UBC Social Ecological Economic Development Studies (SEEDS) Student Report

Life Cycle Assessment of Bioethanol Derived from Corn and Corn Stover

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Abstract

This paper follows the growing research of bioethanol fuels produced from farmed corn as well as corn stover in comparision to petroleum fuels. A Life Cycle Analysis (LCA) using the GaBi database was done to effectively compare results in terms of their respective emissions to the air, water, and industrial soil. Various basis' that were also involved in the comparison include 1) Mass [kg], 2) TRACI – Global Warming Air [kg CO2-Equiv.], 3) TRACI, Acidification Rain [kg mol H + Equiv.], and 4) TRACI, Smog Air [kg NOx-Equiv.]. Production and processes of corn and petroleum from crude oils are also observed and are replicated in the GaBi simulation. To normalize the three fuels, a functional unit of distance (km), and a conventional car (2001 Ford Taurus) was selected to describe the combustion of each fuel source based on a travel distance of 100km on average road conditions.

The first section will illustrate the LCA conducted on gasoline and the results of the analysis. Following will show the LCA conducted for E85 produced from corn and corn stover, with overall results comparing each fuel source in the end.

Based on LCA results, E85 was shown to have a 39% reduction in GHG emissions when compared to gasoline. The type of feedstock for ethanol production (corn versus corn stover) had little effect on the life cycle emissions of E85, however, the resource inputs varied dramatically. To travel 100km, 12.9kg of corn (food) and 190.4kg of water. In comparison, no food is required when corn stover is used as the feedstock, however, 274.5kg of water is consumed.

Table of Contents

1.0 Introduction

With the growing acceptance that Green House Gas (GHG) emissions are responsible for negatively impacting the world through climate change, greater importance has been placed on lowering these emissions worldwide. Environment Canada reported that twenty-seven percent (201.7 Megatonnes) of Canada's 2007 GHG emissions was attributed to transportation alone. This represents the single largest contribution of GHG emissions of all sectors, as seen below.

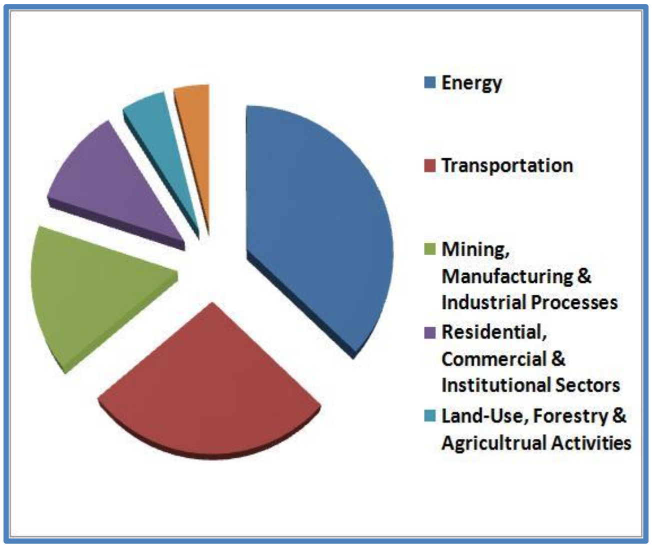


Figure 1.1: Pie chart outlining GHG origins and their proportions

One potential alternative fuel source is ethanol, which is derived from plant material and is also known as bioethanol. While ethanol derived from corn is the current practice for biofuel production, ethanol from corn stover is also being looked at as a potential future feedstock. Critics of these biofuels, however, suggest the inputs required to grow the biomass and produced the ethanol eliminate any environmental savings over gasoline ((Gomez et al., 2008), (Pimentel, D., 2003)). To determine whether bioethanol offers any significant environmental benefits over conventional fuel, a life cycle assessment (LCA) approach was adopted.

An LCA was conducted on 1) conventional gasoline, 2) ethanol derived from corn, as well as 3) ethanol derived from corn stover. In addition, E85, an eighty five percent blend of ethanol in gasoline as well as a *2001 Ford Taurus* as the conventional vehicle were included for the requirements of this study. With ethanol consisting of a lower energy value than gasoline, thus resulting in a lower fuel efficiency, the differences in fuel efficiencies will be measured under the basic unit of distance travelled in kilometres (km). Results will be based on emissions produced per 100km travelled using average fuel efficiency as shown below in Table 1.1.

	Gasoline	**E85**
City fuel efficiency (km/L)	8.0	6.0
Highway fuel efficiency (km/L)	12.0	9.0
Average fuel efficiency (km/L)	10	7.3

Table 1.1: Fuel efficiency of gasoline versus E85 in a 2001 For Taurus (Sheehan, Aden, Paustian, & al, 2004)

In order to determine if bioethanol has any significant advantages over gasoline, various environmental indicators have been selected for comparison. These include:

- Total emissions
- Global warming potential (kg CO_2 equivalents)
- Acid rain potential (mol H^+ equivalents)
- Smog formation potential (kg NOx equivalents)
- Water consumption
- Food consumption

2.0 Gasoline Fuelled Vehicles

Typical family households in Canada own two or fewer vehicles. According to *Statistics Canada 2009*, of the 96,684 vehicles registered by jurisdiction and vehicle model year in the third quarter, “Canadian vehicles were driven 96.7 billion kilometres” on the road. This amounts to approximately 4,647 kilometres driven on average by each Canadian vehicle owner. The highlights of Canadian vehicle usage are mentioned further below from Statistics Canada.

Highlights:

• Canadians drove more during the third quarter of 2009 compared to the same quarter last year. For the third quarter, Canadian vehicles were driven 96.7 billion kilometres, up 9.4% from the same time last year.

• The number of vehicles on the road increased by 2.3% in the third quarter of 2009.

• Canadians drove their vehicles, on average, 4,647 kilometers during the quarter. This was 7.0% more than in the same quarter in the previous year.

Table 2.1: Statistic highlights – *Canadian Vehicle Survey: Quarterly. "July to September 2009". Catalogue no. 53F0004X*

With approximately 32012.2 million litres of fuel consumed in total for all vehicles in Canada in 2009 alone, the need for gasoline today's society is evident.

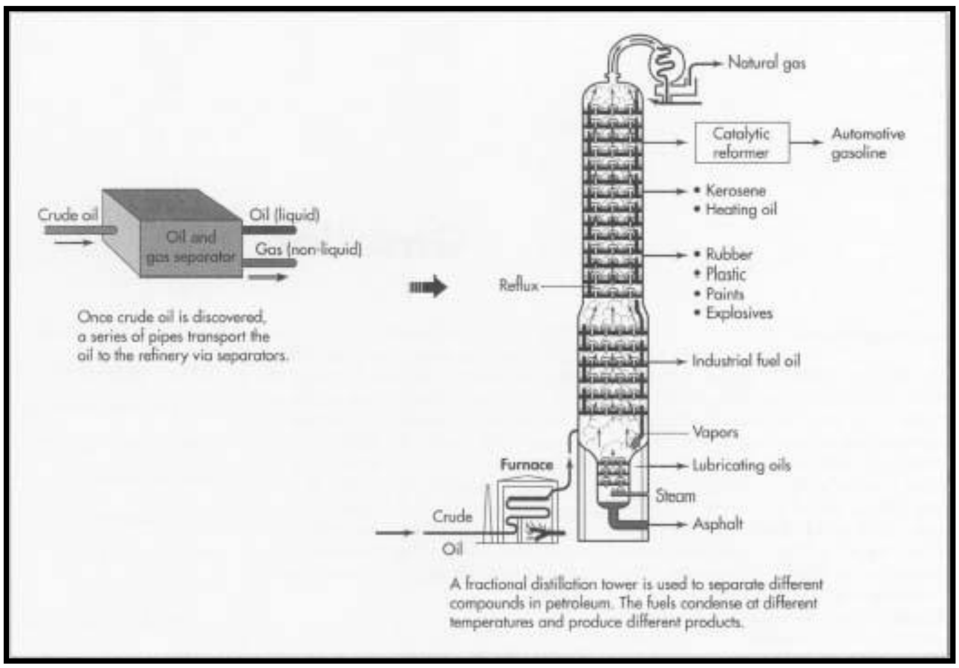
2.1.1 Introduction to Production Process

Gasoline is a volatile liquid manufactured from the refinement of crude oil, also known as petroleum or a fossil fuel. With its significant ability to vaporize at lower temperatures, gasoline is known to be a useful fuel for many types of machines, vehicles, and other equipment. Petroleum is derived from degrading plants and animals that have been under heavy pressure over millions of years. After extraction of this fossil fuel, it is taken to a refinery where it is distilled and refined to produce gasoline. Various chemicals are then introduced to the treated liquid to stabilize and improve colour and odour – this procedure is called "sweetening".

2.1.2 Process of Production

Extraction

In order to manufacture gasoline, petroleum is first required. Exploration of crude oil locations is necessary and requires examination of rocky land surfaces to locate concentrated oil areas. Once a site has been found, core samples are taken to verify crude oil are indeed within the porous rocks before drilling is initiated. Rotary drillers are used to recover crude oil from wells that can go down to and over 300 metres. As the drill is drilling a hole, water is added to create a thick mud that aids in holding the oil and prevents the liquid from spilling up and over the surface due to internal pressure. For as long as there is internal pressure under the surface, the oil-mud mixture is extracted through by means of a complicated pipe system, which includes an oil and gas separator, to a refinery. After all the internal pressure is expended, secondary methods are used to recover the remaining the crude oil. This includes water flooding or gas injection.



Distillation & Refining

The crude oil-mix mixture is pumped into a furnace and heated to temperatures greater than 300^{o}C. The vapours rise into a fractionating column where the heavier and lighter molecules will condense into separate areas of the tower. The heavier matter is used for materials such as plastics and lubricants, where the lighter matters that are released are natural gases, gasoline, as well as kerosene. After separating the various compounds in the crude oil and obtaining the gasoline, further refining is done to increase the quality. Processes such as catalytic cracking as well as polymerization is done to refine the gasoline further by breaking down or combining molecules so that liquid fuels will be achieved.

2.3 Environmental Assessment using GaBi

Using the GaBi software, an LCA was done to simulate the entire process of petroleum extraction to production to usage in a vehicle. Unlike the bioethanol fuels produced by corn stover and corn, the process is evidently simpler with also many processes already included within the software. These processes include:

1. **Crude oil mix PE (Petroleum)** – Consists of the database for the extraction and addition of water of petroleum from the earth with an outflow result of a crude oil mixture
2. **Crude oil, in refinery** – Evaluates energy and mass flow values in the refinery/distillation process of gasoline production
3. **Crude oil, at production** – Takes values of refined crude oil and evaluates them while taking account of further refining after distillation in refinery. Outflow includes gasoline
4. **Car Petrol** – Acquires values for petroleum and uses them within the conventional car's combustion process (***Note****: assume combustion differences between bioethanol and gasoline similar enough that can be negligible*)

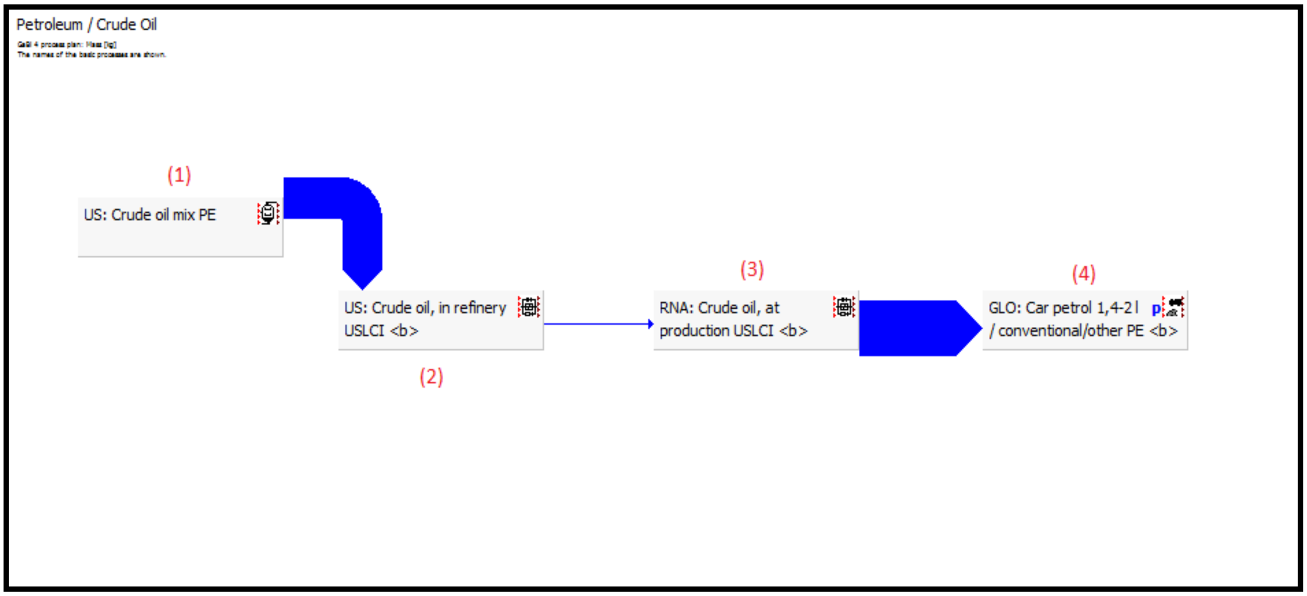


Figure 2.2: Simulation of gasoline process in GaBi

2.4 Results for Gasoline LCA

These results were acquired based on process flow sheets that have been entered in the simulation. Results concluded that the global warming potential was 28.43 kg equivalent of CO_2, acid rain potential and the smog forming potential of the gasoline combustion LCA was found to be 10.1 kg of H^+ equivalent and 0.17 kg of NO_x equivalent respectively. More detailed results of the GaBi simulation are found in Table A1 in the Appendix A. The gasoline results will provide a basis for comparison for Corn Stover and Corn LCA values. The following Figure 2.3 portrays the global warming potential for each sector of Gasoline LCA.

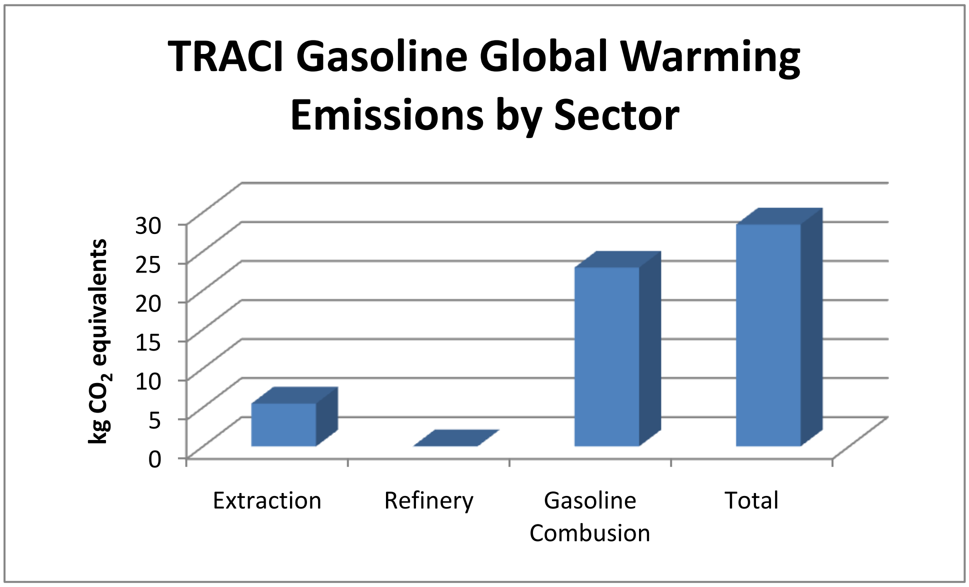


Figure 2.3: Global Warming (CO_2 equivalents) emissions from gasoline LCA based on 100km travelled

3.0 Ethanol Fuelled Vehicles

High energy prices, increasing energy imports, shortages of petroleum supplies and environmental consequences of fossil fuels have increased interest in biofuels. As a green technology that has the potential to drastically reduce carbon dioxide emissions due to the carbon life cycle of plant based fuels, the benefits appear valuable to the world's environmental problems. When burning these biofuels, the carbon dioxide that was absorbed by the plant source is emitted back into the atmosphere, representing a theoretical zero net emission lifecycle (Figure 3.1).

Biofuels have the following benefits over petroleum based fuels:

- The potential to be low carbon fuels as a result of the carbon lifecycle (Figure 3.1)
- A renewable source of energy
- Increased energy security for oil importing countries

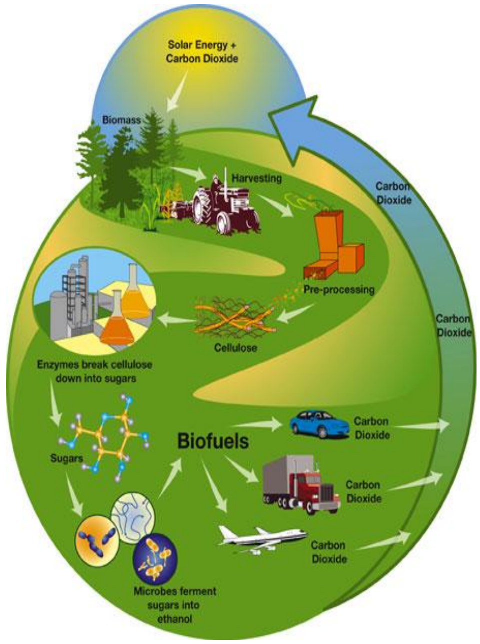


Figure 3.1 – Stages in the lifecycle of bioethanol

Bioethanol is a particularly appealing biofuel because it can be blended with currently-used petroleum fuel (Champagne, 2008). This would allow for an immediate yet gradual implementation of biofuels into today's current transportation systems, which will also allow the biofuel industry to grow at a steady rate.

Corn has proven over the recent years to be a useful renewable resource for producing ethanol. Food grade corn consists of 75% starch, which can be hydrolyzed and fermented in ethanol (Brehmer, B., & Sanders, J. 2009). Ninety percent of bioethanol produced in the United States is derived from corn (M. E. Dias De Oliveira, 2005). This act of converting food grade material into fuel has raised ethical issues, however, as the use of corn for bioethanol production has been identified as a factor in increased corn prices (Odling-Smee, 2007).

The production of bioethanol from lignocellulosic (non-food grade) biomass has been touted as a possible solution to the ethical dilemma of using food for fuel. Corn stover, the inedible portion of a corn plant, represents a low value agricultural byproduct which has the potential to be the ideal bioethanol feedstock. With corn stover containing at least seventy percent of cellulose and hemicellulose as its components, this indicates there is a great production potential for ethanol (Brehmer, B., & Sanders, J. 2009).

3.1 Processes Involved in Producing Bioethanol

There are several processes that are energy intensive when ethanol from corn or corn stover is produced. These processes include:

Farming:

The growing, harvesting and transportation of corn is very energy intensive. This step is shared between the two sources of ethanol production, corn and corn stover. For the LCA, the use of fertilizers, the use of neutralizers, and CO_2 and other air pollutant emissions are done for this first process. For example, corn production in the United States requires a significant amount of energy and dollar investment. However, the use of corn, a human food resource, for ethanol production, raises major ethical and moral issues that are currently being debated. The current food shortages throughout the world make corn as a food resource much more important than a fuel resource.

On the other hand, one of the major advantages of corn stover is that it is not a food resource and it does not take extra energy to produce it. Corn stover is nearly free of energy cost and finances because it is a by-product of a food source. Transportation from the farm to the mill plant does, however, include the farming energy input and GHG emissions to the atmosphere.

Dry Mill Corn Processing:

In the dry-milling process, whole corn is hammer-milled to the required size followed by liquification, saccharification, fermentation, and downstream distillation. Approximately 13 gallons of water are added to the hammered corn per 10.2 kg. The glucoseladen mash is then cooled and transferred to fermenters where yeast is added for fermentation. The dry-milling process typically yields ethanol, CO2, and dried distillers grains and soluble (DDGS). Dry mills are less capital intensive but produce less valued by-products than wet mills (Kim & Dale, 2007).

Corn Stover Pretreatment:

One of the major barriers preventing large scale ethanol production from lignocellulosic biomass is the need for an efficient pre-treatment to remove lignin, which has been proven to interfere with enzymatic hydrolysis (Lin, Y., & Tanaka, S. (2006)). Current research is being conducted at the University of British Columbia (UBC) on a biomass pretreatment called oxygen delignification, which has been proven to be effective at enhancing hydrolysis yields of corn stover by selectively solubilizing lignin. The pretreatment takes place by exposing the substrate to caustic and oxygen at high temperature, which destabilizes the lignin molecule.

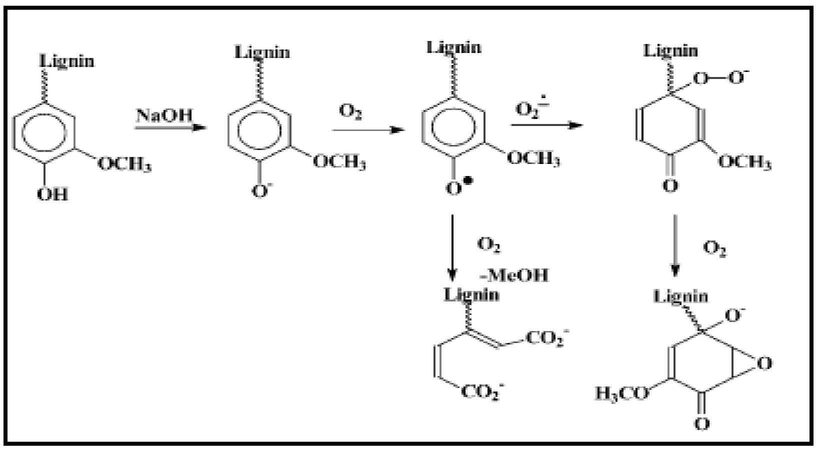


Figure 3.2: Reaction mechanism for oxygen delignification ((Lucia & Smereck, 2001)13)

Hydrolysis and Fermentation:

Simultaneous saccharification and fermentation uses enzymatic hydrolysis to break sugar polymers to sugar subunits. Yeast is grown in the same reactor that the enzymes are added, and can ferment sugar subunits into ethanol. This process uses amylase enzymes for corn and cellulase enzymes for corn stover, with the difference in energy inputs between the two feedstocks negligible.

Distillation:

When fermentation is complete, the alcohol content of the mash (beer) is from 12-15 % (vol). The “beer” is then transferred into 3 distillation units where the ethanol concentration becomes 95% and is separated from the solids and water. To be mixed with gasoline, the 95% ethanol must be processed further and more water is removed requiring additional fossil energy inputs to achieve 99.5% pure ethanol (Table 2). The distillation accounts for the large quantities of fossil energy required in the fermentation/distillation process (Pimentel, 2003).

Growing Corn / Corn Stover

The Gabi database has an entry for corn growth in which it includes corn stover as a by-product. Presently there is no consensus on deciding how to allocate life cycle flow to corn versus corn stover (Sheehan, J. et, al.). For the sake of this study, allocation will be based on mass. Per hectare of farmland devoted to corn growth, 45% (mass) is corn grain, while the other 55% is corn stover (Brehmer, B., & Sanders, J.). Therefore all inputs and outputs for this Gabi database entry were factored by the mass percentage when conducting an LCA for each ethanol type.

Carbon Dioxide Absorption

The Gabi database for corn/stover growth accounts for atmospheric carbon dioxide absorption due to plant growth. For consistency, the amount of carbon dioxide absorption allocated to corn and corn stover is also based on mass, therefore 45% of the absorption is contributed to corn while the other 55% is contributed to the stover. When calculating total GHG over the life cycle of the fuel, the carbon dioxide emissions absorbed are subtracted from those emitted giving a net emission value.

Energy Sources

When not being restricted to an energy source by the Gabi database, a mixture of hydroelectricity and grid power was selected. This is because the ethanol production plant is intended for Canada, where depending on province location; hydropower can play a significant role.

3.2 Gabi LCA for E85 Derived From Corn

The primary contributions of the corn ethanol production LCA were:

1. **Growing/harvesting corn**
2. **Transporting corn**
3. **Dry milling corn**
4. **Hydrolysis, fermentation and distillation**
5. **Combustion of ethanol**

Each of these primary contributions had associated secondary contributions to account for, such as the production of diesel required for fuelling the transportation vehicles. The following table shows the assumptions and the processes used to simulate the LCA in GaBi program. Figure 3.3 and 3.4 shows the whole simulation flow sheet of E85 ethanol from corn

Process	**Assumptions**	**References**
Corn Growth	Modified GaBi database: 45% (mass) inputs and outputs	(Brehmer, B., & Sanders, J. 2009)
Corn Transportation	GaBi database: Railway available, diesel powered	
Dry Milling	New entry 13MJ hydro electricity/kg corn Corn consists of 75% starch	(Kim & Dale, 2007)
Hydrolysis, Fermentation, Distillation	New entry 1.8MJ hydroelectricity/kg corn 0.137kg coal / kg corn Hydrolysis efficiency: 0.95 Fermentation efficiency: 0.90	(Pimentel, 2003) (Spatari, Bagley, & Maclean, 2010)
Ethanol Combustion	New entry 1.91kg CO_2, 0.037kg CO, 0.106kg formaldehyde, 0.031NOx per kg corn	(Sheehan, Aden, Paustian, & al, 2004)

Table 3.1: Input assumptions for corn ethanol process

GaBi Simulation for Growing/Harvesting Corn

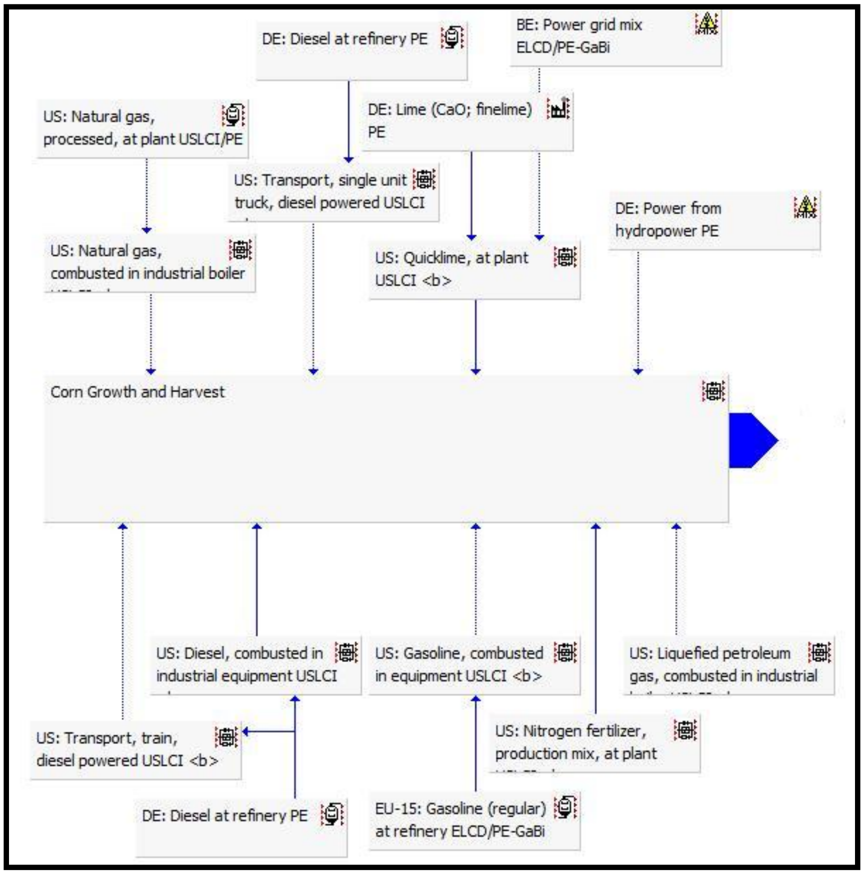


Figure 3.3: Simulation of corn growth and harvesting in GaBi

GaBi Simulation for Ethanol Production from Corn

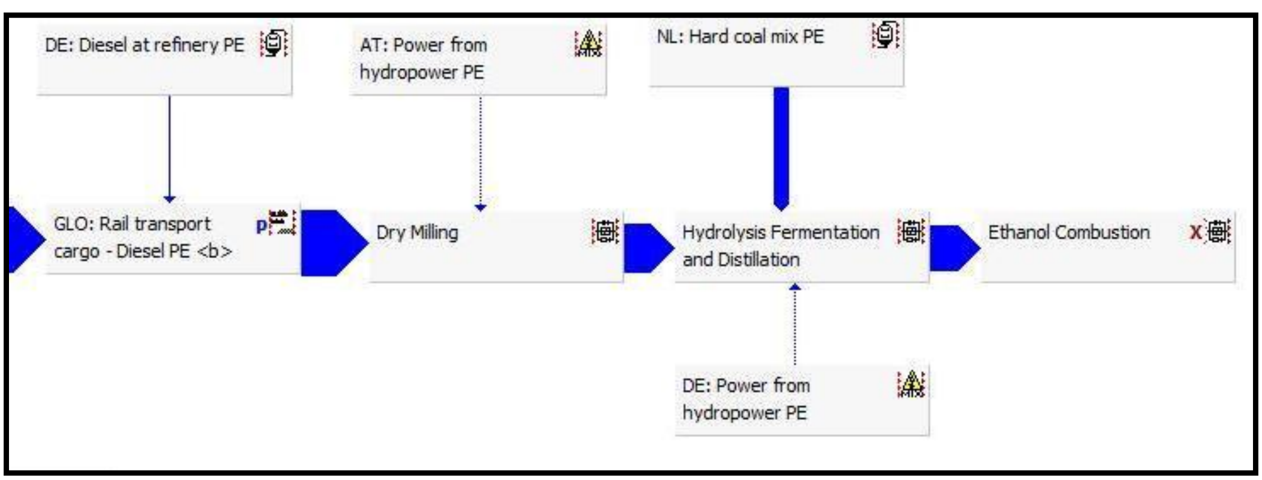


Figure 3.4: Simulation of Ethanol Production from Corn in GaBi

3.21 Results for LCA on E85 Derived from Corn

The results of the GaBi simulation are shown in Table A2 in the Appendix A.The process of dry milling and hydrolysis fermentation, distillation and ethanol combustion were built upon the values that were found on various literature reports. All results are based on a distance of 100km travelled. According to the program, the global warming potential was 18.05 kg equivalent of CO_2. The acid rain potential and the smog forming potential of the gasoline combustion LCA was found to be 16.29 kg of H^+ equivalent and 0.38 kg of NO_x equivalent respectively. These results would provide a basis between comparison for Corn Stover and Corn grain LCA results. Figure 3.5 shows the Global warming potential for each sector of Corn ethanol LCA. Table 3.2 below shows the resource consumption and CO_2 absorption during a life cycle of corn-grain Ethanol.

Corn Consumed	12.89
Water Consumed	190.43
Carbon dioxide absorbed	8.68

Table 3.2: Resource consumption and CO_2 absorption

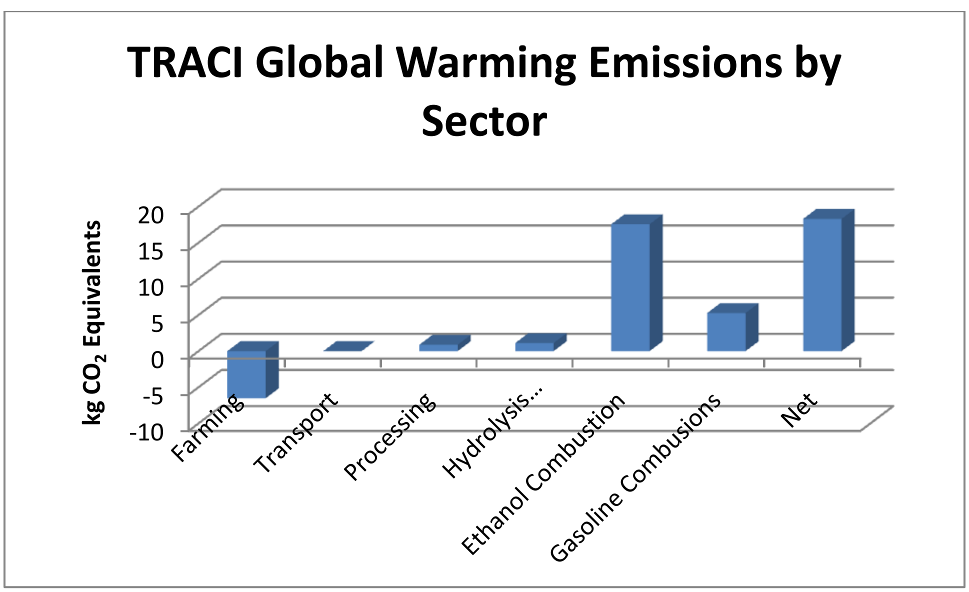


Figure 3.5: Global warming emissions by sector for E85 produced from corn

3.3 Gabi LCA for E85 Derived from Corn Stover

In this section, the E85 life cycle from Corn Stover is analysed using Gabi simulation program. The primary contributions of the corn stover ethanol production LCA were:

1. **Growing/harvesting stover**
2. **Transporting stover**
3. **Pretreatment of stover**
4. **Hydrolysis, fermentation and distillation**
5. **Combustion of ethanol**

The following table provides the processes and the assumptions that were used to simulate the LCA of ethanol from Corn Stover. Figure 3.6 and 3.7 shows the simulation flow sheet of Ethanol form Corn Stover in GaBi program.

Process	**Assumptions**	**References**
Corn Growth	Modified gabi database: 55% (mass) inputs and outputs	(Brehmer, B., & Sanders, J. 2009)
Corn Transportation	**Gabi database**: Railway available, diesel powered	
Pretreatment	**New entry** 26MJ hydro electricity/kg corn Stover consists for 42% cellulose, 28% hemicellulose 10% NaOH, Compressed oxygen	(Kim & Dale, 2007) Energy estimated based on dry milling Brehmer, B., & Sanders, J. (2009) Experimental research
Hydrolysis, Fermentation, Distillation	**New entry** 1.8MJ hydroelectricity/kg corn 0.137kg coal / kg corn Hydrolysis Efficiency: Cellulose – 0.95 Hemicellulose – 0.85 Fermentation efficiency: 0.90	(Pimentel, 2003) (Spatari, Bagley, & Maclean, 2010)
Ethanol Combustion	New entry 1.91kg CO_2, 0.037kg CO, 0.106kg formaldehyde, 0.031NOx per kg corn	(Sheehan, Aden, Paustian, & al, 2004)

Table 3.4: Input assumptions for Corn Stover ethanol process

Growing/Harvesting Corn

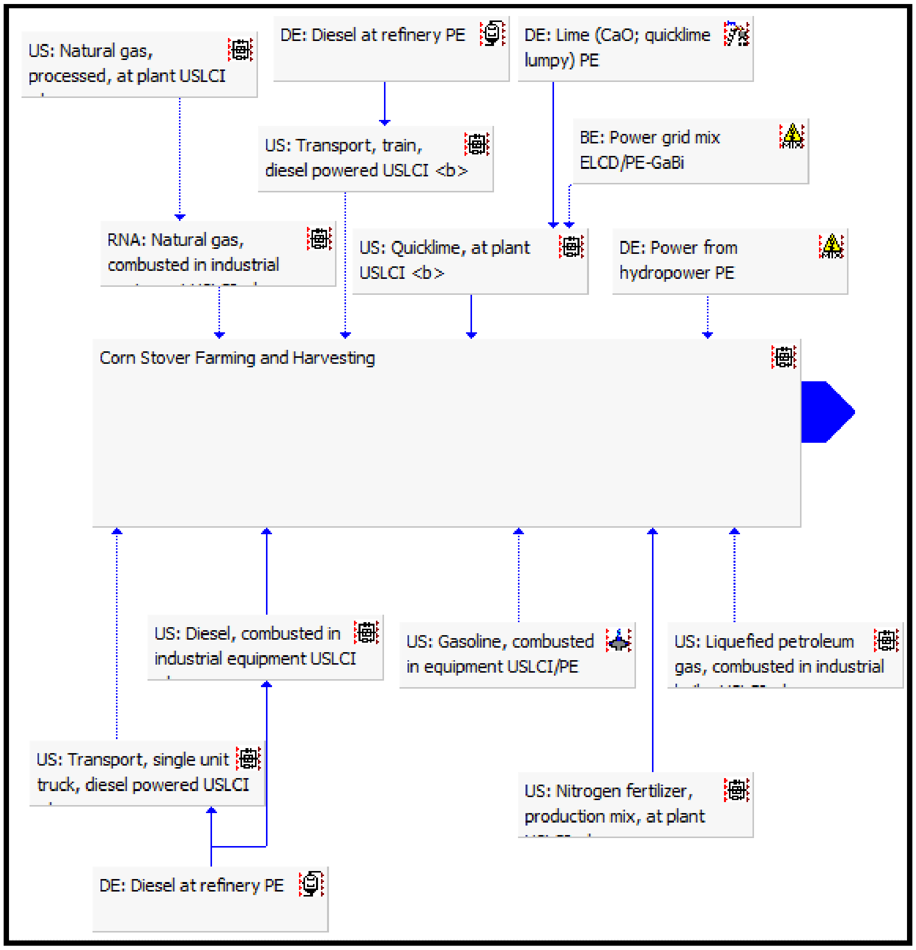


Figure 3.6: Simulation of corn stover growth and harvesting on GaBi

Ethanol Production from Corn Stover

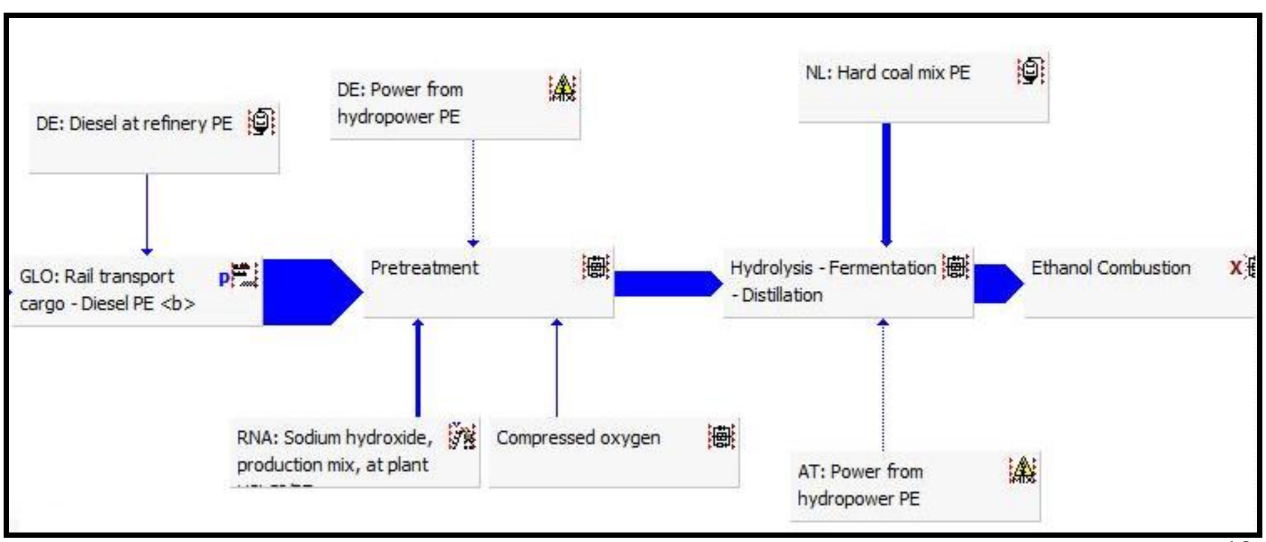


Figure 3.7: Simulation of ethanol production from corn stover in GaBi

3.31 Results for LCA on E85 from Corn Stover

In this section, the result of the GaBi simulation has been shown in Table A3 in the Appendix A. These results were acquired based on the process flow sheets that were already have been inputted in the simulation program and the values that have been found in the literature. The process of dry milling and hydrolysis fermentation, distillation and Ethanol combustion were built upon the values that were found on various literature reports. All results are based on a distance of 100km travelled. According to the program, the global warming potential was 17.97 kg equivalent of CO_2. The acid rain potential and the smog forming potential of the gasoline combustion LCA was found to be 17.53 kg of H^+ equivalent and 0.39 kg of NO_x equivalent respectively. These results would provide a basis for comparison between Corn Stover and Corn grain LCA results. The figure 3.8 shows the Global warming potential for each sector of Corn ethanol LCA. The table below shows the resource consumption and CO_2 absorption during a life cycle of Corn-Stover Ethanol.

Table 3.5: Resource consumption and CO_2 absorption

Corn Stover Consumed (kg)	15.05
Water Consumed	274.54
Carbon dioxide absorbed (kg)	12.52

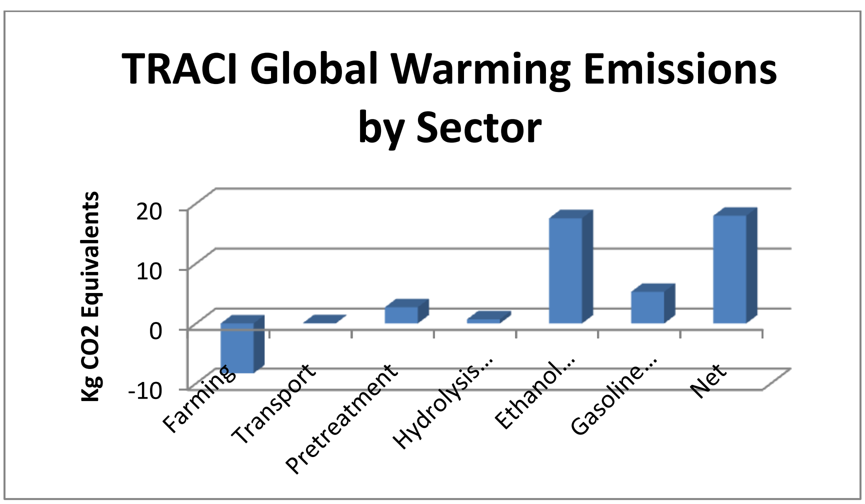


Figure 3.8: Global warming emissions by sector for E85 produced from corn stover

4.0 Summary of Results

In this section, the summary of all parts of the last section is presented with the comparison and discussion that would follow in the following section.

	Gasoline	E85 From Corn	E85 From Corn Stover
Total Emissions (kg)	33.33	19.43	19.04
TRACI Global Warming Emissions (kg CO_2 equivalents)	28.43	18.05	17.97
TRACI Acid Rain Emissions (mol H^+ equivalents)	10.10	16.29	17.53
TRACI Smog Forming Emissions (kg NOx equivalents)	0.17	0.38	0.30
Food Consumed (kg corn)	0	12.89	0
Water Consumed (kg)	11.38	190.43	274.54

Table 4.0 :Summary of LCA results

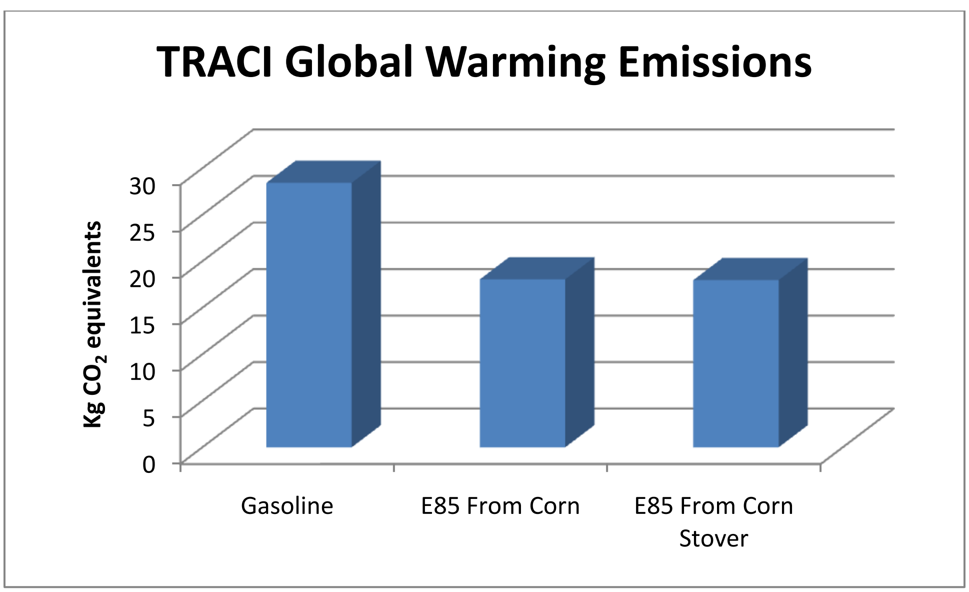


Figure 4.0 Comparison of green house gas emissions for each LCA

5.0 Discussion

The emission profiles observed over the lifecycle of E85 produced from corn and corn stover were observed to be similar. The two important observations from this comparison come by looking at the resources consumed. E85 from corn requires 11.38kg corn / 100km travelled, while corn stover avoids this problem since it is a by-product of corn production. However, producing E85 from corn stover requires 41% more water consumption.

According to the result presented in Table 4.1, gasoline had the highest global warming potential out all the investigated fuels. These emissions are primarily observed from combustion and emission from the refinery process. E85 demonstrated a 39% reduction in GHG emissions compared to gasoline. This confirms that based on the aspects of the lifecycle included in the analysis, use of E85 would reduce carbon dioxide emissions. Other scholars such as J.Hill share this conclusion as well, in which E85 was shown to only release 88% of the net GHG emissions of production and combustion of gasoline.

The carbon dioxide emissions absorbed during the farming of corn and corn stover (Figure 3.5 and 3.8) have shown to have a dramatic effect in reducing the total net GHG emissions of E85, explaining why GHG emissions are lower than gasoline. Looking at the downstream sectors, the transport of corn / corn stover and production of ethanol had only a small contribution to the overall GHG emissions, as the bulk of the emissions were produced during combustion of the fuel. The emissions produced from the pre-treatment of corn stover were higher than the dry milling of corn, because pre-treament is a more energy intensive process.

The next environmental emission indicators observed were for acid rain and smog forming potentials, calculated based on acidic proton and NOx equivalents emitted. Here, gasoline was shown to be advantageous producing 38% less acidic proton equivalents, and 55% less NOx equivalents. These findings are also supported by literature, in which combusting E85 was shown to increase five air pollutants such as NO_x and $SO_{x,}$ and the acid rain formation (J.Hill, 2006).

A comparison of the natural resources used for E85 and gasoline was also shown to favour gasoline. This is especially evident for water, in which gasoline consumes a mere 11.4kg of water, compared to the 190-275kg observed for E85. Gasoline, like corn stover, also avoids the consumption of food observed for corn ethanol. This does not take into account the fact that gasoline itself is a non-renewable resource.

Finally, the ecological footprint of E85 is also important to consider. This requires land usage and deforestation to be taken into account which was not possible to evaluate within the simulation. However, De Oliveira calculated the ecological foot print using the forest area required to sequester Co2 emitted during the production and combustion E85, as well as the area required for growing crops of corn. De Oliveira et al came to the conclusion that gasoline alone has an ecological foot print of 1.11 (from the area needed for CO_2 assimilation) but E85 has ecological footprint of 1.74 (area of harvest and the area needed for CO_2 assimilation). Based on these results of ecological footprint, the use of ethanol would require enormous areas of corn agriculture, and the accompanying environmental impacts far outweigh its benefits. However, because E85 was shown to emit lower levels of pollutants when burned, it could be important in regions or cities with critical pollution problems. Using corn stover instead of corn is likely to enhance the ecological footprint of E85, as all existing corn farmland would already be producing the corn stover needed, mean less deforestation for new bioethanol production.

6.0 Conclusion

It was shown that the only consequences in switching the petroleum for ethanol production from corn to corn stover were increased consumption of water. Air emissions were found to be relatively parallel. The benefit of such a change, however, would be food was not being consumed to make fuel and a reduction in deforestation for new farmland improving the ecological footprint.

E85 was shown to reduce GHG compared to gasoline; however, gasoline was better for smog, acid rain, and water consumption.

7.0 Future Consideration for Concluding Which Fuel is Better

The first consideration to take into account is the fact an LCA using Gabi cannot fully quantify the advantage of a fuel derived from renewable resources, as is used for bioethanol production.

Another other major consideration, which was outside the scope of this study, was the cost of each fuel. Corn Stover is cheaper than corn; however, production costs may be higher due to the pre-treatment. The cost of bioethanol has been on the steady decline as technological advances are made, but currently remains higher than gasoline. However, the use of a fuel that emits lower levels of pollutants when burned may be important in regions or cities with critical pollution problems. However, further research should be done to improve the conversion process. The price of gasoline on the other hand typically follows a steady increase, indicative of its finite supply. Prices may become increasingly high for gasoline that as a result, ethanol production would become economically feasible.

To properly choose the best fuel, a weighting system must be applied, indicating the importance of each environmental impact, as well as cost, and renewable versus non-renewable resource consumption.

8.0 References

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Appendix A: Simulation Results and LCA Results & Figures

Table A1: Significant emissions to the air, water, and soil; *Values obtained from GaBi software*

		Compound	Amount (kg)
Emissions to Air	**Total emissions**		33.33
	Inorganic emissions		29.56
		Carbon Dioxide	26.71
		Carbon Monoxide	0.92
		Nox	0.17
		SO2	0.06
	Organic Emissions		0.27
		NMVOC	0.20
		Methane	0.07
Emissions to Fresh Water			0.24
Emissions to Industrial Soil			7.74E-04
TRACI Global Warming Potential (kg CO_2 equivalents)			28.43
TRACI Acid Rain Potential (mols H^+ equivalents)			10.1
TRACI Smog Forming Potential (kg NOx equivalents)			0.17

(NMVOC = non methane volatile organic compound)

Table A2: emissions to the air, water, and soil for E85 derived from corn; *Values obtained from GaBi software*

		Compound	Amount (kg)
Emissions to Air			19.43
	Inorganic emissions		17.46
		Carbon Dioxide	16.34
		Carbon Monoxide	0.28
		Nox	0.38
		SO2	0.01
	Organic Emissions		1.01
		NMVOC	0.98
		Methane	0.03
Emissions to Fresh Water			4.83
Emissions to Industrial Soil			4.89E-04
TRACI Global Warming Potential (kg CO_2 equivalents)			18.05
TRACI Acid Rain Potential (mol H^+ equivalents)			16.29
TRACI Smog Forming Potential (kg NOx equivalents)			0.38

(NMVOC = non methane volatile organic compound)

Table A3: emissions to the air, water, and soil for E85 derived from corn stover; *Values obtained from GaBi software*

		Compound	**Amount (kg)**
Emissions to Air			19.04
	Inorganic emissions		17.02
		Carbon Dioxide	15.84
		Carbon Monoxide	0.28
		Nox	0.39
		SO2	0.02
	Organic Emissions		1.01
		NMVOC	0.98
		Methane	0.03
Emissions to Fresh Water			7.10
Emissions to Industrial Soil			7.40E-4
TRACI Global Warming Emissions (kg CO_2 equivalents)			17.97
TRACI Acid Rain Emissions (mol H^+ equivalents)			17.53
TRACI Smog Forming Emissions (kg NOx equivalents)			0.39

Appendix B: Calculations

Fuel Consumption for 100km travelled

- Consumption based on average road conditions

Fuel consumption = $\left(\frac{Distance\ Travelled}{Fuel\ Efficiency}\right)$

Gasoline = $\frac{100km}{10km/L}$ = 10.0 Litres

E85 = $\frac{100km}{7.3km/L}$ = 13.7 Litres

E85 Components by Mass to Travel 100km

- 85% volume ethanol, 15% volume gasoline

Ethanol = 13.7L *0.85 * $\frac{0.789kg}{L}$ = 9.19kg Ethanol

Gasoline = 13.7L * 0.15 * $\frac{0.720kg}{L}$ = 1.48kg Gasoline