation of environmental impacts from microalgae cultivation in open-air raceway ponds: Analysis of the prior literature and investigation of wide variance in …
RM Handler, CE Canter, TN Kalnes, FS Lupton… - Algal Research, 2012 - Elsevier
... to reliably compare studies and present the range of processing possibilities and potential environmental impacts, we present a detailed examination of microalgae **LCAs** that have

appeared recently in the peer-reviewed literature and reports. Our initial **LCA** comparison will **...**

15. APPENDIX 5 – SUGAR CANE LITERATURE SEARCH

15.1 SEARCH TERMS - "SUGAR CANE" "N_2O EMISSIONS"

Search returned 677 results.

Synergies between the mitigation of, and adaptation to, climate change in agriculture
P Smith, JE Olesen - The Journal of Agricultural Science, 2010 - Cambridge Univ Press
... Significant potential is also available from reductions in CH4 and **N2O emissions**, and such emission re ductions are permanent. **...** USA 14.55 Maize 1.25 Soybean 15.8 Brazil 10.44 **Sugar cane** 0.17 Soybean 10.6 EU 1.24 Wheat, maize, sugar beet 4.52 Rapeseed 5.8 **...**
Cited by 177

Emissions of methane and nitrous oxide from Australian sugarcane soils
OT Denmead, BCT Macdonald, G Bryant… - Agricultural and Forest …, 2010 - Elsevier
Climatic conditions and cultural practices in the sub-tropical and tropical high-rainfall regions in which sugarcane is grown in Australia are conducive to rapi.
Cited by 91

Using the APSIM model to estimate nitrous oxide emissions from diverse Australian sugarcane production systems
PJ Thorburn, JS Biggs, K Collins, ME Probert - Agriculture, ecosystems & …, 2010 - Elsevier
Sugarcane is an important crop in the tropics and sub-tropics and its production requires very high rates of nitrogen (N) fertiliser. This N use, together with.
Cited by 72

Effect of nitrogen fertilizer management and waterlogging on nitrous oxide emission from subtropical sugarcane soils
DE Allen, G Kingston, H Rennenberg, RC Dalal… - Agriculture, ecosystems …, 2010 - Elsevier
Considerable potential for N_2O emission from Australian sugarcane systems exists from high N fertilizer application rates and periodic waterlogging. To determin.
Cited by 82

Greenhouse gas footprints of different biofuel production systems
R Hoefnagels, E Smeets, A Faaij - Renewable and Sustainable Energy …, 2010 - Elsevier
... Ethanol, **Sugar cane**, Brazil, Fermentation, **...** No reference land use selected (no LUC). JRC DNDC
model for N_2O emissions from **sugar cane**, wheat, sugar beet, maize and rapeseed. IPCC model for miscanthus, palm fruit, soy beans, switchgrass, eucalyptus and jatropha. **...**
Cited by 177

Sugar beet as an energy crop
L Panella - Sugar Tech, 2010 - Springer
... concluded that sugar beet and **sugar cane** were effective in
reducing **N2O emissions** compared with maize; however, the authors stressed that management of crop nutrition, especially optimization of nitrogen fertilization was crucial in reducing **N2O emissions** from the soil. **...**
Cited by 26

Mitigating N_2O emissions from soil: from patching leaks to transformative action
C Decock, J Lee, M Necpalova, EIP Pereira… - …, 2015 - re.indiaenvironmentportal.org.in

... For example, there is evidence that **N2O emissions** from **sugar cane** cultivation might be larger than expected based on 5 IPCC emission factors, which could change the picture on the greenhouse gas balance of sugarcane based biofuels (Lisboa et al., 2011). **...**
Cited by 34

The carbon footprint of sugar
PW Rein - Proc. Int. Soc. **Sugar Cane** Technol, 2010 - issct.org
... 5. Energy value of process chemicals. Page 7. Rein, PW Proc. Int. Soc. **Sugar Cane** Technol., Vol. 27, 2010 **...** **N2O emissions** can vary by more than two orders of magnitude, depending on a complex combination of soil composition, climate, crop and farming practices. **...**
Cited by 13

Bioethanol production from sugarcane and emissions of greenhouse gases–known and unknowns
CC Lisboa, K BUTTERBACH-BAHL, M Mauder… - GCB …, 2011 - Wiley Online Library
Our site uses cookies to improve your experience. You can find out more about our use of cookies in About Cookies, including instructions on how to turn off cookies if you wish to do so. By continuing to browse this site you agree **...**
Cited by 58

No reason for complacency
JM Hall-Spencer - Nature Climate Change, 2011 - researchgate.net
... the relatively high temperatures and soil water contents in the tropics — where most of it is cultivated — can enhance denitrification rates, boosting emissions of the greenhouse-gas nitrous oxide (N2O)2,3. Recent studies examining **N2O emissions** from **sugar-cane** production **...**
Cited by 5

Does eating local food reduce the environmental impact of food production and enhance consumer health?
G Edwards-Jones - Proceedings of the Nutrition Society, 2010 - Cambridge Univ Press
... A general rule adopted by the Inter- national Panel on Climate Change in their tier 1 methodology for calculating **N2O emissions** is that 1% N applied to **...** The sugar cubes and raw sugar were made from **sugar cane** produced in Columbia and organic cane sugar from Paraguay. **...**
Cited by 66

Facile fabrication of a well-ordered porous Cu-doped SnO2 thin film for H2S sensing
S Zhang, P Zhang, Y Wang, Y Ma… - ACS applied materials …, 2014 - ACS Publications
Cited by 36

Nitrous oxide emissions from a sugarcane soil under different fallow and nitrogen fertiliser management regimes
WJ Wang, B Salter, SH Reeves, TC Brieffies… - … Aust Soc **Sugar Cane** …, 2012 - assct.com.au
... Proc Aust Soc **Sugar Cane** Technol Vol 34 2012 _____ 2 High **N2O emissions** (3–25 kg N/ha/yr) have been recorded from Australian sugarcane soils (Wang et al., 2008 **...**
Cited by 8

N_2O emissions from an irrigated and non-irrigated organic soil in eastern Canada as influenced by N fertilizer addition
P Rochette, N Tremblay, E Fallon… - European Journal of …, 2010 - Wiley Online Library

... 1) and by Terry et al. (1981) for **sugar cane** (48 kg N ha −1 year −1), grass (97 kg N ha −1 year −1) and fallow (165 kg N ha −1 year −1) in a warmer climate (Florida, USA). These observations suggest that temperate drained **...**
Cited by 35

N_2O emissions from the global agricultural nitrogen cycle–current state and future scenarios
BL Bodirsky, A Popp, I Weindl, JP Dietrich… - …, 2012 - biogeosciences.net
... 4172 BL Bodirsky et al.: **N2O emissions** from the global agricultural nitrogen cycle **...** The Nr fixed by leguminous crops and **sugar cane** is estimated by multiplying Nr in plant biomass (harvested or- gan, AG and BG residue) with regional plant-specific percentages of plant Nr **...**
Cited by 45

Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil
A Keith, B Singh, BP Singh - Environmental Science & Technology, 2011 - ACS Publications
... Sugar cane residue (source of LOM) at a rate of 0, 1, 2, and 4% (w/w) in combination with two wood biochars (450 and 550 °C) at a rate of 2% (w/w) were applied to the soil. **... Sugar cane** residue (C4 biomass), obtained from a local nursery, was used as the source of LOM. **...**
Cited by 144

On sustainability of bioenergy production: integrating co-emissions from agricultural intensification
A Popp, H Lotze-Campen, M Leimbach, B Knopf… - Biomass and …, 2011 - Elsevier
... Food and feed energy for the ten demand categories can be produced by 20 cropping activities (temperate cereals for food or feed, maize for food or feed, tropical cereals for food or feed, rice, five oil crops, pulses, potatoes, cassava, sugar beets, **sugar cane**, vegetables/fruits **...**
Cited by 46

Use of the life cycle assessment (LCA) for comparison of the environmental performance of four alternatives for the treatment and disposal of bioethanol stillage
MH Rocha, EES Lora, OJ Venturini… - International Sugar …, 2010 - issct.org
... sugar production in Queensland. Proc. Aust. Soc. **Sugar Cane** Technol., 19: 213–220. CETESB. (2005). **...** Gas Inventories. Volume 4: Agriculture, Forestry and Other Land Use. Chapter 11: **N2O Emissions** from Managed Soils, and CO2 Emissions from Lime and Urea Application. **...**
Cited by 10

Infield greenhouse gas emissions from sugarcane soils in Brazil: effects from synthetic and organic fertilizer application and crop trash accumulation
JB Carmo, S Filoso, LC Zotelli, S Neto… - Gcb …, 2013 - Wiley Online Library
Our site uses cookies to improve your experience. You can find out more about our use of cookies in About Cookies, including instructions on how to turn off cookies if you wish to do so. By continuing to browse this site you agree **...**
Cited by 55

Minimizing land use and nitrogen intensity of bioenergy
SA Miller - Environmental science & technology, 2010 - ACS Publications
... The results of the study indicate that **sugar cane** has the best nitrogen and land use profile of the analyzed feedstocks. **Sugar cane** is the largest contributor to bioenergy production worldwide and is an effective policy choice from a nutrient and land use perspective. **...**
Cited by 55

15.2 SEARCH TERMS - "SUGAR CANE" "N_2O EMISSIONS" "META ANALYSIS"

Search returned 93 results.

Mitigating N_2O emissions from soil: from patching leaks to transformative action
C Decock, J Lee, M Necpalova, EIP Pereira… - …, 2015 - re.indiaenvironmentportal.org.in
... For example, there is evidence that **N2O emissions** from **sugar cane** cultivation might be larger than expected based on 5 IPCC emission factors, which could change the picture on the greenhouse gas balance of sugarcane based biofuels (Lisboa et al., 2011). **...**
Cited by 34

Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions
ZM Harris, R Spake, G Taylor - Biomass and Bioenergy, 2015 - Elsevier
... Conference. Edited By Patricia Thornley, Gregory Tucker and Iain Donnison. Cover image Cover image. Research Paper. Land use change to bioenergy: A **meta**-**analysis** of soil carbon and GHG emissions. **...** 2.2.2. **Meta**-**analysis**. Random **...**
Cited by 15

Losses of NO and N_2O emissions from Venezuelan and other worldwide tropical N-fertilized soils
S Marquina, L Donoso, T Pérez, J Gil… - Journal of …, 2013 - Wiley Online Library
Cited by 10

Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils
BP Singh, BJ Hatton, B Singh… - Journal of …, 2010 - dl.sciencesocieties.org
Cited by 433

Impact of crop yield reduction on greenhouse gas emissions from compensatory cultivation of pasture and forested land
R Carlton, P Berry, P Smith - International Journal of Agricultural …, 2010 - Taylor & Francis
... Page 5. In the case of sugar production, **sugar cane** production in Brazil compensates for displaced European sugar beet production. **...** 4. Twenty-year **N2O emissions** are calculated for soil organic N released plus additional N applications required to meet crop N requirements. **...**
Cited by 10

Innovations for a sustainable future: rising to the challenge of nitrogen greenhouse gas management in Latin America
MMC Bustamante, LA Martinelli, JPHB Ometto… - Current Opinion in …, 2014 - Elsevier
... Paruelo et al. [21] estimated that the burning of 8.7 million tons of biomass yr −1 due to deforestation fires in Argentina produced emissions of 0.2 Gg of N 2 O. Between 1994 and 2000, GHG emissions, mostly due to the burning of **sugar cane** residues, ranged between 187 and **...**
Cited by 4

Effects of urea formulations, application rates and crop residue retention on N_2O emissions from sugarcane fields in Australia
WJ Wang, SH Reeves, B Salter, PW Moody… - Agriculture, Ecosystems …, 2016 - Elsevier
... 2009). A **meta**-**analysis** by Akiyama et al. (2010 **...** plot. Weather conditions (a) in relation to daily (b) and cumulative (c) **N2O emissions** ... Weather conditions (a) in relation to daily (b) and cumulative (c) **N2O emissions** ... Fig. 2. Weather **...**
Cited by 5

Soil N_2O and NO emissions from land use and land-use change in the tropics and subtropics: a meta-analysis.
J van Lent, K Hergoualc'h… - Biogeosciences …, 2015 - search.ebscohost.com
... 111 NO case studies), determine the trend and magnitude of flux changes with land-use change (LUC) using a **meta- analysis** approach (43 **...** annual **N2O emissions** were exponentially related to N fertilization rates and average water-filled pore space (WFPS) whereas in non **...**
Cited by 2

No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis
K Abdalla, P Chivenge, P Ciais… - Biogeosciences …, 2015 - biogeosciences-discuss.net
... conditions: results from a **meta-analysis** K. Abdalla 1,2 , P. Chivenge 1,3 , P. Ciais 4 , and V. Chaplot 1,5 **...** But this estimate is highly uncertain, due to the lack of detailed site-level **meta-analysis** for different climates, soil types and management intensities. Six et al. **...**
Cited by 2

Ecosystem Services and Agricultural Production in Latin America and Caribbean
LA Martinelli - … bank. Environmental safeguards unit (VPS/ESG). …, 2012 - services.iadb.org
... Soybean 43 95 42 Maize 27 100 12 **Sugar cane** 11 900 54 Wheat 9 21 3 Beans 7 6 29 **...** properties, leading to an increase in crop productivity.96 However, no till management and the use of cover crops like legumes may increase **N2O emissions**, which would offset the carbon **...**
Cited by 2

Impact of EU biofuel policies on the French arable sector: A micro-level analysis using global market and farm-based supply models
K Louhichi, H Valin - Revue d'Études en Agriculture et …, 2012 - researchgate.net
... This increase would boost farm income of most arable farms (+10% on average); however, the environment would face increase pressure from agricultural production with more use of pesticide (+5%) and increase in **N2O emissions** (+2.5%). **...**
Cited by 6

Agricultural land management for reduction of N_2O emissions: Meta-analysis
MA Arango, A Anandhi, CW Rice - ipsr.ku.edu
... High variability was found among the group of soil. Clay soil had the highest %N lost by **N2O emissions**, and silt and clay -loam **...** statistical treatment is applied to the data set, the objective of this **meta-analysis** is to detect the **...** emission were potato (5.3%) and **sugar cane** (3.8%). **...**

Reviews and syntheses: Soil N_2O and NO emissions from land use and land use change in the tropics and subtropics: a meta-analysis
J van Lent, K Hergoualc'h, LV Verchot - Biogeosciences, 2015 - cifor.org
... NO case studies), we determine the trend and magnitude of flux changes with land-use change (LUC) using a **meta-analysis** approach (44 **...** In agricultural soils annual **N2O emissions** were exponentially related to N fer- tilization rates and average water-filled pore space (WFPS **...**
Cited by 1

Impacts of Jatropha and Sugar Cane biofuel plantations on biodiversity and long term carbon balances: a literature analysis
N Burgess - 2010 - diskurs.kb.dk

... biodiesel and bioethanol respectively. The analysis performed here was based 1) on a **meta**-**analysis** of biodiversity data from comparisons between **sugar cane** plantations and different reference habitats in South America and Sub-Saharan Africa, 2) a **...**

Nitrous Oxide and Methane Fluxes Following Ammonium Sulfate and Vinasse Application on Sugar Cane Soil
DS Paredes, BJR Alves, MA dos Santos… - … science & technology, 2015 - ACS Publications
... Nitrous Oxide and Methane Fluxes Following Ammonium Sulfate and Vinasse Application on **Sugar Cane** Soil. **...** on emissions. The study was carried out in a traditional area of unburned **sugar cane** in São Paulo state, Brazil. **...**

No-tillage lessens soil CO_2 emissions the most under arid and sandy soil conditions: results from a meta-analysis
K Abdalla, P Chivenge, P Ciais, V Chaplot - Biogeosciences, 2016 - oar.icrisat.org
... No-tillage lessens soil CO2 emissions the most under arid and sandy soil conditions: results from a **meta**-**analysis** **...** But this estimate is highly uncertain, due to the lack of detailed site- level **meta**-**analysis** for different climates, soil types and man- agement intensities. Six et al. **...**

Sugarcane bagasse biochars impact respiration and greenhouse gas emissions from a latosol
W Deng, L Van Zwieten, Z Lin, X Liu… - Journal of Soils and …, 2016 - Springer
... Materials and methods Biochar was produced from **sugar**- **cane** bagasse pyrolyzed at 300, 500, and 700 °C (BC **...** In an updated **meta**-**analysis** (Cayuela et al. **...** Studies have shown that **N2O emissions** are lowered in biochar- amended soils under laboratory conditions (Singh et al **...**

The use of Meta-Regression Analysis to harmonize LCA literature: an application to GHG emissions of 2nd and 3rd generation biofuels
F Menten, B Chèze, L Patouillard, F Bouvart - 2013 - iaea.org
... to Ethanol and biodiesel produced from conventional crops such as **sugar cane**, sugar beet **...** cycle GHG estimations (due to uncertainties in the quantification of **N2O emissions** from agricultural **...** of research literature, but only studies with quantitative results: "**Meta**- **analysis** is the **...**

Environmental assessment of organic juice imported to Denmark: a case study on oranges (Citrus sinensis) from Brazil
MT Knudsen, GF de Almeida, V Langer, LS de Abreu… - Organic Agriculture, 2011 - Springer
... a The organic fertilizer is chicken manure, cattle manure and/or **sugar cane** filter cake b Small letters denotes significant differences between **...** related to the orange production were estimated using the IPCC 2006 guidelines (IPCC 2006) for the direct and indirect **N2O emissions**. **...**
Cited by 23

Carbon Footprint Analysis of Gasoline and Diesel from Forest Residues and Corn Stover using Integrated Hydropyrolysis and Hydroconversion
J Fan, J Gephart, T Marker, D Stover… - ACS Sustainable …, 2015 - ACS Publications
Cited by 1

15.3 SEARCH TERMS - "METHANE EMISSIONS" VINASSE

Search returned 114 results.

Soil greenhouse gas fluxes from vinasse application in Brazilian sugarcane areas
BG de Oliveira, JLN Carvalho, CEP Cerri, CC Cerri… - Geoderma, 2013 - Elsevier
... Geoderma. Volumes 200–201, June 2013, Pages 77–84. Cover image Cover image. Soil greenhouse gas fluxes from **vinasse** application in Brazilian sugarcane areas. **...** 2.4. Chemical characterisation of the **vinasse** applied to the soil. **...**
Cited by 32

Net greenhouse gas fluxes in Brazilian ethanol production systems
MV Galdos, CC Cerri, R Lal, M Bernoux, B Feigl… - GCB …, 2010 - Wiley Online Library
... Therefore, **methane emissions** from **vinasse** were considered insignificant and not included in this assessment. **... Methane emissions** from organic residues of ethanol production such as **vinasse** need further research in order to be estimated and included in future assessments. **...**
Cited by 41

Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions
E Dunkelberg, M Finkbeiner, B Hirschl - Biomass and Bioenergy, 2014 - Elsevier
... Output **vinasse**, t t −1, 2.4, Questionnaire. a **...** This was the case for emissions from pre-harvest burning and soil N 2 O emissions stemming from the use of chemical fertilizer: Based on IPCC data [26], **methane emissions** from pre-harvest burning amount to 2.7 g kg −1 of sugarcane **...**
Cited by 8

Atmospheric impacts of the life cycle emissions of fuel ethanol in Brazil: based on chemical exergy
AR Ometto, WNL Roma - Journal of Cleaner Production, 2010 - Elsevier
... to using ethanol as fuel in automotive vehicles; recycling corresponds to the application of sugarcane **vinasse** in fertilizing **...** The sugarcane related CO2 , CO and Hydrocarbons, except for **methane emissions** (from sugarcane burning, bagasse energy cogeneration and fuel **...**
Cited by 33

Greenhouse gas emissions from first generation ethanol derived from wheat and sugar beet in Germany–Analysis and comparison of advanced by-product utilization …
J Weinberg, M Kaltschmitt - Applied energy, 2013 - Elsevier
... separation from wheat and biogas production from sugar beet pulp and **vinasse** the GHG emissions due to process energy supply are completely replaced. Only inevitable emissions like raw material supply, transportation processes and diffuse **methane emissions** from biogas **...**
Cited by 7

Predicting methane production in simple and unheated biogas digesters at low temperatures
CH Pham, JM Triolo, SG Sommer - Applied Energy, 2014 - Elsevier
... stirring. Zeeman [37] has studied **methane emissions** from animal storages, reporting µm of 0.02, 0.025 and 0.09 at pig manure storage, respectively, and 0.02, 0.071 and 0.12, respectively, for cow manure at 15, 20 and 30 °C. Fig. **...**
Cited by 13

Effects of organic and inorganic fertilizers on greenhouse gas (GHG) emissions in tropical forestry
DI de Urzedo, MP Franco, LM Pitombo… - Forest Ecology and …, 2013 - Elsevier
The production of organic wastes tends to increase in a manner that is proportional to human population growth. Currently, applying these wastes to soils is bei.
Cited by 16

Nitrous oxide emission and ammonia volatilization induced by vinasse and N fertilizer application in a sugarcane crop at Rio de Janeiro, Brazil
D da Silva Paredes, ACR Lessa… - Nutrient cycling in …, 2014 - Springer
... (2013) published the first results of N_2O and CH_4 emissions from soils treated with **vinasse** and N fertilizer in typical sugarcane areas of São Paulo State in Brazil. **Methane emissions** were not detected but results suggested the CH 4 oxidation as the dominant process. **...**
Cited by 6

A comparative assessment of anaerobic digestion power plants as alternative to lagoons for vinasse treatment: life cycle assessment and exergy analysis
EL Barrera, E Rosa, H Spanjers, O Romero… - Journal of Cleaner …, 2016 - Elsevier
The treatment of **vinasse** in lagoons causes **methane emissions** during the anaerobic decomposition of the organic matter. **...** Abstract. The treatment of **vinasse** in lagoons causes **methane emissions** during the anaerobic decomposition of the organic matter. **...**
Cited by 1

Nitrous Oxide and Methane Fluxes Following Ammonium Sulfate and Vinasse Application on Sugar Cane Soil
DS Paredes, BJR Alves, MA dos Santos… - … science & technology, 2015 - ACS Publications
... Nitrous Oxide and Methane Fluxes Following Ammonium Sulfate and **Vinasse** Application on Sugar Cane Soil. **...** On average, the soil was a sink for CH 4 , which was not affected by the treatments. Emissions of N 2 O were induced by N fertilizer and **vinasse** applications. **...**

Greenhouse gas emissions from sugarcane vinasse transportation by open channel: a case study in Brazil
BG de Oliveira, JLN Carvalho, CEP Cerri… - Journal of Cleaner …, 2015 - Elsevier
... Methane emissions represented 10,714 kg CO 2 eq day −1 , while the N 2 O fluxes contributed with 30 kg CO 2 eq day −1 , resulting **...** 2 O converted in CO 2 eq and extrapolated to the respective areas of the channel and GHG emission intensity during the **vinasse** transportation. **...**

Enteric methane emissions from German pigs
C Rösemann - vTI Agriculture and Forestry Research - ti.bund.de
... H.-D. Haenel, C. Rösemann/Landbauforschung-vTI Agriculture and Forestry Research 3 2012 (62) 83-96 87 Table 3: **Methane emissions** from growing **...** milk Kuhmilch (Vollmilch) 0.000[1] fish meal 64% XP Fischmehl 64% RP 0.001[1] yeast Bierhefe, Weinhefe (**Vinasse**) 0.306[1 **...**

Enhancing biogas production from vinasse in sugarcane biorefineries: Effects of urea and trace elements supplementation on process performance and stability
L Janke, AF Leite, K Batista, W Silva, M Nikolausz… - Bioresource …, 2016 - Elsevier
... During the ethanol distillation, large amounts of sugarcane **vinasse** (SCV), also called stillage, are produced. **...** of metals to groundwater, changes in soil quality, increase of

phytotoxicity, unpleasant odor, as well as leading to considerable **methane emissions** during temporary **...**
Cited by 3

Life cycle assessment for enhancing environmental sustainability of sugarcane biorefinery in Thailand
T Silalertruksa, P Pongpat, SH Gheewala - Journal of Cleaner Production, 2016 - Elsevier
... The **methane emissions** from the open lagoon wastewater treatment system of the molasses ethanol plant are estimated to be around 2 kg CH 4 /liter ethanol based on the 10 L of **vinasse**/liter ethanol; the COD of **vinasse** about 100,000 mg/L; the methane producing capacity **...**
Cited by 3

Valorization of sugar-to-ethanol process waste vinasse: A novel biorefinery approach using edible ascomycetes filamentous fungi
RB Nair, MJ Taherzadeh - Bioresource Technology, 2016 - Elsevier
... such as leaching of metals to groundwater, changes in soil quality, increase of phytotoxicity, unpleasant odor, as well as leading to considerable **methane emissions** during temporary storage or transportation and also nitrous oxide emissions (after application of **vinasse** to the **...**

Novel Uses of Biochar
HP Schmidt - 2013 - scholarworks.umass.edu
... 4. 1- 1,5 % BC in liquid manure Reducing NH3-losses, **methane emissions**, increases plant nutrient efficiency, decreases nutrient leaching and odors 4. Liquid manure additive **...** Rolf Zimmermann Injecting **vinasse** (rich in sugar, proteins, N, P, K) rock powder (micro nutrients) **...**
Cited by 1

Sustainability of using composting and vermicomposting technologies for organic solid waste biotransformation: recent overview, greenhouse gases emissions and …
SL Lim, LH Lee, TY Wu - Journal of Cleaner Production, 2016 - Elsevier
Organic solid waste poses a serious threat to the environment as the world struggles to keep up with its rapid generation. Biological waste treatment technologi.
Cited by 42

Recalculating GHG emissions saving of palm oil biodiesel
G Pehnelt, C Vietze - Environment, development and sustainability, 2013 - Springer
... The main environmental impact related to **methane emissions** from production of palm oil in the palm oil mill relates to the technology for treating palm oil mill effluent (POME). **...** As value for the **methane emissions** from POME, we apply 1,093.59 g CO 2 eq per kg CPO. **...**
Cited by 16

Life-cycle fossil energy consumption and greenhouse gas emissions of bioderived chemicals and their conventional counterparts
F Adom, JB Dunn, J Han, N Sather - Environmental science & …, 2014 - ACS Publications
... et al.(5) assessed the life-cycle impacts of producing four compounds [N-methylpyrrolidone (NMP), N-vinylpyrrolidone (NVP), acrylonitrile (ACN), and succinonitrile (SCN)] from glutamic acid, which could be isolated from biorefinery byproducts including **vinasse** or distiller's **...**
Cited by 15

Energy use and greenhouse gas emissions in organic and conventional farming systems in the Netherlands

JFFP Bos, J de Haan, W Sukkel, RLM Schils - NJAS-Wageningen Journal …, 2014 - Elsevier
... Nutrient management on the organic farms was based on cattle slurry, solid cattle manure and **vinasse**, a by-product of the sugar beet industry containing readily available N. Spring applied fertilizer doses per ha on the organic arable farm are 16 Mg solid cattle manure, 4 Mg **...**
Cited by 8

15.4 Search terms - "methane emissions" "sugar cane"

Search returned 1,010 results.
Effect of calcium nitrate as NPN source on growth performance and methane emissions of goats fed sugar cane supplemented with cassava foliage
NN Anh, KT Hue, DN Khang, TR Preston - … change and resource depletion. http://www …, 2010
Cited by 12

… production from ruminants; effect of supplementary sulphate and nitrate on methane production in an in vitro incubation using sugar cane stalk and cassava …
PTR Le Thuy Binh Phuong, RA Leng - Livestock Research for …, 2011 - lrrd.cipav.org.co
... Added sulphur increased **methane emissions** in the presence of nitrate over the early incubation periods indicating a greater fermentation rate in that period, but sulphur was additive in decreasing methane in longer incubations, indicating nitrate had been fully reduced and **...**
Cited by 21

Emissions of methane and nitrous oxide from Australian sugarcane soils
OT Denmead, BCT Macdonald, G Bryant… - Agricultural and Forest …, 2010 - Elsevier
Climatic conditions and cultural practices in the sub-tropical and tropical high-rainfall regions in which sugarcane is grown in Australia are conducive to rapi.
Cited by 91

… of supplementation with urea or calcium nitrate and cassava leaf meal or fresh cassava leaf in an in vitro incubation using a basal substrate of sugar cane …
O Phommasack, TR Preston, A LENG - Livestock Research for Rural …, 2011 - lrrd.org
... A substrate of **sugar cane** stalk and either cassava leaf meal or fresh cassava leaves was incubated in an in vitro system in which the source of fermentable N was calcium **...** These factors have led to a global search for strategies to mitigate **methane emissions** from ruminants. **...**
Cited by 20

Greenhouse gas savings potential of sugar cane bio-energy systems
TLT Nguyen, SH Gheewala, M Sagisaka - Journal of Cleaner Production, 2010 - Elsevier
... Cover image Cover image. Greenhouse gas savings potential of **sugar cane** bio-energy systems. **...** Improving efficiency in electricity generation from **sugar cane** residues eg excess bagasse and cane trash is such a beneficial option. **...**
Cited by 52

Sustainability considerations for electricity generation from biomass
A Evans, V Strezov, TJ Evans - Renewable and Sustainable Energy …, 2010 - Elsevier
... In the case of bagasse, it is the **sugar cane** residue once sugar and molasses have been extracted. It can also be the tops and leaves of the **sugar cane**. **...** However, the seasonality of **sugar cane** harvesting may limit applicability of bagasse as a stand alone product. **...**
Cited by 168

Carbon footprint of sugar produced from sugarcane in eastern Thailand
M Yuttitham, SH Gheewala, A Chidthaisong - Journal of Cleaner Production, 2011 - Elsevier
... For **methane emissions** from wastewater, the estimate was based on the amount of total organically degradable material in wastewater (kg COD y −1), following the methodology of IPCC. 3. Results. 3.1. General characteristics of sugarcane farm in eastern Thailand. **...**
Cited by 44

Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use
JEA Seabra, IC Macedo, HL Chum… - Biofuels, Bioproducts …, 2011 - Wiley Online Library
... For residues returned to the soil, Table 3 presents the total above-ground nitrogen available, for which it is assumed that a fraction is emitted as N 2
O. **Methane emissions** from stillage and bagasse degradation were not considered, since current storage and application **...**
Cited by 109

Production systems–An example from Brazil
JBS Ferraz, PE de Felício - Meat Science, 2010 - Elsevier
... These feedlots use a low percentage grain ration, composed of maize, sorghum or grass silage, **sugar cane** and agriculture by-products. **...** A baseline projection of **methane emissions** by the Brazilian beef sector: Preliminary results. **...**
Cited by 127

LCA of the South African sugar industry
L Mashoko, C Mbohwa, VM Thomas - Journal of Environmental …, 2010 - Taylor & Francis
... contributes significantly to this impact category. **Sugar cane** burning is also a significant contributor to this impact category. This is a result of **methane emissions** during cane burning. Transportation is also a significant contributor **...**
Cited by 24

Dietary nitrate supplementation reduces methane emission in beef cattle fed sugarcane-based diets
RBA Hulshof, A Berndt, WJJ Gerrits… - Journal of Animal …, 2012 - dl.sciencesocieties.org
... Chopped **sugar cane**, 600, 600. **...** Experiments using Charolais heifers
showed **methane emissions** between 22 and 26 g methane/kg DMI [Boadi and Wittenberg, 2002 (90:10 roughage:concentrate); Foley et al., 2009 (40:60 roughage:concentrate); Hart et al., 2009 (100:0 **...**
Cited by 89

Net greenhouse gas fluxes in Brazilian ethanol production systems
MV Galdos, CC Cerri, R Lal, M Bernoux, B Feigl… - GCB …, 2010 - Wiley Online Library
... Methane emissions from organic residues of ethanol production such as vinasse need further research in order to be estimated and included in future assessments. **...** (2006) The impact of **sugar cane**-burning emissions on the respiratory system of children and the elderly. **...**
Cited by 41

Life cycle inventory of electricity cogeneration from bagasse in the South African sugar industry
L Mashoko, C Mbohwa, VM Thomas - Journal of Cleaner Production, 2013 - Elsevier
... Transportation has a contribution of 4.9% due to the high volumes of **sugar cane** moved by road and also the long distances travelled by the trucks. Use of fossil fuel to power farming machinery also results in significant carbon dioxide emissions.
4.2.3. **Methane emissions**. **...**
Cited by 15

Mitigating methane production from ruminants; effect of calcium nitrate as modifier of the fermentation in an in vitro incubation using cassava root as the …
S Inthapanya, TR Preston, RA Leng - in vitro, 2011 - lrrd.org
... http://www.lrrd.org/lrrd22/8/huye22146.htm. Nguyen Ngoc Anh, Khuc Thi Hue, Duong Nguyen Khang and Preston TR 2010 Effect of calcium nitrate as NPN source on growth performance and **methane emissions** of goats fed **sugar cane** supplemented with cassava foliage. **...**
Cited by 32

Maize silage for dairy cows: mitigation of methane emissions can be offset by land use change
TV Vellinga, IE Hoving - Nutrient Cycling in Agroecosystems, 2011 - Springer
... dairy farming have been mentioned focusing on reduction of nitrous oxide emissions by reducing fertilizer use and reduction of **methane emissions** by changing **...** what is found in the case of land use change for the production of biofuel crops as soy bean and **sugar cane** in Brazil **...**
Cited by 42

Pozzolanic activity of industrial sugar cane bagasse ash
S Janjaturaphan, S Wansom - Suranaree Journal of Science and …, 2010 - ird.sut.ac.th
... Pozzolanic Activity of Industrial **Sugar Cane** Bagasse ASH 350 **...** The use of SCBA as an SCM to partially replace ordinary Portland cement not only helps reduce **methane emissions** from disposal of the organic waste and reduce the production of cement, which is infamous for its **...**
Cited by 20

Sustainable sunlight to biogas is via marginal organics
A Shilton, B Guieysse - Current opinion in biotechnology, 2010 - Elsevier
... biomass yield of 0.253–0.342 and 0.251–0.292 m 3 /volatile solids added [27 •], for maize and **sugar cane**, respectively **...** shift would have substantial environmental benefits including, among others, offsetting fossil fuel use and reducing uncontrolled **methane emissions** from farm **...**
Cited by 22

Further considerations of the potential of nitrate as a high affinity electron acceptor to lower enteric methane production in ruminants
RA Leng, TR Preston - Livestock Research for Rural …, 2010 - lrrd.cipav.org.co
... Globally ruminants produce around 80 million tonnes of methane annually, which accounts for about 28% of anthropogenic **methane emissions**. **...** Hao et al 2009) clearly indicates little or no harmful effects in the rumen since nitrate supplementation of a **sugar cane**-based diet to **...**
Cited by 31

Biochar lowers net methane production from rumen fluid in vitro
RA Leng, S Inthapanya, TR Preston - Livestock Research for Rural …, 2012 - lrrd.org
... Introduction. **Methane emissions** from biological sources are a balance between production by methanogenic Archae and oxidation by methanotrophic micro-organisms. **...** Inclusion of biochar in the diet of ruminants would lead to a reduction in enteric **methane emissions**. **...**
Cited by 23

Conservation tillage systems: a review of its consequences for greenhouse gas emissions
M Abdalla, B Osborne, G Lanigan… - Soil Use and …, 2013 - Wiley Online Library

... 80 hr, Reicosky et al. (1999). 0.56 b, Loamy sand; corn–soybean–clover; NT, residue, Brazil, 13.62 a, Clayey soil; **sugar cane**; CONT, no fertilizer, 30 day, La Scala et al. (2006). 5.24 b, Clayey soil; **sugar cane**; NT, no fertilizer, 8.95 c, Clayey soil; **sugar cane**; RT, no fertilizer, **...**
Cited by 33

15.5 SEARCH TERMS - "SUGAR CANE" "MECHANICAL HARVESTING" "ENERGY USE"

Search returned 132 results.
Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use
JEA Seabra, IC Macedo, HL Chum… - Biofuels, Bioproducts …, 2011 - Wiley Online Library
... In this work, we assessed the life cycle **energy use** and greenhouse gases (GHG) emissions related to cane sugar and ethanol (the already large-scale, commercial products derived from sugarcane in Brazil), assuming bagasse and **... Mechanical harvesting**, 48%, CTC (167 mills). **...**
Cited by 109

Sugarcane straw availability, quality, recovery and energy use: a literature review
MRLV Leal, MV Galdos, FV Scarpare, JEA Seabra… - Biomass and …, 2013 - Elsevier
... Sugarcane straw availability, quality, recovery and **energy use**: A literature review. **...** In Brazil there is a federal law establishing a time schedule for phasing out cane burning, ie 2018 in the areas where **mechanical harvesting** is possible with the current technology (slopes less **...**
Cited by 62

Biofuels and sustainable energy development in Brazil
EL La Rovere, AS Pereira, AF Simões - World Development, 2011 - Elsevier
... The pre-harvesting burning of the plantation (source of air pollution in cities nearby) is being progressively banned by law in the state of São Paulo (where 60% of the **sugar cane** production is located), as it can be avoided thanks to the penetration of **mechanical harvesting** (**...**
Cited by 78

Techno-economic evaluation of 2nd generation bioethanol production from sugar cane bagasse and leaves integrated with the sugar-based ethanol process
S Macrelli, J Mogensen… - Biotechnology …, 2012 - biotechnologyforbiofuels. …
... Sugar cane leaves and tops, often called trash, constitute the residues of **mechanical harvesting**, and are suitable as raw material for 2G bioethanol production because of their lignocellulosic nature. The amount of trash that **...**
Cited by 135

A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering
JEA Seabra, L Tao, HL Chum, IC Macedo - Biomass and Bioenergy, 2010 - Elsevier
... Tops and leaves (cane trash) represent an additional 140 kg (dry) of residues per tonne of stalks [19] but are not used for production today – the material is either burnt on the field during the cane pre-harvesting or, increasingly, left in the field after the **mechanical harvesting**. **...**
Cited by 94

Comparative analysis for power generation and ethanol production from sugarcane residual biomass in Brazil
JEA Seabra, IC Macedo - Energy Policy, 2011 - Elsevier

... Cane productivity, t/ha, 95. Harvested area % total area, %, 90. Total diesel consumption b, L/ha, 350. Unburned cane harvesting, %, 100. **Mechanical harvesting**, %, 100. Total trash yield, kg dry /t cane, 140. Cane trash collection, %, 40. Above ground nitrogen c, g/t cane, 992. Agr **...**
Cited by 93

Trends in global warming and human health impacts related to Brazilian sugarcane ethanol production considering black carbon emissions
M Galdos, O Cavalett, JEA Seabra, LAH Nogueira… - Applied Energy, 2013 - Elsevier
... inventory (LCI) is the methodological step where an overview is given of the environmental interventions (**energy use**, resource extraction or **...** The sugarcane **mechanical harvesting** was effectively established in Brazil during the 1980s and has been progressively growing ever **...**
Cited by 49

Greenhouse gas footprints of different biofuel production systems
R Hoefnagels, E Smeets, A Faaij - Renewable and Sustainable Energy …, 2010 - Elsevier
... manufacture as animal feed may play a large role in offsetting (in)direct land-use change effects and related GHG emissions [5]. Overall, calculating the performance of biofuels on GHG emissions and fossil **energy use** is difficult **...** Ethanol, **Sugar cane**, Brazil, Fermentation, Gasoline **...**
Cited by 177

An assessment of mechanical vs manual harvesting of the sugarcane in Sudan–The case of Sennar Sugar Factory
AE Ahmed, AOM Alam-Eldin - Journal of the Saudi Society of Agricultural …, 2015 - Elsevier
... The tonnage harvested or cut per labor varies depending upon the tonnage of sugarcane in the field, as the tonnage of **sugar cane** in the field **...** This is mainly due to increasing area under **mechanical harvesting** and restricted area with lower yield or crop density for manual cuts. **...**
Cited by 8

Methodological complexities of product carbon footprinting: a sensitivity analysis of key variables in a developing country context
K Plassmann, A Norton, N Attarzadeh… - … Science & Policy, 2010 - Elsevier
... GHG emissions from **energy use**, combustion processes, chemical reactions, refrigerant losses and other fugitive **...** in detail here the study farms were typical of the **sugar cane** production systems in **...** to remove large rocks and level the land to allow **mechanical harvesting** was also **...**
Cited by 59

The production-ecological sustainability of cassava, sugarcane and sweet sorghum cultivation for bioethanol in Mozambique
SC de Vries, VEN VAN DE, WJ GERRIE… - GCB …, 2012 - Wiley Online Library
... Using methods of De Vries et al. (2010), we concentrated on sustainability indicators relating to **energy use** and the quality of soil and water resources **...** Mulching is normally combined with **mechanical harvesting** (Wood, 1991) and residue or trash burning with manual harvesting. **...**
Cited by 16

Bioethanol production from sugarcane and emissions of greenhouse gases–known and unknowns
CC Lisboa, K BUTTERBACH-BAHL, M Mauder… - GCB …, 2011 - Wiley Online Library

... of bioethanol from sugarcane GHGs can be produced at several stages and can be attributed to two different categories: (a) biogenic GHG emissions from the plant–soil system related to crop production and (b) anthropogenic GHG emissions due to **energy use** related to farm **...**
Cited by 58

Brazilian sugarcane ethanol: developments so far and challenges for the future
A Walter, MV Galdos, FV Scarpare… - Wiley …, 2014 - Wiley Online Library
... southeastern Brazil. Therefore, the large areas currently being converted to **mechanical harvesting** in Brazil will demand significant adjustments in agronomic management, ranging from fertilizer application to cultivar selection. With **...**
Cited by 30

Biorefineries for the production of first and second generation ethanol and electricity from sugarcane
MOS Dias, TL Junqueira, O Cavalett, LG Pavanello… - Applied energy, 2013 - Elsevier
... Sugarcane trash (comprised by sugarcane leaves and tops) was usually burnt in the field to allow manual harvesting, but since **mechanical harvesting** is being employed more frequently and sugarcane burning is being prohibited due to environmental reasons, large amounts **...**
Cited by 42

Economic and GHG emissions analyses for sugarcane ethanol in Brazil: Looking forward
L Wang, R Quiceno, C Price, R Malpas… - … and Sustainable Energy …, 2014 - Elsevier
... fuel vehicle; FPU, filter paper unit; GHG, greenhouse gas; GREET, The Greenhouse Gases, Regulated Emissions, and **Energy Use** in Transportation **...** 10 years is cane planting and harvesting (Table A.2 in Appendix A), which will involve more **mechanical harvesting** of unburned **...**
Cited by 21

Energy recovery from sugarcane-trash in the light of 2nd generation biofuel. Part 2: socio-economic aspects and techno-economic analysis
WA Pippo, CA Luengo, LAM Alberteris… - Waste and Biomass …, 2011 - Springer
... 10.1007/s12649-011-9069-3. Copyright information. Abstract. Since last decade of twentieth century, the change in cane harvesting method from manual harvesting of burned cane to **mechanical harvesting** of green cane brought the real possibility of sugarcane-trash **energy use ...**
Cited by 4

Sugarcane ethanol production in Malawi: Measures to optimize the carbon footprint and to avoid indirect emissions
E Dunkelberg, M Finkbeiner, B Hirschl - Biomass and Bioenergy, 2014 - Elsevier
... However, switching from manual to **mechanical harvesting** would cause employment losses to a large extent. In developing countries we therefore recommend switching from pre-harvest burning to green harvesting while maintaining manual harvesting in a transitional phase. **...**
Cited by 8

Straw availability, quality, recovery, and energy use of sugarcane
MAK Azad, MS Islam, L Amin - Biomass and Bioenergy, 2014 - Springer
... Sugarcane straw can be recovered from 24 to 95 %
through **mechanical harvesting** (Paes and Hassuani **...** JCAR, Pahl R, PessoaJr A, Costa SA (2013) Use of **sugar cane** straw as a **...** A, Oliveira COF (2013) Sugarcane straw availability, quality, recovery and **energy use**: a literature **...**

Cited by 2

2G ethanol from the whole sugarcane lignocellulosic biomass
SC Pereira, L Maehara… - Biotechnology …, 2015 - biotechnologyforbiofuels. …
... There is currently an ongoing progressive shift in the sugarcane harvesting method, from manual harvesting of burned sugarcane to **mechanical harvesting** of unburned sugarcane, with the trash remaining on the ground [14-16]. **...**
Cited by 23

Decentralized energy from waste systems
B Antizar-Ladislao, JL Turrion-Gomez - Energies, 2010 - mdpi.com
... been allocated a target to increase the proportion of its **energy use** provided from **...** increase the harvest index (seed yield divided by biomass), facilitate **mechanical harvesting**, and suppress **...** LA; Arbex, MA; Zanobetti, A.; Braga, ALF The impact of **sugar cane** - burning emissions **...**
Cited by 10

15.6 Search terms - "sugarcane ethanol" "power production"

Search returned 234 results.
Life-cycle greenhouse gas emissions and energy balances of sugarcane ethanol production in Mexico
CA García, A Fuentes, A Hennecke, E Riegelhaupt… - Applied Energy, 2011 - Elsevier
... Thus, these variables determine **sugarcane ethanol** effective GHG emissions mitigation potential and fossil fuel substitution level. **...** Boilers use only bagasse for steam and **power production**, which is consistent with practices in about 17 mills in Mexico. **...**
Cited by 76

A comparison of commercial ethanol production systems from Brazilian sugarcane and US corn
HL Chum, E Warner, JEA Seabra… - Biofuels, bioproducts …, 2014 - Wiley Online Library
... the two US regulatory systems with RED and the UK Renewable Fuel Obligation on GHG emissions reductions for Brazilian **sugarcane ethanol**. **...** accept that electricity generation sold by the system as equivalent to marginal electricity in Brazil [natural gas (NG) **power production**]. **...**
Cited by 27

Will second-generation ethanol be able to compete with first-generation ethanol? Opportunities for cost reduction
JD Stephen, WE Mabee… - Biofuels, Bioproducts and …, 2012 - Wiley Online Library
... rate with shorter residence times rather than maximizing ethanol yield and using the unhydrolyzed residue for heat and **power production**, showed some **...** Both US corn and Brazilian **sugarcane ethanol** production costs are in the range of $0.30 –$0.40 L -1 , while lignocellulosic **...**
Cited by 89

Global land-use implications of first and second generation biofuel targets
P Havlík, UA Schneider, E Schmid, H Böttcher, S Fritz… - Energy Policy, 2011 - Elsevier
... estimates are large, they tend to be positive for all the principal first generation biofuels, like
sugarcane ethanol, rapeseed biodiesel **...** Biomass for energy can be converted in several processes: combined heat and **power production**, fermentation for ethanol, heat, power and gas **...**
Cited by 412

[Evaluation of a regional bioenergy system with local production of biofuel for transportation, integrated with a CHP plant]
L Daianova, E Dotzauer, E Thorin, J Yan - Applied energy, 2012 - Elsevier
... hurdles to overcome for local lignocellulose-based bioethanol production, for example, its higher market price compared with imported **sugarcane ethanol**. **...** Case 1 system includes heat and **power production** at the CHP plant and ethanol production from straw at the standalone **...**
Cited by 36

[Integration of solid oxide fuel cell in a sugar–ethanol factory: analysis of the efficiency and the environmental profile of the products]
Y Casas, J Dewulf, LE Arteaga-Pérez… - Journal of Cleaner …, 2011 - Elsevier
... The LCA and LCC included gasoline production, agricultural production of **sugarcane**, **ethanol**, bagasse, sugar and electricity co-production, and **...** by-product of this sugar industry, typically used as fuel for steam and electricity (heat and **power**) **production** through cogeneration **...**
Cited by 17

[Gasoline, diesel, and ethanol biofuels from grasses and plants]
RB Gupta, A Demirbas - 2010 - books.google.com
... Page 12. Contents xi 13. Economic Impact of Biofuels . . . . . 191 13.1 Biofuel Economy 191 13.2 Economic Impact of Corn Ethanol 192 13.3 Economic Impact of **Sugarcane Ethanol** 193 13.4 Economic Impact of Biodiesel 194 13.5 Future Economic **...**
Cited by 104

[Least-cost adaptation options for global climate change impacts on the Brazilian electric power system]
AFP de Lucena, R Schaeffer, AS Szklo - Global Environmental Change, 2010 - Elsevier
... important in the Brazilian energy sector, both for electricity generation (eg sugarcane bagasse) and liquid biofuels production (eg **sugarcane ethanol**). **...** the loss in reliability was measured as a decrease in the system's capacity factor (ie the ratio of actual **power production** of the **...**
Cited by 52

[Opportunities and barriers for international bioenergy trade]
M Junginger, J Van Dam, S Zarrilli, FA Mohamed… - Energy Policy, 2011 - Elsevier
... trade barrier. Regarding the bioethanol trade, a Swedish respondent remarked “Especially the development of the Flexifuel car market (in Europe) is strongly inhibited by the customs on **sugarcane ethanol** in the EU. A lower **...**
Cited by 104

[The Indian sugar industry: an overview]
S Solomon - Sugar Tech, 2011 - Springer
... ways. Fuel Ethanol. Fuel ethanol and surplus **power production** through co-generation provide the two key by-products' related opportunities. **...** dynamics. Bio-Butanol. **Sugarcane ethanol** today is made predominantly from the cane molasses. **...**
Cited by 19

[The vulnerability of wind power to climate change in Brazil]
AFP de Lucena, AS Szklo, R Schaeffer, RM Dutra - Renewable Energy, 2010 - Elsevier
... 1]. Bioenergy has also become increasingly important in the Brazilian energy sector, both for electricity generation (eg sugarcane bagasse) and liquid biofuels production (eg **sugarcane ethanol**). **...** Other studies on impacts of GCC on wind **power production** include [14] and [15]. **...**

Cited by 52

Life cycle water use of low-carbon transport fuels
C Harto, R Meyers, E Williams - Energy Policy, 2010 - Elsevier
In society's quest to mitigate climate change it is important to consider potential trade-offs in climate solutions impacting other environmental issues. This.
Cited by 95

Competing uses of biomass: Assessment and comparison of the performance of bio-based heat, power, fuels and materials
SJ Gerssen-Gondelach, D Saygin, B Wicke… - … and Sustainable Energy …, 2014 - Elsevier
... The explicit inclusion of co- and/or by-products is an important methodological aspect in calculating levelized costs and GHG emissions of eg combined heat and **power production** (CHP) or biodiesel production with glycerin as a by-product. **...**
Cited by 36

Influence of different pretreatment methods on bioethanol production from wheat straw
M Tutt, T Kikas, J Olt - Agronomy Research, 2012 - agronomy.emu.ee
... These are used by direct combustion for heating, cooking or **power production**. **...** Wheat straw 3.57 31.01 46.47 7.94 Pretreatment of a biomass Cellulosic ethanol production is a complex process compared to first generation grain or **sugarcane ethanol** production. **...**
Cited by 27

Energy security, agroindustrial development, and international trade: The case of sugarcane in Southern Africa
B BATIDZIRAI, FX Johnson - Socioeconomic and Environmental …, 2012 - books.google.com
... Keywords: energy security, regional trade, southern Africa, **sugarcane ethanol** 1. Introduction Energy security has become a significant concern in **...** 3.4. Reliability of supply and avoided costs Independent **power production** from facilities such as bagasse cogeneration plants can **...**
Cited by 9

Spatiotemporal cost-supply curves for bioenergy production in Mozambique
F Van Der Hilst, APC Faaij - Biofuels, Bioproducts and …, 2012 - Wiley Online Library
... The supply chains of eucalyptus (torrefied) pellets and **sugarcane ethanol** are used as a case study. **...** Two divergent bioenergy supply chains are assessed in this study: (torrefied) pellets from eucalyptus and **sugarcane ethanol**. **...**
Cited by 17

The water consumption of energy production: an international comparison
ES Spang, WR Moomaw, KS Gallagher… - Environmental …, 2014 - iopscience.iop.org
... Biofuel processing, Ethanol, [1], 0.145, 0.092, 0.290, [9]. Biodiesel, [1], 0.031, 0.031, 0.031, [9]. Biofuel cultivation, **Sugarcane** (**ethanol**), [3], [6], 24.550, 0.000, 156.000, [10]. Maize (ethanol), [3], [6], 8.090, 0.000, 554.000, [10]. Sugarbeet (ethanol), [3], [6], 9.790, 0.000, 157.000, [10 **...**
Cited by 18

Sustainability certification of bioethanol: how is it perceived by Brazilian stakeholders?
DA Huertas, G Berndes, M Holmén… - Biofuels, Bioproducts …, 2010 - Wiley Online Library
... stakeholders involved in the process and different approaches for implementing such certification.1–6 The sustainability of **sugarcane ethanol** production in **...** of the dynamics of TIS comes from the energy sector in Sweden which is expanding its **power production** from biomass **...**

Cited by 17

Sustainable potential of bioenergy resources for distributed power generation development in Nigeria
YS Mohammed, MW Mustafa, N Bashir… - … and Sustainable Energy …, 2014 - Elsevier
Rising concerns about global energy security and climate change due to emissions of noxious gases resulting from the combustion of fossil fuels have strongly re.
Cited by 13

Design optimization of a polygeneration plant producing power, heat, and lignocellulosic ethanol
C Lythcke-Jørgensen, F Haglind - Energy Conversion and Management, 2015 - Elsevier
... economy of a system producing lignocellulosic ethanol, biogas and district heating (DH) might be increased by integrating **power production**. **...** [14] studied the integration of lignocellulosic ethanol production in the conventional first generation **sugarcane ethanol** process and **...**
Cited by 9

16. APPENDIX 6 – CELLULOSIC ETHANOL LITERATURE

The results from three specific searches related to cellulosic ethanol production are summarized below.

16.1 SEARCH TERMS - "CELLULOSIC ETHANOL" "ENZYME CONSUMPTION"

Search returned 68 results.
β-glucosidase coating on polymer nanofibers for improved cellulosic ethanol production
SM Lee, LH Jin, JH Kim, SO Han, HB Na… - Bioprocess and …, 2010 - Springer
... a mechanism of product inhibition [3–5]. Glucose and cellobiose inhibitory effects are one of major reasons for the high **enzyme consumption**, which is a critical issue because the commercial application of **cellulosic ethanol** production is hampered by the high cost of enzymes. **...**
Cited by 39

Energetic-environmental assessment of a scenario for Brazilian cellulosic ethanol
F Agostinho, E Ortega - Journal of Cleaner Production, 2013 - Elsevier
... Cover image Cover image. Energetic-environmental assessment of a scenario for Brazilian **cellulosic ethanol**. **...** Highlights. ► A Brazilian Biorefinery scenario producing **cellulosic ethanol** is assessed through an energetic-environmental approach. **...**
Cited by 28

Possibilities for sustainable biorefineries based on agricultural residues–a case study of potential straw-based ethanol production in Sweden
A Ekman, O Wallberg, E Joelsson, P Börjesson - Applied Energy, 2013 - Elsevier
... In the Energy Independence and Security Act (EISA) absolute targets for the supply of biofuels have been set in which also 2nd generation biofuels are included. For 2010 the target was a production of 6.5 million gallons of **cellulosic ethanol**. **...**
Cited by 65

Will second-generation ethanol be able to compete with first-generation ethanol? Opportunities for cost reduction
JD Stephen, WE Mabee… - Biofuels, Bioproducts and …, 2012 - Wiley Online Library
... feedstocks. Progress ratio. According to the 2007 Energy Independence and Security Act (EISA), **cellulosic ethanol** production schedule/blend mandate (Fig. **...** EISA **cellulosic ethanol** production mandate from 2010 to 2020.5. Based **...**
Cited by 89

Technology prospecting on enzymes: application, marketing and engineering
S Li, X Yang, S Yang, M Zhu, X Wang - Computational and structural …, 2012 - Elsevier
... Nevertheless, North America and Western Europe will see the slower gains in **enzyme consumption**, restrained by the relatively mature markets. In particular, the American subprime lending crisis and the European debt crisis will have a negative effect on **enzyme consumption**. **...**
Cited by 75

Advancements and future directions in enzyme technology for biomass conversion
Z Zhang, AA Donaldson, X Ma - Biotechnology advances, 2012 - Elsevier
Enzymatic hydrolysis of pre-treated lignocellulosic biomass is an ideal alternative to acid hydrolysis for bio-ethanol production, limited primarily by pre-trea.
Cited by 41

Economic evaluation of the conversion of industrial paper sludge to ethanol

H Chen, R Venditti, R Gonzalez, R Phillips, H Jameel… - Energy Economics, 2014 - Elsevier
... Also, delivered biomass cost and availability, high pretreatment and chemical cost, intensive CAPEX and overall production costs have been identified as the major obstacles for commercializing **cellulosic ethanol** with competitive financial returns (Gonzalez et al., 2011a and **...**
Cited by 14

Conversion of rye straw into fuel and xylitol: a technical and economical assessment based on experimental data
G Franceschin, M Sudiro, T Ingram, I Smirnova… - … Research and Design, 2011 - Elsevier
... Its maximum capacity is 30 tonnes per day of feedstock, to produce approximately 2 million litres of **cellulosic ethanol** per year. **...** The **enzyme consumption** is 12 FPU (filter paper unit) of cellulase per g of cellulose (Aden et al., 2002). **...**
Cited by 28

Bioethanol production from various waste papers: Economic feasibility and sensitivity analysis
L Wang, M Sharifzadeh, R Templer, RJ Murphy - Applied energy, 2013 - Elsevier
As a significant fraction of municipal solid waste, waste paper is a potential source for producing bioethanol. In the present paper, bioethanol production from.
Cited by 34

History and future of world's most advanced biorefinery in operation
G Rødsrud, M Lersch, A Sjöde - Biomass and bioenergy, 2012 - Elsevier
... This process, named the BALI™-process, is characterized by low **enzyme consumption**, high yields of sugars in solution, pure sugars treams, low concentration of both fermentation inhibitors and inhibitors for enzymes and valuable products from all main components of the **...**
Cited by 66

A framework for model-based optimization of bioprocesses under uncertainty: Lignocellulosic ethanol production case
R Morales-Rodriguez, AS Meyer, KV Gernaey… - Computers & Chemical …, 2012 - Elsevier
... The framework is evaluated on four different process configurations for **cellulosic ethanol** production including simultaneous saccharification and co-fermentation and separate hydrolysis and co-fermentation (SSCF and SHCF, respectively) technologies in different operation **...**
Cited by 29

Genetic improvement of plants for enhanced bio-ethanol production
S Saha, S Ramachandran - Recent patents on DNA & gene …, 2013 - ingentaconnect.com
... Cellulosic ethanol production is more expensive than sugar-derived ethanol as significant costs are involved in the pretreatment required to remove **...** 0291650A1 Methods for reducing **enzyme consumption** in second gen- eration bioethanol fermentation in the presence of lignin **...**
Cited by 11

Evaluation of simultaneous saccharification and ethanol fermentation of undetoxified steam-exploded corn stover by Saccharomyces cerevisiae Y5
S Tian, Y Li, Z Wang, X Yang - Bioenergy Research, 2013 - Springer
... The lack of high ethanol-producing strains that are highly toxin-tolerant is a bottleneck in reducing the cost of **cellulosic ethanol** production from steam **...** Mixed **enzyme consumption** was calculated as the ratio of the enzymes' activity to cellulose mass in the reaction system. **...**

Cited by 6

Assessment of combinations between pretreatment and conversion configurations for bioethanol production
C Conde-Mejía, A Jiménez-Gutiérrez… - ACS Sustainable …, 2013 - ACS Publications
Cited by 16

Optimization of ethanol production from NaOH-pretreated solid state fermented sweet sorghum bagasse
M Yu, J Li, S Chang, R Du, S Li, L Zhang, G Fan, Z Yan… - Energies, 2014 - mdpi.com
... into sugar-based ethanol by advanced solid state fermentation technology [5]. Major challenge for large scale application of ethanol production from sweet sorghum is the efficient conversion of the solid state fermented sweet sorghum (SS) bagasse into **cellulosic ethanol**. **...**
Cited by 6

Enzymatic hydrolysis of cellulose and the use of TiO_2 nanoparticles to open up the cellulose structure
H Abushammala, R Hashaikeh - Biomass and bioenergy, 2011 - Elsevier
... The proposed process promises to use low cost equipment, introduces efficient low cost acid recovery method, and promises to reduce **enzyme consumption** as well as increase cellulose hydrolysis rate. **...** Overview of biomass pretreatment for **cellulosic ethanol** production. **...**
Cited by 6

Influence of enzyme loading on enzymatic hydrolysis of cardboard waste and size distribution of the resulting fiber residue
T Kinnarinen, A Häkkinen - Bioresource technology, 2014 - Elsevier
... Another apparent conclusion from Fig. 2(a) is that the **enzyme consumption** increases relatively more sharply than the obtained glucose concentration: doubling the enzyme loading does not result in a doubling of the glucose concentration of the hydrolysate. **...**
Cited by 8

Outlook for ethanol production costs in Brazil up to 2030, for different biomass crops and industrial technologies
JGG Jonker, F Van Der Hilst, HM Junginger, O Cavalett… - Applied Energy, 2015 - Elsevier
This paper presents an economic outlook of the ethanol industry in Brazil considering different biomass feedstocks and different industrial processing options.
Cited by 22

Combination of wet disk milling and hydrogen peroxide treatments for enhancing saccharification of sugarcane bagasse
MT Gao, S Yano, H Inoue, K Sakanishi - Biochemical engineering journal, 2012 - Elsevier
... bagasse, and there was no removal of lignin. The high lignin content in the WDM bagasse may lead to high **enzyme consumption** due to the adsorption of cellulase to lignin. To improve the delignification process, the WDM treatment **...**
Cited by 4

Waste textiles bioprocessing to ethanol and biogas
A Jeihanipour - 2011 - diva-portal.org
Page 1. CHALMERS Mixture of fibers Thermal treatment Synthetic fibers Othernatural fibers Residual fibers Reuse Recycling Physico-chemical processing Different products Different products Fuels, chemicals, energy Waste textiles Separation of fibers Cellulosic fibers **...**
Cited by 7

16.2 SEARCH TERMS - "CELLULOSIC ETHANOL" "CHEMICAL CONSUMPTION"

Search returned 86 results.

Assessing resource intensity and renewability of cellulosic ethanol technologies using Eco-LCA

A Baral, BR Bakshi, RL Smith - Environmental science & …, 2012 - ACS Publications

... saccharification and fermentation (SSF) process,(23) whereas the Gravity Pressure Vessel method(24) was assumed for **cellulosic ethanol** production from **...** yield of 405 L and assuming that an increase in yield results in a linear decrease in energy and **chemical consumption**. **...**

Cited by 38

Economics of cellulosic ethanol production in a thermochemical pathway for softwood, hardwood, corn stover and switchgrass

R Gonzalez, J Daystar, M Jett, T Treasure… - Fuel Processing …, 2012 - Elsevier

... Cover image Cover image. Economics of **cellulosic ethanol** production in a thermochemical pathway for softwood, hardwood, corn stover and switchgrass. **...** Current barriers to economically feasible **cellulosic ethanol** production have been widely researched and discussed. **...**

Cited by 38

Biomass pretreatment: fundamentals toward application

VB Agbor, N Cicek, R Sparling, A Berlin… - Biotechnology advances, 2011 - Elsevier

Development of sustainable energy systems based on renewable biomass feedstocks is now a global effort. Lignocellulosic biomass contains polymers of cellulose,.

Cited by 610

Simultaneous saccharification and cofermentation of lignocellulosic residues from commercial furfural production and corn kernels using different nutrient …

Y Tang, D Zhao, C Cristhian… - Biotechnology …, 2011 - biotechnologyforbiofuels. …

... The integration of **cellulosic ethanol** with starch ethanol can also decrease **chemical consumption**. SSCF with mineral-salt medium produced the same ethanol yield as that with organic medium. The number of live yeast cells **...**

Cited by 37

Pretreatment of corn stover using low-moisture anhydrous ammonia (LMAA) process

CG Yoo, NP Nghiem, KB Hicks, TH Kim - Bioresource technology, 2011 - Elsevier

... simple pretreatment method using anhydrous ammonia was developed to minimize water and ammonia inputs for **cellulosic ethanol** production, termed **...** in improving the applications of biomass, there are still some economical issues with high water and **chemical consumption**. **...**

Cited by 40

Efficient conversion of sugarcane stalks into ethanol employing low temperature alkali pretreatment method

L Wu, Y Li, M Arakane, M Ike, M Wada, Y Terajima… - Bioresource …, 2011 - Elsevier

... et al., 2005), it is still difficult to practically apply the techniques to commercial-scale **cellulosic ethanol** production due **...** results, taking various factors, such as delignification level, characteristics of feedstock, and energy and pretreatment **chemical consumption**, into consideration **...**

Cited by 28

Low-liquid pretreatment of corn stover with aqueous ammonia

X Li, TH Kim - Bioresource technology, 2011 - Elsevier
... liquid ammonia (LLA) process, was proposed as an effective pretreatment of lignocellulosic biomass with minimized water and **chemical consumption**. **...** yet this ammoniation has never been attempted for use as a biomass pretreatment method for **cellulosic ethanol** production. **...**
Cited by 37

Rheology modification and enzyme kinetics of high-solids cellulosic slurries: an economic analysis
JS Knutsen, MW Liberatore - Energy & Fuels, 2010 - ACS Publications
Page 1. 6506 r 2010 American Chemical Society pubs.acs.org/EF Energy Fuels 2010, 24, 6506–6512 . DOI:10.1021/ef100746q Published on Web 11/10/2010 Rheology Modification and Enzyme Kinetics of High-Solids Cellulosic Slurries: An Economic Analysis **...**
Cited by 10

Integrated process of starch ethanol and cellulosic lactic acid for ethanol and lactic acid production
Y Tang, L Zhu, W Zhang, X Shang, J Jiang - Applied microbiology and …, 2013 - Springer
... paper, we present results that demonstrate the feasibility of the integrated starch ethanol and cellulosic LA process, without additional **chemical consumption**. **...** materials (EFR-L) cannot be used as animal feed because of lignin accumulation that occurs in the **cellulosic ethanol**. **...**
Cited by 7

Critical analysis of techno-economic estimates for the production cost of lignocellulosic bio-ethanol
S Chovau, D Degrauwe, B Van der Bruggen - Renewable and Sustainable …, 2013 - Elsevier
Bio-ethanol has been claimed to be a green and sustainable alternative to gasoline. The use of food crops on a large scale is ethically unacceptable, but lignoc.
Cited by 37

Bioethanol and biodiesel: Alternative liquid fuels for future generations
G Sivakumar, DR Vail, J Xu, DM Burner… - Engineering in Life …, 2010 - Wiley Online Library
... has the advantages that: (i) it allows greater yeast cell biomass concentrations because no inert carrier or other chemical occupies the working volume of the fermentors; this provides higher ethanol productivity; (ii) it requires no inert carrier or **chemical consumption** because the **...**
Cited by 100

Combined sodium hydroxide and ammonium hydroxide pretreatment of post-biogas digestion dairy manure fiber for cost effective cellulosic bioethanol …
S Elumalai, A Roa-Espinosa… - Sustainable …, 2014 - sustainablechemicalprocesses. …
... Although pretreatment leads to acceptable saccharification for this low-cost feedstock, the high **chemical consumption** costs of the process likely will **...** of PBD manure fiber is 25–28% lower than those of other commonly used substrates for **cellulosic ethanol** production (corn stover **...**
Cited by 6

Reducing acid in dilute acid pretreatment and the impact on enzymatic saccharification
Y Chen, MA Stevens, Y Zhu, J Holmes… - Journal of industrial …, 2012 - Springer
... This condition was therefore used in this study as a baseline control to determine potential improvement of substrate digestibility as well as possible reduction

in **chemical consumption**. Table 2 Dilute acid pretreatment conditions for corn stover. Pretreatment run. Temp (°C). **...**
Cited by 19

Comparison of different alkali-based pretreatments of corn stover for improving enzymatic saccharification
Q Li, Y Gao, H Wang, B Li, C Liu, G Yu, X Mu - Bioresource technology, 2012 - Elsevier
Corn stover was treated with NaOH, NaOH + anthraquinone (AQ), NaOH + Na2SO3 (alkaline), NaOH + Na2SO3 (neutral), and NaOH +&#.
Cited by 48

Exploring impacts of process technology development and regional factors on life cycle greenhouse gas emissions of corn stover ethanol
J McKechnie, M Pourbafrani, BA Saville, HL MacLean - Renewable Energy, 2015 - Elsevier
... This biorefinery produces 230 million litres ethanol per year. Table 4 compares the ethanol yield, electricity production (surplus) and **chemical consumption** reported in Ref. **...** The whole cell broth, rich in cellulase, is then fed to the **cellulosic ethanol** process. **...**
Cited by 8

Economics, environmental impacts, and supply chain analysis of cellulosic biomass for biofuels in the southern US: Pine, eucalyptus, unmanaged hardwoods, forest …
J Daystar, R Gonzalez, C Reeb, RA Venditti… - …, 2013 - ojs.cnr.ncsu.edu
... of published plant characteristics data (productivity, carbohydrate content, bulk density, moisture content at harvest) and cost of establishment, maintenance, and harvest 4. Reasonable performance data for existing and proposed **cellulosic ethanol** conversion technologies A **...**
Cited by 23

The pretreatment of corn stover with Gloeophyllum trabeum KU-41 for enzymatic hydrolysis
Z Gao, T Mori, R Kondo - Biotechnology …, 2012 - biotechnologyforbiofuels. …
... followed by thermochemical pretreatment could potentially lower the severity requirements of acid, temperature and pressure in thermochemical pretreatment[5]. Lower pretreatment severity is expected to translate directly into lower **chemical consumption**, and because of lower **...**
Cited by 27

Advances in the valorization of lignocellulosic materials by biotechnology: an overview
HMN Iqbal, G Kyazze, T Keshavarz - BioResources, 2013 - ojs.cnr.ncsu.edu
... Page 10. PEER-REVIEWED REVIEW ARTICLE bioresources.com Iqbal et al. (2013). "Biotech applications of biomass," BioResources 8(2), 3157-3176. 3166 the high **chemical consumption**, chemical pulping also poses some serious effects to the environmental ecosystem. **...**
Cited by 43

Autohydrolysis: A promising pretreatment for the improvement of acetone, butanol, and ethanol production from woody materials
H Amiri, K Karimi - Chemical Engineering Science, 2015 - Elsevier
... a detoxification process (Sun and Liu, 2012). Some sugar loss, production of environmental pollutants, and extra **chemical consumption** accompanied the detoxification. An alternative approach to obtain proper hydrolysates **...**
Cited by 3

Improvement of methane production from waste paper by pretreatment with rumen fluid
Y Baba, C Tada, Y Fukuda, Y Nakai - Bioresource technology, 2013 - Elsevier

... hemicellulose. In general, while thermal pretreatment results in a significant increase in cellulose degradability in a short time, the thermal process consumes a substantial amount of energy in comparison to **chemical consumption**. **...**
Cited by 14

16.3 Search terms - "cellulosic ethanol" "electricity production"

Search returned 1,440 results.

Second generation ethanol in Brazil: can it compete with electricity production?
MOS Dias, MP Cunha, CDF Jesus, GJM Rocha… - Bioresource …, 2011 - Elsevier
... Ethanol and **electricity production** costs – excluding return on capital – were calculated as follows: their prices were reduced simultaneously at the same rate until the IRR per year reached zero. Table 5. **...** Enzyme average price (US$/L **cellulosic ethanol**) e, 0.05, 0.15, 0.25. **...**
Cited by 127

Impact of pretreatment and downstream processing technologies on economics and energy in cellulosic ethanol production
D Kumar, GS Murthy - Biotechnology for biofuels, 2011 - biotechnologyforbiofuels. …
... Impact of pretreatment and downstream processing technologies on economics and energy in **cellulosic ethanol** production. **...** Cost of ethanol and process energy use in **cellulosic ethanol** plants are dependent on technologies used for conversion of feedstock. **...**
Cited by 121

A techno-economic evaluation of the effects of centralized cellulosic ethanol and co-products refinery options with sugarcane mill clustering
JEA Seabra, L Tao, HL Chum, IC Macedo - Biomass and Bioenergy, 2010 - Elsevier
... A techno-economic evaluation of the effects of centralized **cellulosic ethanol** and co-products refinery options with sugarcane mill clustering. **...** anaerobic digestion are combusted in a fluidized bed combustor to produce high-pressure steam for **electricity production** and process **...**
Cited by 94

Integrated versus stand-alone second generation ethanol production from sugarcane bagasse and trash
MOS Dias, TL Junqueira, O Cavalett, MP Cunha… - Bioresource …, 2012 - Elsevier
... Scenario 1 represents the optimized autonomous distillery with maximization of surplus electricity (all the bagasse and trash are used as fuels for **electricity production**). **...** Anhydrous ethanol price (US$/L) d, 0.60. Enzyme price – current technology (US$/L **cellulosic ethanol**) e, 0.11. **...**
Cited by 143

Techno-economic analysis of lignocellulosic ethanol: a review
E Gnansounou, A Dauriat - Bioresource technology, 2010 - Elsevier
... Ethanol production costs as calculated by the spreadsheet model are given in Table 4. The main technical parameters including details of feedstock costs, ethanol yield, **electricity production** and consumption, project investment are also provided. Table 4. **...**
Cited by 258

Techno-economic evaluation of 2nd generation bioethanol production from sugar cane bagasse and leaves integrated with the sugar-based ethanol process
S Macrelli, J Mogensen… - Biotechnology …, 2012 - biotechnologyforbiofuels. …
... Nowadays, bagasse is also generally recognized as a very promising feedstock for **cellulosic ethanol** production, ie second-generation (2G **...** disadvantages regarding their effects on

downstream processing [29]; boiler pressure, which affects the **electricity production** efficiency [30 **...**

Biorefineries for the production of first and second generation ethanol and electricity from sugarcane
MOS Dias, TL Junqueira, O Cavalett, LG Pavanello… - Applied energy, 2013 - Elsevier
... The use of sugarcane lignocellulosic fractions as fuels in **electricity production** for sale to the grid is commercially and technically feasible in **... Cellulosic ethanol** production can have its production cost decreased and benefit from the sale of process by-products, such as electricity **...**

Process and technoeconomic analysis of leading pretreatment technologies for lignocellulosic ethanol production using switchgrass
L Tao, A Aden, RT Elander, VR Pallapolu, YY Lee… - Bioresource …, 2011 - Elsevier
... Six biomass pretreatment processes to convert switchgrass to fermentable sugars and ultimately to **cellulosic ethanol** are compared on a **...** from anaerobic digestion are burned in a fluidized bed combustor to produce high-pressure steam for **electricity production** and process heat **...**

Assessing resource intensity and renewability of cellulosic ethanol technologies using Eco-LCA
A Baral, BR Bakshi, RL Smith - Environmental science & …, 2012 - ACS Publications
... Assessing Resource Intensity and Renewability of **Cellulosic Ethanol** Technologies Using Eco-LCA. **...** The relative use intensity of natural resources encompassing land and ecosystem goods and services by **cellulosic ethanol** was estimated using the Eco-LCA framework. **...**

Optimal plant size and feedstock supply radius: a modeling approach to minimize bioenergy production costs
J Gan, CT Smith - Biomass and Bioenergy, 2011 - Elsevier
... Under the same conditions, the optimal feedstock supply radius for ethanol production (Fig. 4) tends to be longer than that for **electricity production** (Fig. 3). This is partially because **cellulosic ethanol** production is more energy efficient than electricity generation. **...**

Converting Eucalyptus biomass into ethanol: Financial and sensitivity analysis in a co-current dilute acid process. Part II
R Gonzalez, T Treasure, R Phillips, H Jameel… - Biomass and …, 2011 - Elsevier
... These elements are necessary to make the **cellulosic ethanol** production business more profitable and competitive so that more investors will invest in this emerging **...** The relationship between carbohydrate content, lignin content and **electricity production** can be observed in Fig. **...**

Combined production of sugar, ethanol and electricity: thermoeconomic and environmental analysis and optimization
LF Pellegrini, S de Oliveira Junior - Energy, 2011 - Elsevier
... agroindustry has evolved from a typical single product industry (sugar) to a polygeneration plant (sugar, ethanol and electricity) nowadays [1]. In the future, other products might be obtained considering different energy conversion routes (**cellulosic ethanol**, chemicals) and/or **...**

Techno-economic analysis and life-cycle assessment of cellulosic isobutanol and comparison with cellulosic ethanol and n-butanol

L Tao, ECD Tan, R McCormick, M Zhang… - Biofuels, Bioproducts …, 2014 - Wiley Online Library
... Seed strain production is assumed to be the same as that used for Zymomonas mobilis production in the **cellulosic ethanol** design, although **...** from anaerobic digestion are burned in a fluidized bed combustor to produce high-pressure steam for **electricity production** and process **...**
Cited by 41

Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the US context
M Wang, H Huo, S Arora - Energy Policy, 2011 - Elsevier
... chemical. Cellulosic biomass, Ethanol, Lignin, Steam and **electricity production** in **cellulosic ethanol** plants. Soybeans, Renewable diesel, Fuel gas and heavy oils, Energy sources for plant internal use; or energy products for sale. **...**
Cited by 150

Possibilities for sustainable biorefineries based on agricultural residues–a case study of potential straw-based ethanol production in Sweden
A Ekman, O Wallberg, E Joelsson, P Börjesson - Applied Energy, 2013 - Elsevier
... For 2010 the target was a production of 6.5 million gallons of **cellulosic ethanol**. **...** On the other hand, this will reduce the potential of co-generated electricity, and, depending on the reference **electricity production** system replaced, will have different greenhouse gas (GHG **...**
Cited by 65

Next-generation cellulosic ethanol technologies and their contribution to a sustainable Africa
WH Van Zyl, AFA Chimphango… - Interface …, 2011 - rsfs.royalsocietypublishing.org
Skip to main content. Other Publications: Philosophical Transactions B; Proceedings B; Biology Letters; Open Biology; Philosophical Transactions A; Proceedings A; Royal Society Open Science; Interface; Interface Focus; Notes and Records; Biographical Memoirs. **...**
Cited by 26

Environmental profile of ethanol from poplar biomass as transport fuel in Southern Europe
S González-García, CM Gasol, X Gabarrell… - Renewable Energy, 2010 - Elsevier
... Poplar is an ideal candidate for **cellulosic ethanol** production [23], [24] and [25] and an alternative to other energy crops since its biomass **...** forest waste with this aim because of forest wastes are commonly used as raw materials in power plants (heat and **electricity production**) [27 **...**
Cited by 78

Improving second generation ethanol production through optimization of first generation production process from sugarcane
MOS Dias, TL Junqueira, CDF Jesus, CEV Rossell… - Energy, 2012 - Elsevier
... conversion. Several authors have evaluated the optimization of different technologies for second generation biofuels production [6], [21], [22] and [23] and sugar, ethanol and **electricity production** from sugarcane [13], [24], [25] and [26]. **...**
Cited by 41

Challenges in scaling up biofuels infrastructure
TL Richard - Science, 2010 - science.sciencemag.org
... decentralized CHP units previously described. Integrating these preprocessing operations with heat and **electricity production** could provide important synergies for both capital cost and operations. Economic analysis of both **...**
Cited by 202

Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar)

S González-García, MT Moreira, G Feijoo… - Biomass and …, 2012 - Elsevier
A life cycle assessment (LCA) study was carried out to evaluate the environmental implications of the production and use of ethanol from three fast-growing wood.