Engineering Management
Field Project

The Future of Corn-Ethanol in Fuel Sector of United States from Environmental and Economic Standpoint

By

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EXECUTIVE SUMMARY

The U.S. ethanol industry grew from practically zero production in the late 1970's to over 1 billion gallons in 1994, spurred by national energy security concerns, new Federal gasoline standards, and government incentives. In 2006, approximately 4.9 billion gallons of fuel ethanol was produced from corn to be blended with gasoline for use in motor vehicles.

The United States has long since been one of the highest consumers of crude oil for transportation purposes in the world and right now imports about 66% of the total oil consumed worldwide. Also, U.S automobiles and light trucks are responsible for nearly half of all greenhouse gases emitted by automobiles globally. Given all these facts, ethanol has been suggested as a viable alternative to gasoline owing to its environmental and economic advantages.

Since the late 1970's, studies have estimated net energy value of corn ethanol as one of the indicators of sustainability. However, variations in data and assumptions used among the studies have resulted in a wide range of estimates.

My project aims at emphasizing the environmental and economic impacts of using corn-ethanol as an alternative fuel in the United States by making more complete assumptions about its life cycle and, thereby, more conclusively answer the question:

"**Is Corn-Ethanol a sustainable development, Environmentally and Economically**."

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INTRODUCTION

The search for sustainable transportation fuels from biomass is a top research priority in the United States. One driver for this research is increasing crude oil costs and concerns about future supplies. According to Department of Transportation statistics, more than 240 million U.S vehicles were registered in 2006. The use of oil is projected to peak in 2008 and supply is then projected to be extremely limited in 40–50 years. Right now about 66% of the total oil consumed in the U.S is imported. Another issue which is of great concern is the effect of burning gasoline on global warming. U.S. automobiles and light trucks are responsible for nearly half of all greenhouse gases emitted by automobiles globally. Production of fuel-grade ethanol from corn has increased greatly in recent years; however there are varying opinions on the environmental benefits of this technology.

This project aims to emphasize the environmental effects and economic impacts of using corn ethanol as an alternative fuel in the United States. The environmental effects of ethanol are studied by the use of life cycle analysis. Life cycle analysis is systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle. This process will lead us to identifying the various green house gases emitted and the amount of global warming caused by corn ethanol.

Sustainability of corn ethanol can be determined by its net energy value. Net energy value (NEV) of ethanol is the difference between the energy content of ethanol and the energy used in producing and distributing it. Despite the advent of a national ethanol mandate, ethanol's "real" NEV remains a controversial and, from an analytical standpoint, unresolved issue. Incomplete assumptions made by earlier researchers have made inconclusive results about ethanol's sustainability. By making more complete assumptions for life cycle of ethanol I indent to provide better conclusions.

The economic aspect of corn ethanol use is covered by analyzing both the cost and consumption of corn as well as U.S dependence on oil imports.

LITERATURE REVIEW

Ethanol is a renewable fuel made from plants. Essentially non-drinkable grain alcohol, ethanol is produced by fermenting plant sugars. It can be made from corn, sugar cane, and other starchy agricultural products. In United States, most ethanol is made from corn, although because of the rapidly developing research, cellulosic ethanol may soon become a larger part of the market if proven effective.

Most corn-ethanol in United States is produced by either a wet milling or dry milling process. The wet milling process converts corn into corn oil, two animal feed products and starch based products such as ethanol, corn syrups or cornstarch. The dry milling process traditionally generates two products only – ethanol and dry distillers grains (DDGS), an animal feed product. Farmer's organizations building mills today favor the dry mill since it requires less capital to build, a smaller staff to run and tends to receive tax advantages due to smaller capacity.

Studies conducted in mid- 1970's analyzed the energy benefits of substituting ethanol for gasoline and generally concluded that the net energy value of corn ethanol was slightly negative. In the late 1980's, environmental concerns placed ethanol on spotlight once again and energy balance resurfaced. However, there was a considerable amount of variation in the findings of these reports.

<u>David Pimentel</u> (1991)

David Pimentel, a professor at Cornell University in Ithaca, New York, conducted research on corn-ethanol and concluded that ethanol's promise as an alternative fuel is greatly overstated because it is not economical to produce. Pimentel asserted that it took more energy to produce ethanol from corn than ethanol can create. He also stated that for ethanol to be a substitute for gasoline, and fuel all the cars in the United States, 97 percent of U.S. land would have to be planted with corn. Other major findings of his research are:

- An acre of U.S. corn yields about 7,110 pounds of corn for processing into 328 gallons of ethanol. But planting, growing and harvesting that much corn requires about 140 gallons of fossil fuels and costs $347 per acre. Thus, even before corn is converted to ethanol, the feedstock costs $1.05 per gallon of ethanol.
- Adding up the energy costs of corn production and its conversion to ethanol, about 70 percent more energy is required to produce ethanol than the energy that actually is in ethanol. Every time a gallon of ethanol is made, there is a net energy loss of 54,000 Btu.
- According to Pimentel, most economic analyses of corn-to-ethanol production overlook the costs of environmental damages and estimates this should add another 23 cents per gallon to the cost.
- Corn production in the U.S. erodes soil about 12 times faster than the soil can be reformed and irrigating corn mines groundwater 25 percent faster than the natural recharge rate of ground water. The environmental system in which corn is being

produced is being rapidly degraded. Corn should not be considered a renewable resource for ethanol energy production, especially when human food is being converted into ethanol.

- If all the automobiles in the United States were fueled with 100 percent ethanol, a total of about 97 percent of U.S. land area would be needed to grow the corn feedstock. Corn would cover nearly the total land area of the United States.

One of the factors in Pimentel’s study which makes the NEV negative is due to the inclusion of energy value embodied in farm machinery. This procedure is debatable since farm machinery would be used for a long time and the energy embodied in it should be spread over its life time. Another factor that makes Pimentel’s estimates higher is that he uses corn yield based on pre-1989 data. Since this data is very old, the inferences made are obsolete.

David Morris and Irshad Ahmed (1992)

Analysis by Morris and Ahmed conclude that production of ethanol from corn is a net energy generator. More energy is contained in the ethanol and the other by-products than is used to grow the corn and convert it into ethanol and the other by-products. According to their research, if corn farmers used state-of-art energy efficient farming techniques and ethanol plants integrated state-of-art production processes, then the energy contained in a gallon of ethanol is twice the energy used to grown corn and convert it into ethanol.

Morris and Ahmed report, assuming an average efficiency corn farm and an average efficiency ethanol plant, the total energy used in growing the corn and processing it into ethanol and other products is 75,297 Btu. Ethanol contains 76,000 Btu's per gallon and the replacement energy value for the other co-products is 24,950 Btu's. Thus, the total energy output is 100,950 Btu's and the net energy gain is 25,653 Btu's for an energy output-input ratio of 1.33:1.

Though Morris and Ahmed report positive NEV, there is one issue which they seem to have neglected in their analysis – the energy required to transport corn and ethanol from farms and ethanol processing plants respectively.

Hosein Shapouri, James A. Duffield and Michael S. Graboski (1995)

This report concludes that the NEV of corn ethanol is positive when fertilizers are produced by modern processing plants, corn is converted in modern ethanol facilities, farmers achieve normal corn yields and energy credits are allocated to co-products. Shapouri and Graboski estimates NEV of 16,193 Btu/gal. They indicate that ethanol production utilizes abundant domestic energy supplies of coal and natural gas to convert corn into a premium liquid fuel that can replace petroleum imports by a factor of 7 to 1.

Michael Wang (2005)

Michael Wang is a senior researcher at the Center for Transportation Research, Argonne National Laboratory. His research indicates that in terms of energy and environmental benefits, corn ethanol comes out clearly ahead of petroleum based fuels. He shows that the fossil energy input per unit of ethanol is lower – 0.74 million Btu of fossil energy consumed for each million of ethanol delivered, compared to 1.23 million Btu fossil energy consumed for each million Btu of gasoline delivered.

Moreover, ethanol has a positive benefit in greenhouse gas (GHG) emissions reduction. On a per gallon basis, corn ethanol reduces GHG emissions by 18% to 29%, while cellulosic ethanol has an even greater benefit with an 85% reduction in GHG emissions.

Study/year	Corn yield	Nitrogen fertilizer application rate	Inputs for nitrogen fertilizer	Corn ethanol conversion rate	Ethanol conversion process	Total[1] energy use	Coproducts[1] energy credits	Net[1] energy value
	bu/acre	lb/acre	Btu/lb	gal/bu	Btu/gal	Btu/gal	Btu/gal	Btu/gal
Pimentel (1991)	110	136.0	37,551	2.50	73,687 (LHV)	131,017	21,500	-33,517
Keeney and DeLuca (1992)	119	135.0	37,958	2.56	48,434 (LHV)	91,127	8,072	-8,431
Marland and Turhollow (1991)	119	127.0	31,135	2.50	40,105 (HHV)	73,934	8,127	18,324
Morris and Ahmed (1992)	120	127.0	31,000	2.55	46,297 (LHV)	75,297	24,950	25,653
Ho (1989)	90	NR	NR	NR	57,000 (LHV)	90,000	10,000	-4,000
Shapouri (1995)	122	124.5	22,159	2.53	53,277 (HHV)	82,824	15,056	16,193
Average	113	129.9	31,961	NA	NA	NA	NA	2,373

Table 1: Energy input assumptions of recent corn-ethanol studies

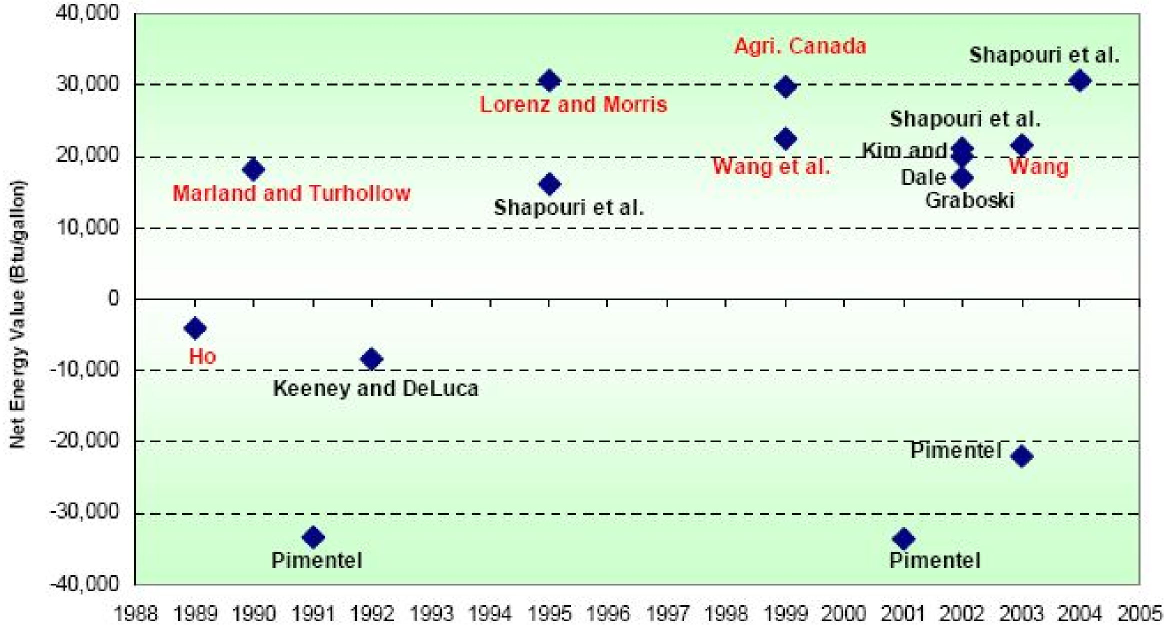


Figure 1: Comparative results of corn-ethanol fossil energy balance

ENVIRONMENTAL ANALYSIS:

Corn-ethanol's ability to cater to the U.S fuel demand and to slow down the depletion of fossil reserves is only justifiable if it is proven as a sustainable energy. In this project, we use life cycle analysis (LCA) as a tool to analyze the various environmental impacts and the sustainability of corn-ethanol.

Life cycle analysis is a systematic evaluation of the environmental and resource consequences of a particular product, process, or activity from "cradle to grave." LCAs enable us to quantify how much energy and raw materials are used, and how much solid, liquid and gaseous waste is generated, at each stage of the product's life.

By analyzing entire life cycle of corn-ethanol from extraction and processing of raw materials through final use and disposal, we can assess systematically the impact of each component process. There are four separate but interrelated components in a LCA: Goal and scope, an inventory analysis, an impact analysis and an interpretation.

In the first phase of LCA, we formulate and specify the goal and scope of study in relation to the intended application. The process of conducting an LCA as well as its outcomes is largely determined by the goal and scope of a study. The object of study is described in terms of a functional unit which is one of the most important elements of LCA. The functional unit represents a quantitative measure of the output of products which the system delivers. In comparative LCA studies it is crucial that alternative systems are compared on the basis of an equivalent function i.e. functional unit. Apart from describing the functional unit, the goal and scope addresses the overall approach to be used to establish the system boundaries. The system boundary determines which unit processes are included in the LCA, and reflects the goal of the study.

In the second phase, the life cycle inventory (LCI) uses inventory, monitoring and material flow data to quantify energy and raw materials requirements, air emissions, waterborne effluents, solid waste, and other environmental releases incurred throughout the life cycle of the product process.

In the third phase, the results from life cycle inventory are then used in a life cycle impact assessment (LCIA), which is the process of assessing the effects of the environmental findings identified in the inventory component. The LCIA addresses ecological and human health impacts, as well as social, cultural, and economic impacts. This is carried out within the following three mandatory steps:

1. Selection of impact categories, category indicators and LCIA models;
2. Classification;
3. Characterization

The selection of impact categories, category indicators and LCIA models are made so that they are consistent with the goal and scope of the study and reflect the environmental issues of the system under study. Classification involves aggregation of the environmental burdens into smaller number of impact categories to indicate their impact on human and ecological health and the extent of resource depletion. The identification of impacts of interest is then followed by their quantification in the next characterization step.

The main objectives of the fourth and the final phase are to analyze results, reach conclusions, explain limitations and provide recommendations based on the findings of LCI and LCIA.

In order to perform a complete LCA of corn-ethanol we break down its life cycle into 5 main stages:

1. Corn Farming
2. Corn Transportation
3. Corn-Ethanol Production
4. Ethanol Transportation
5. Ethanol combustion in vehicles

All the raw materials, energy, solid, liquid and gaseous wastes which form a part of the above 5 processes are accounted for separately and are then analyzed as a whole to get a complete life cycle analysis. In this process of LCA not only the life cycle of corn-ethanol but also the entire life cycle of all raw materials which are used through out the above 5 processes are accounted for since they have indirect effect on the final product, corn-ethanol.

Since the life cycle of all the raw materials used is pretty much standard and well known, we make use of software called SimaPro in our project which has an inbuilt database containing the life cycle analysis of numerous raw materials. SimaPro 7.1 is the most widely used LCA software. It offers ultimate flexibility, parameterized modeling, interactive results analysis and a large included database.

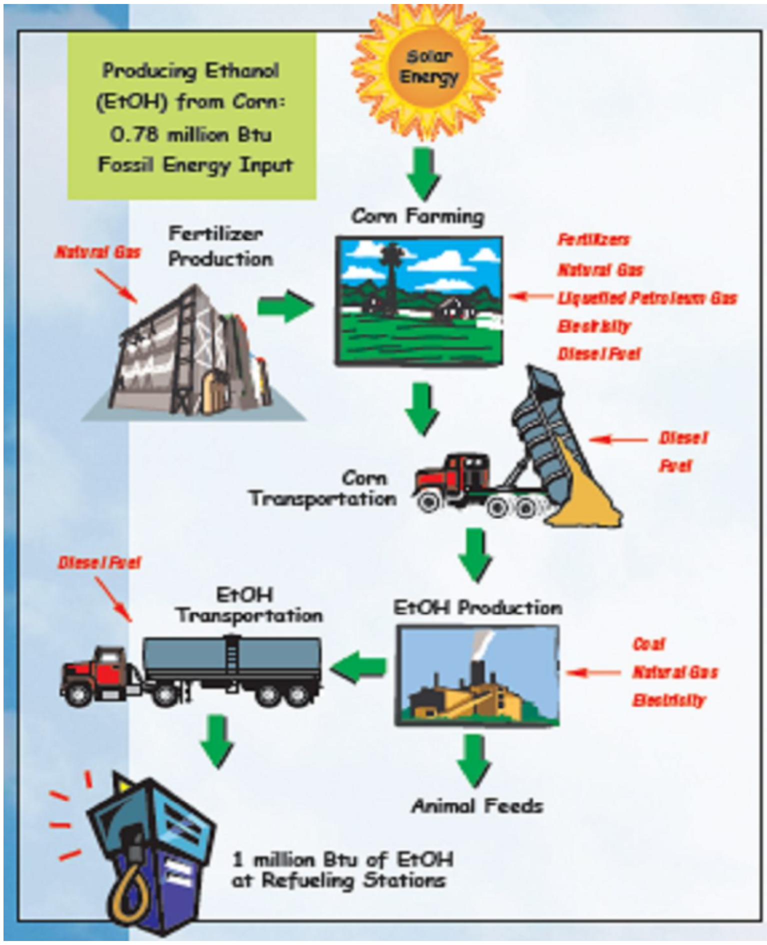


Figure 2: Corn-ethanol life cycle

ECONOMIC ANALYSIS:

Economics of corn- ethanol have been widely discussed by various organizations. Economic analysis of corn ethanol in this project is performed by reviewing all the relevant journals and other related sources, and by presenting these facts in most logical order. All the information presented is acquired from reliable sources.

Goal and Scope: the goal of this analysis is to identify the environmental impacts and net energy balance of corn-ethanol and compare them with those of gasoline in order to evaluate the sustainability of corn-ethanol as a renewable fuel source.

The functional unit used for this analysis is 40 million gallons of corn-ethanol which equates to 30 million gals of gasoline in terms of energy provided to run a vehicle.

Under the scope of this LCA, life cycle of all the raw materials is included as a part of the analysis and forms the system boundary.

Life Cycle Inventory: in order to tackle the complexity of the LCA process, the LCI is conducted separately for all the 5 main stages and is consolidated in the end.

Corn Farming – U.S corn yield per acre has increased over the last 30 years by over 50%, thanks to better corn varieties, improved farming practices and farming conservation measures. LCI of the corn farming is readily available in the SimaPro database and is utilized for our project. All the raw materials required to grow corn like seeds, fertilizers, pesticides etc. which form an integral part of the LCI process are already included in the SimaPro database.

The amount of corn required to be grown in order to manufacture 40 million gallons (functional unit) of ethanol from it is = 358244000 kgs. The calculations involved behind reaching this value are shown in the calculations section of this report. The figure below shows the inputs required to grow 358244000 kg of corn.

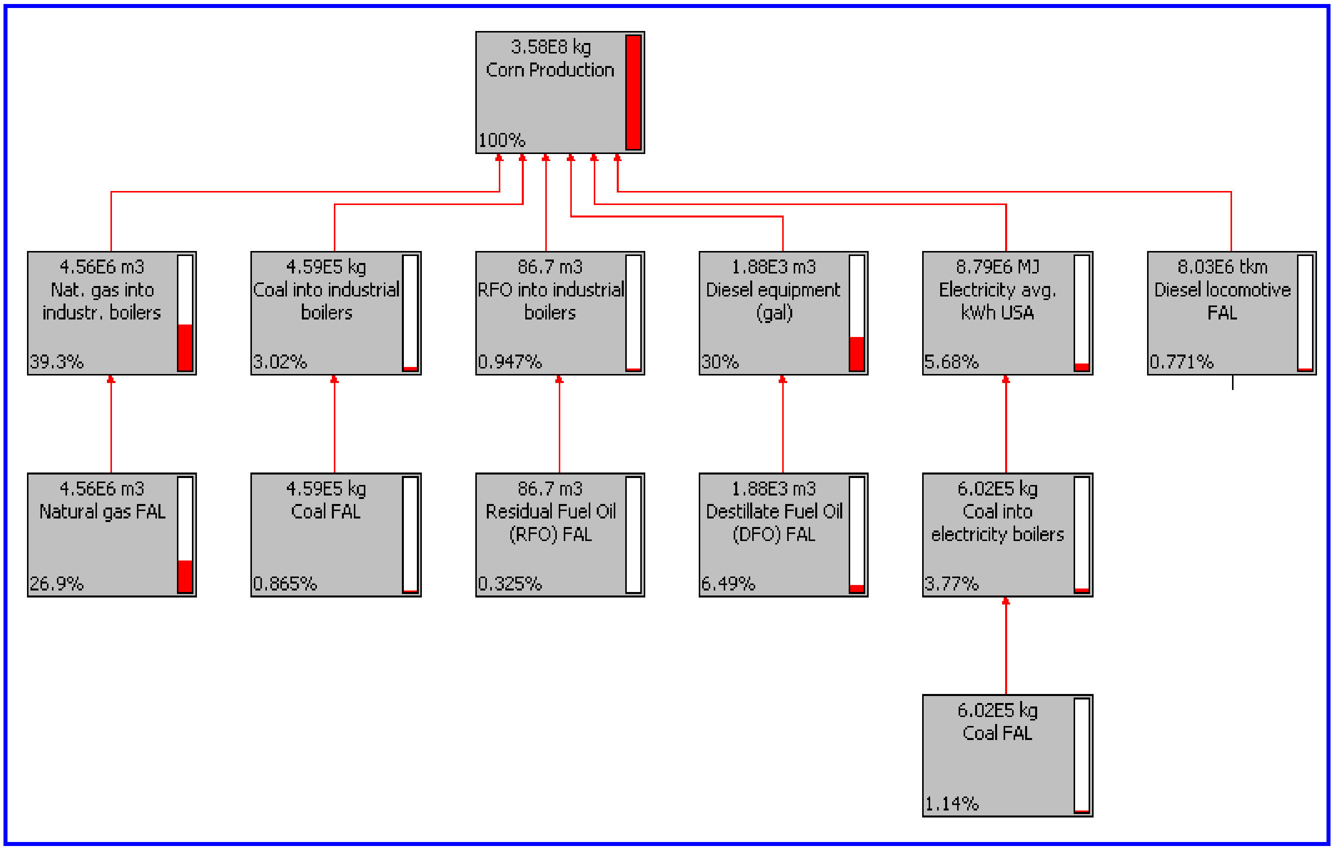


Figure 3: Corn Farming Network Tree (12 nodes visible of 61)

Corn Transportation – corn-ethanol production facilities are generally located near to the corn fields in order to facilitate faster and easy transportation. Our research indicates that, on an average, corn-ethanol plants are located about 60 miles from the corn fields. We use a diesel truck with a transportation capacity of 15 tons in our project. All the assumptions are stated in the assumptions section of this report.

All the above data about the miles to travel, total corn to transport, vehicle type and transportation capacity is fed into the SimaPro software which then calculates the life cycle inventory for this stage.

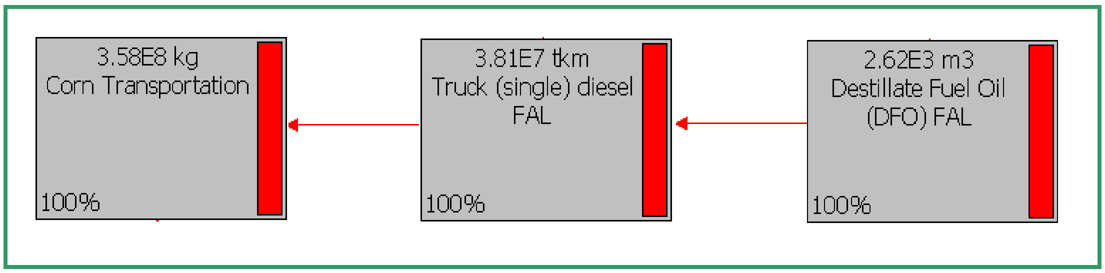


Figure 4: Corn Transportation Network Tree

Ethanol Production – corn-ethanol is generally produced by either wet milling or dry milling process. However, the corn dry-grind process is the most widely used method in the U.S for generating fuel ethanol by fermentation of grains. Dry-milling process is the most complex and therefore the most difficult part of this LCA. A simplified flow diagram of the process is shown in figure 5. The actual process contains more than 100 pieces of equipment and unit operations. The production process under consideration in our project runs 330 days an year with a yield of 40 million gallons of ethanol annually. The following is a description of this process:

The first phase in the ethanol production involves grain receiving. Corn is brought into the facility and held in silos prior to cleaning, where broken corn, foreign objects and finer materials are removed using a blower and screens. The cleaned corn is ground in a hammer mill and sent through weighing tanks to control the feed rate to the process.

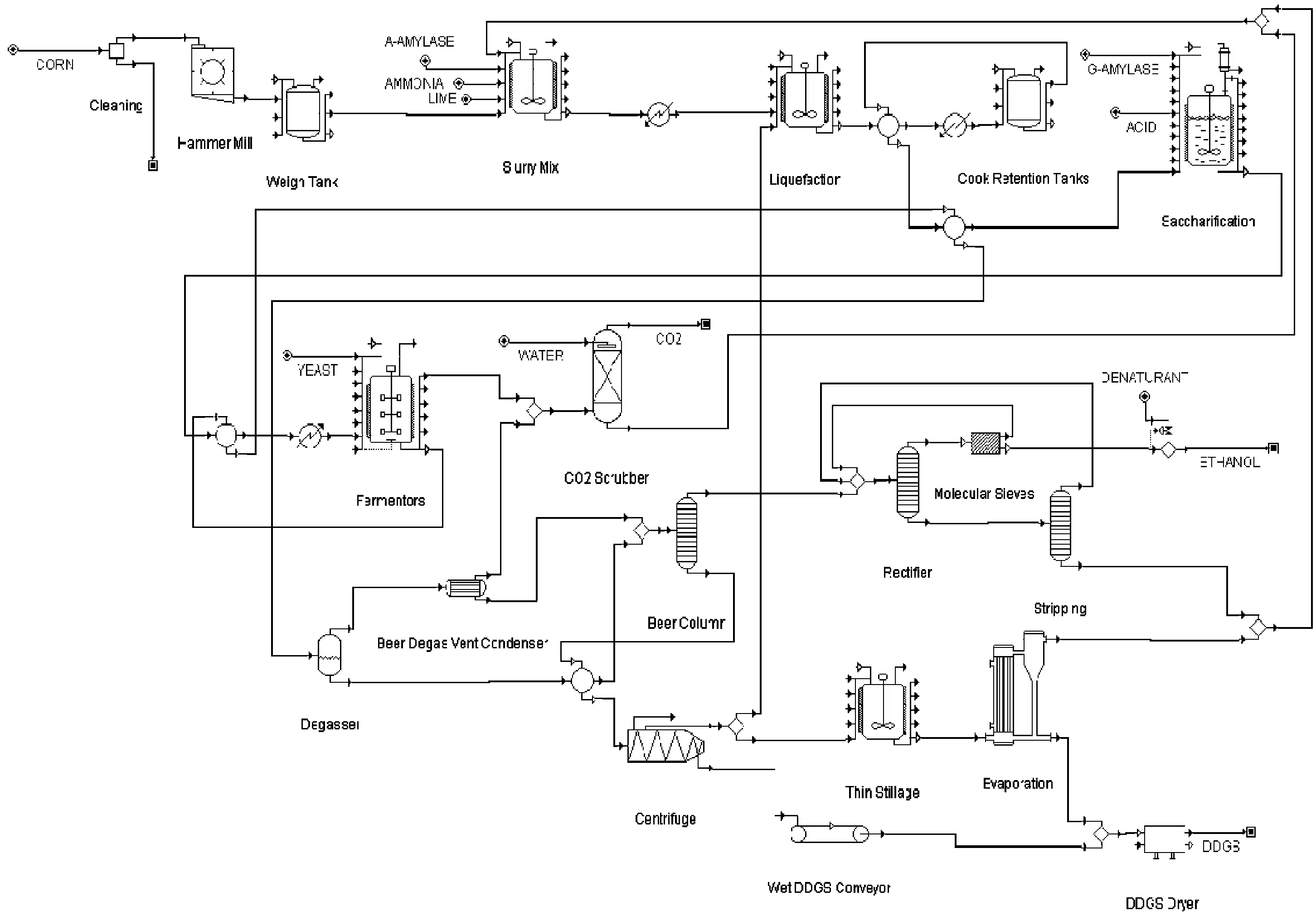


Figure 5: Dry-milling process

In the second phase, measured ground corn is first sent to a slurry tank along with process water, thermostable alpha-amylase, ammonia and lime. After the slurry is prepared, the mixture undergoes liquefaction, where the starch in the corn is gelatinized using a jet cooker and hydrolyzed with thermostable alpha-amylase into dextrins. The starch is cooked and held at 110^{o}C for 15 min and then transferred to the saccharification tank.

Further conversion of the dextrins to glucose is refferd to as saccharafication. Sulfuric acid is used to lower the pH in this tank. During this incubation, almost all of the dextrins are converted to glucose. Following the saccharafication reaction, the slurry is transferred to the fermentation vessel.

Fermentation is the conversion of glucose to ethanol and carbon dioxide using yeast.

$$C_6H_{12}O_6\,(s) \longrightarrow 2\,CO_2\,(g) + 2\,C_2H_5OH\,(l)$$

[Glucose] [Carbon Dioxide] [Ethanol]

After the fermentation is completed, liquid/beer from the fermentation tank is heated using the process stream to the saccharafication tank and then sent through a degasser drum to flash off the vapor. The vapor stream is primarily ethanol and water with some reside carbon dioxide. The ethanol and water vapors are then condensed and recombined with the liquid stream prior to distillation. Any uncondensed vapor is combined with the carbon dioxide produced during fermentation and sent through the carbon dioxide scrubber prior to venting or recovery.

The last phase in this ethanol process is distillation and ethanol recovery. Distillation is the process of separating 2 liquids based upon on the difference in there boiling points. The first step in the ethanol recovery is the beer column, which captures nearly all of the ethanol produced during fermentation. An equal amount of water is also distilled that is separated from the ethanol in the next stage of rectification/stripping. Recovery of the ethanol from the beer column distillate is accomplished through the combined action of the rectifier, stripper and molecular sieves. The distillate from the rectifier, primarily containing ethanol, is then fed to the molecular sieve. Molecular sieves are composed of a microporous substance, designed to separate small molecules from larger ones via a sieving action. Molecular sieves capture the last bit of water creating 99.6% pure ethanol.

A mixture of non-fermentable solids from the bottom of the beer column is fed to the whole stillage tank where 83% of water present is removed using centrifugation, producing wet distiller’s grains. A drum drier reduces the moisture content of these wet distiller’s grains to produce a coproduct known as distiller’s dried grains with solubles (DDGS). This coproduct is widely used as cattle feed.

All the chemicals, materials and there quantities used in this process are listed in the calculation section of this report. The calculations involving the amount of energy used and the amount of wastes/emissions generated are also elaborately presented in this section. The list of all the calculated flow rates, energy and emissions along with there respective processes form the LCI of this stage. This calculated data is then entered into the SimaPro software for final step of LCA process, which is the life cycle impact assessment.

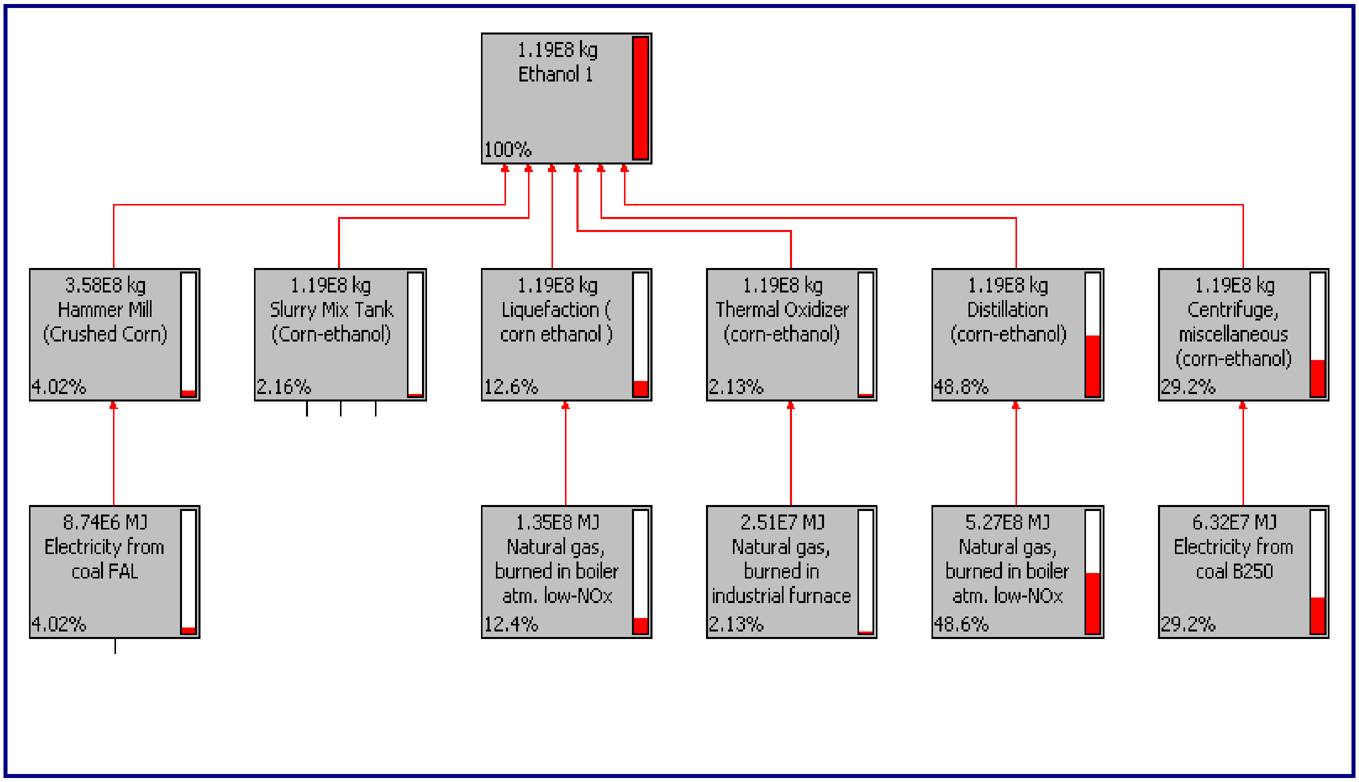


Figure 6: Ethanol Production Network Tree (12 nodes visible of 39)

Ethanol Transportation – Pipelines are generally viewed as the fastest and the most economical mode of transporting liquid fuels. However, the movement of ethanol via pipeline is a limited option. There are three main reasons for this; ethanol absorbs water and impurities found in the pipelines causing phase separation of the ethanol-gasoline blends, logistical limitations of the existing pipelines, and insufficient volumes of ethanol that needs to be transported.

It is estimated that, on an average 3173 Btu of energy is required for transporting a gallon of ethanol to the refueling stations. 40 million gallons of ethanol would require about

126602.7 million Btu. Number of gallons of diesel required to generate this energy would be 910810.79 gallons. All this data is fed into SimaPro for further analysis.

Ethanol Combustion – combustion of ethanol in vehicles produces tailpipe emissions which when accounted for, form a major portion in the global warming category of the LCA process. The carbon dioxide content in the tailpipe emissions from ethanol fueled vehicles is less compared to gasoline fueled vehicles while the acetaldehyde content is the opposite. Following is a list of tailpipe emissions for an ethanol and a gasoline fueled vehicle:

Emissions	g/gal of ethanol	kgs/40 M gals of ethanol
Non-methane hydrocarbons	0.149	93870
Total Hydrocarbons	0.189	119070
Carbon Monoxide	1.33	837900
Nitrogen Oxide	0.09	56700
Carbon Dioxide	389.9	245574000
Methane	0.046	28980
Formaldehyde	0.00226	1423.8
Acetaldehyde	0.01302	8202.6

Table 2: Tailpipe emissions from ethanol fueled vehicle

Emissions	g/gal of gasoline	kgs/30 M gals of gasoline
Non-methane hydrocarbons	0.114	71820
Total Hydrocarbons	0.132	83160
Carbon Monoxide	1.39	875700
Nitrogen Oxide	0.22	138600
Carbon Dioxide	407.6	256788000
Methane	0.023	14490
Formaldehyde	0.00127	800.1
Acetaldehyde	0.00035	220.5

Table 3: Tailpipe emissions from gasoline fueled vehicle

Life cycle impact assessment (LCIA): the environmental burdens quantified in LCI are translated into their related potential environmental impacts with use of the SimaPro software. The results of LCIA are presented in the results section of this report.

A number of LCIA methods exist, but they are divided into two general groups:

- Problem-oriented approaches;
- Damage-oriented methods

In the problem oriented methods the environmental burdens are aggregated according to their relative contribution to the environmental effects they may cause. Typical examples of the problem-oriented approaches are the CML method and EDIP method. Damage-oriented methods, on the other hand, model the endpoint damage caused by the environmental interventions to areas of protection, which include human health, natural and human made environment. Typical examples of damage-oriented methods are EPS 2000 and Eco-indicator 95. In our project, since we want to evaluate the final impacts of corn-ethanol, end point damage is more relevant. We choose damage-oriented method, Eco-indicator 95 as a baseline method for all our analysis.

Interpretation: the interpretation of LCIA results is discussed in the results and conclusion section of this report.

Environmental Impacts: Corn-ethanol vs. Gasoline

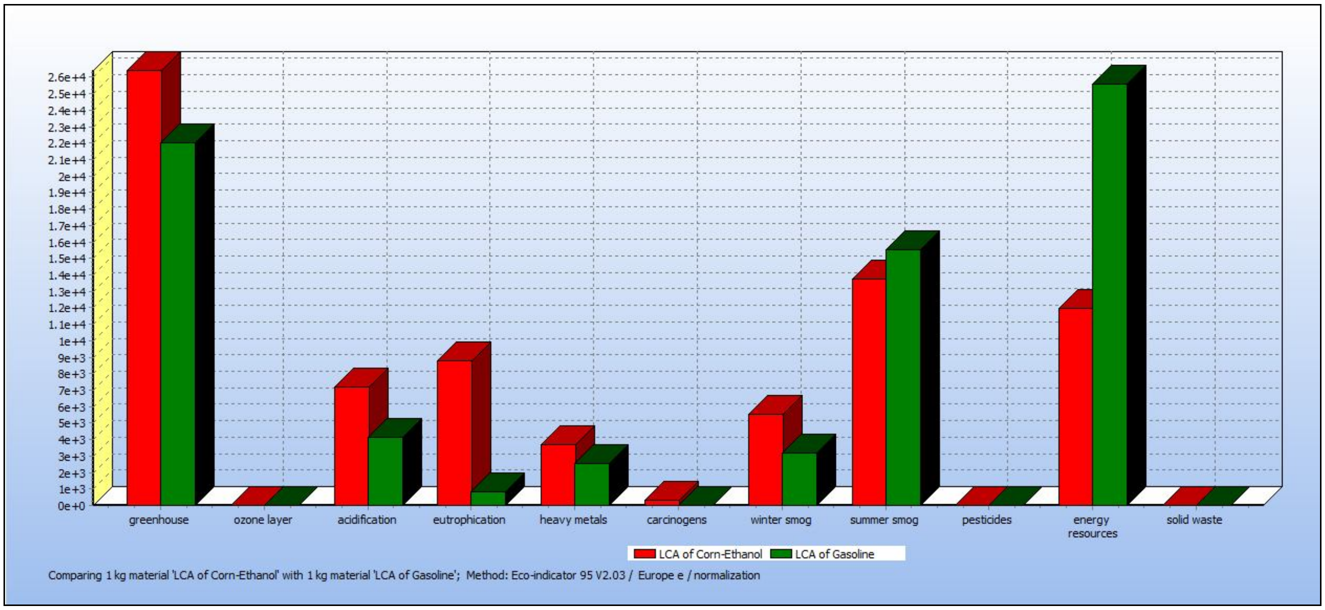


Figure 7: Environmental Impacts of corn vs. gasoline

The above figure representes a comparison between the various environemtal impacts of Corn-ethanol and Gasoline. The graph is generated with the help of SimaPro software by keying in all the parameters involved in the life cycle of corn-ethanol and gasoline. The impact categories considered here are a complete list of categories included in the Eco-Indicator 95 method of LCIA.

The top four impact categories to consider according to their importance are: global warming (greenhouse emissions), acidification, eutrophication and fossil energy use (energy resources). Starting with the first impact category in the graph, which is greenhouse, the graph indicates that corn-ethanol causes more greenhouse emissions than gasoline. But calculations show that corn-ethanol causes 10-20 % less greenhouse emissions compared to gasoline. The controversy between the graph and calculations is due to the inability of the software to account for the carbon dioxide sequestered during corn growth in the graph. So in reality, ethanol causes less global warming compared to gasoline unlike what is portrayed by the graph. More eloborate explanation about carbon balance is presented in the analysis section of this report. Global warming is one of the prime aspects in evaluating technologies and ethanol does well in this regard.

Acidification refers to the potential acid deposition in land, air and water and is based on the contribution of SO2, NOx and NH3. Acid rain which is a result of air acidification is best known for the damage it causes to forests and lakes. It is shown that low pH, monomeric aluminum, and other metal ions have an adverse effect on physiological processes in fish and are a major cause of their death in acidified lakes and rivers. Less well known are the many ways it damages freshwater and coastal ecosystems, soils and even ancient historical monuments, or the heavy metals these acids help release into groundwater. It can be seen from the graph that acidification potential for ethanol is comparitively higher. The main reason for high acidification potential of ethanol is due to the heavy use of fertilizers and pesticides for corn growth. Improvements in corn farming technology can bring about the minimal use of fertilizers and pesticides and hence improve ethanol’s performance from acidification point of view.

Eutrophication is defined as the potential of nutrients to cause over-fertilization of water and soil, which can result in increased growth of biomass - and even further impacts, including lack of oxygen and severe reductions in water quality and in fish and other animal populations. Again the reason for ethanol's higher eutrophication potential is due to the use of nitrogenous and phosphorous fertilizers for corn growth and can be reduced by using hybrid seeds which require fewer fertilizers and also by improving farming technologies.

In terms of fossil energy used it can be clearly seen that gasoline requires almost twice the amount of energy compared to ethanol. Gasoline's production involves refining, distillation which is energy intensive processes and utilizes high amounts of fossil resources. Ethanol's substantially less energy requirements puts in a much better position environmentally.

Net Energy Balance:

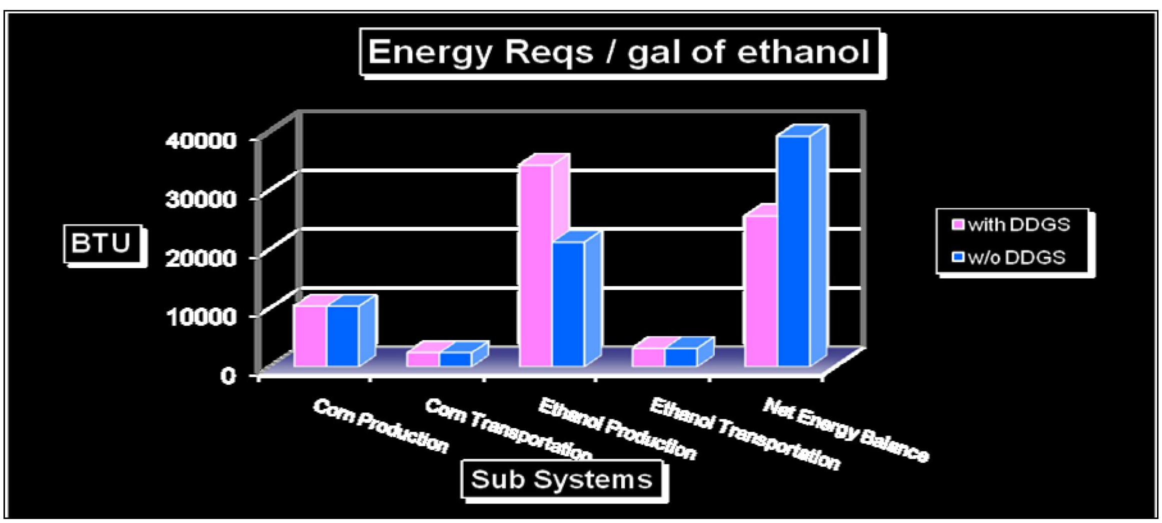


Figure 8: Net energy balance of corn-ethanol

One of the main factors in determining sustainability is the net energy balance. The first four set of bars in above figure represent energy balances for each stage of corn-ethanol's life cycle and the last set represents the net energy balance over its entire life cycle. When all the energy utilized for ethanol's production is only attributed to ethanol and not allocated to the co-product (DDGS), the energy balance thus calculated is represented by the green bars in the above figure. The orange bars represent energy balances with co-product allocation. Co-product allocation is a vital component in energy calculation especially when it has commercial value like in this case. The graph clearly indicates that corn-ethanol has a positive net energy balance of 38,000 BTU/gal. This positive value for ethanol puts it in a sustainable technology category.

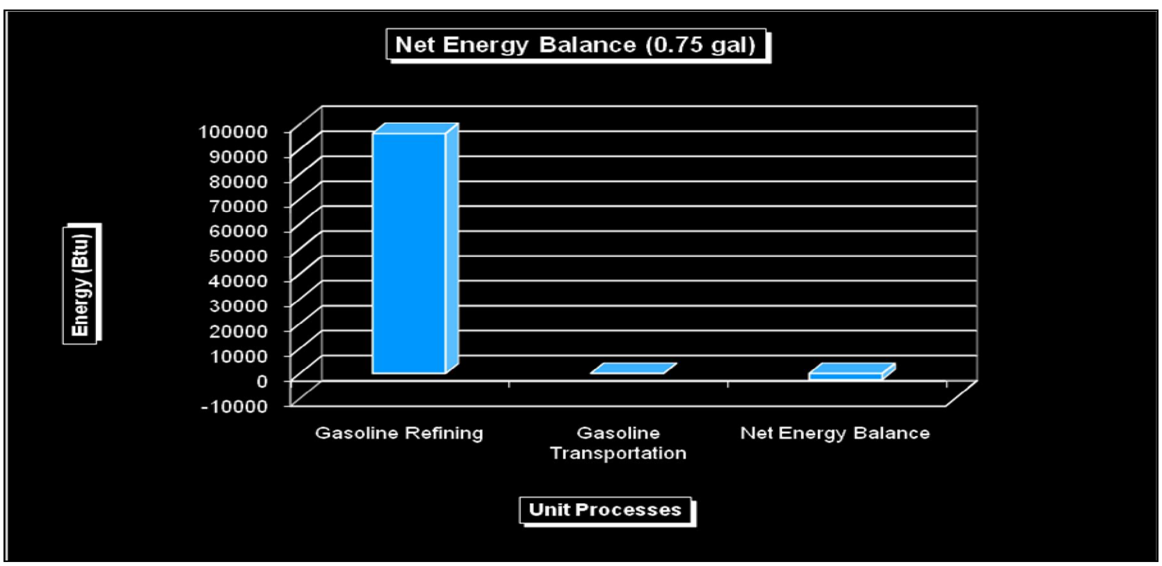


Figure 9: Net energy balance of gasoline

The energy balance for gasoline's life cycle is represented by the above graph. The only stages involved in gasoline's life cycle are refining and transportation. Clearly refining takes up about 99% of the energy use with the remaining accounted for by transportation. As indicated by the graph, the net energy balance for gasoline is marginally negative (-2479.4 BTU/gal) and makes it an unsustainable technology.

Economic Impacts:

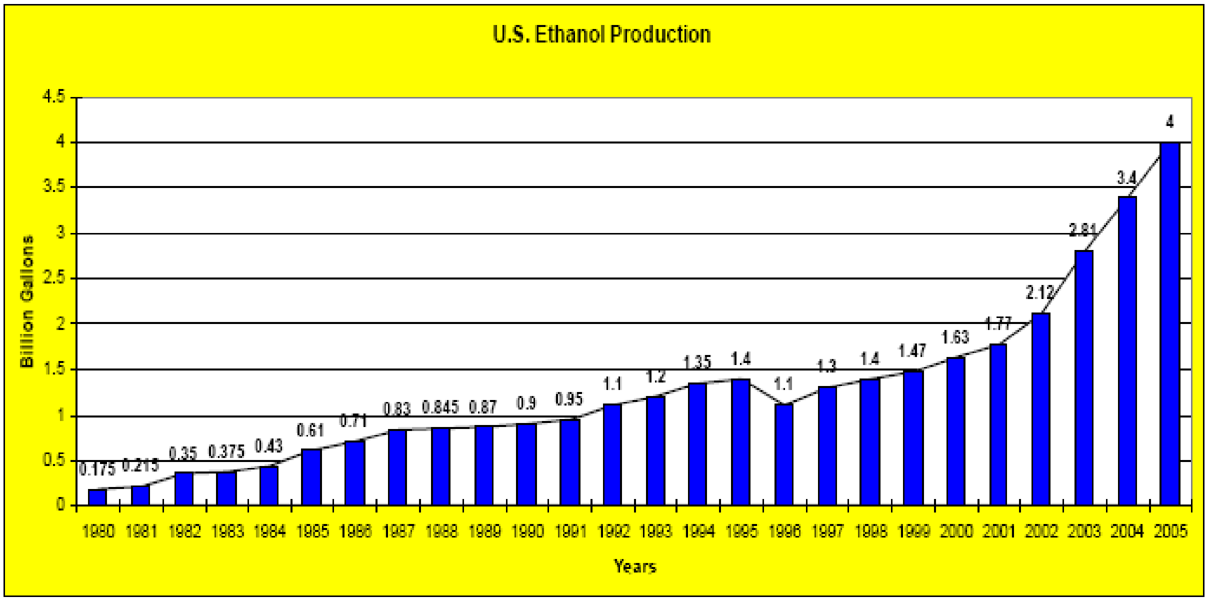


Figure 10: US Ethanol production

The rapid growth of ethanol industry in the US is depicted by the above figure. It can be seen that the ethanol industry grew from mere 0.25 billion gallons to more than 4 billion gallons in just 25 years. The growth was even steeper in the years between 2000 to 2005 mainly due to the heightened awareness about global warming and depleting oil resources. The ethanol production was about 2 billion gallons in 2002 and doubled itself to 4 billion gallons by 2005 with a 20% growth every year. This growth is expected to continue and reach 7.5 billion gallons by 2012. In 2005, 14.3% of the US corn harvest was used to produce 3.9 billion gallons of ethanol. Although the amount of ethanol produced from corn grain is increasing rapidly, it can displace only a small portion of the very large US market for gasoline. Devoting all US corn production to ethanol, it would only generate

12% of the US gasoline consumption. Clearly in this case, availability of crop land is a major limiting factor.

Another factor which is of concern is the amount of purified water required by the ethanol production plants. Approximately 3-5 gallons of water is required for every gallon of ethanol produced equating to about 50 million gallons of water for a 10 million gallon per year ethanol plant. Huge capital and infrastructure is required to purify such quantity of water. Added issue to this is the availability of such large quantities of water for commercial purposes. A typical ethanol plant that produces 50 million gallons of ethanol a year consumes 411,000 gallons of water a day, enough to supply an average Tampa household for more than four years.

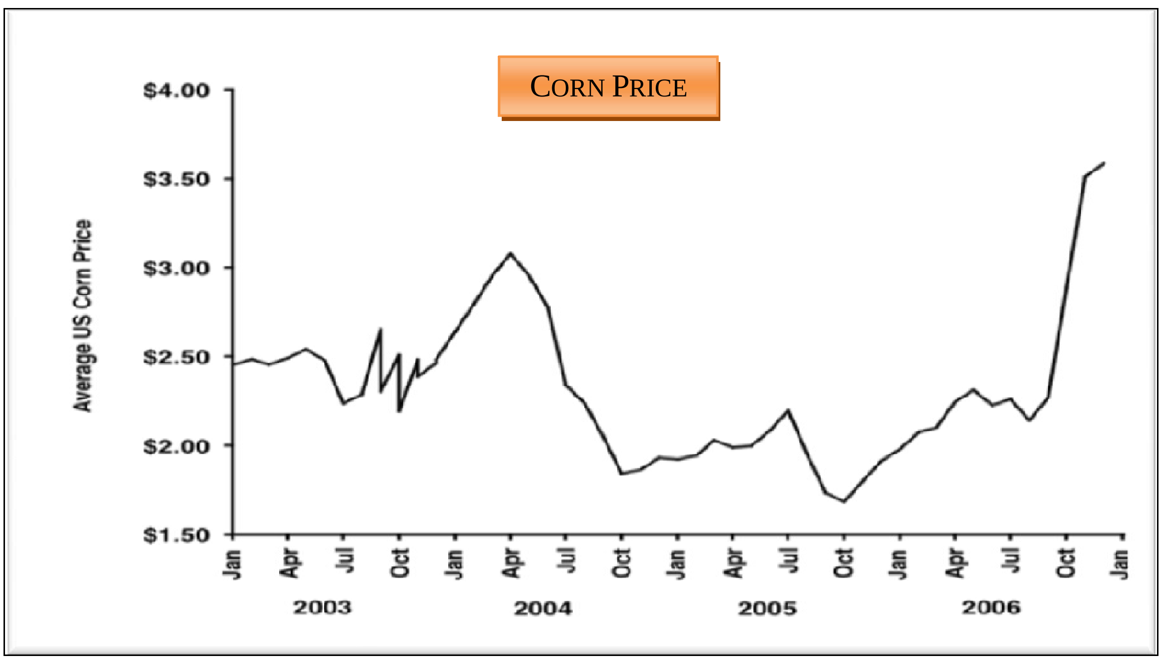
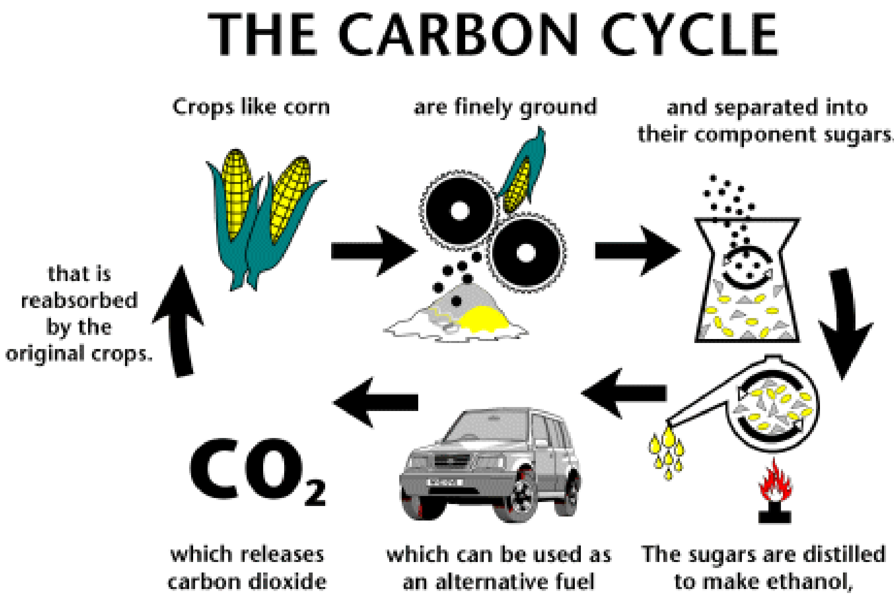


Figure 11: Average US corn prices

Corn prices have soared to the highest in a decade, mainly because skyrocketing demand for ethanol production is straining supplies. A swift increase in ethanol production has already led to sharp gains in corn prices. The higher prices will likely prove to be a boon for farmers who grow corn, which is used not only in a wide variety of food products for people, but also to feed hogs, chickens and dairy cows. On the other hand, the same rise in prices is proving taxing to the consumers. In Mexico, higher corn prices are the prime reason for skyrocketing tortilla prices, which have increased the country's inflation rate.

The impact of rising ethanol production is likely to go beyond corn. With prices for corn rising, farmers are expected to switch acreage to corn from soybeans, wheat and even cotton to cash in on the higher prices. That will lead to lower production for those other products and thus, higher prices.

Carbon Balance:



Carbon cycle basically defines the movement of carbon through the entire life cycle of a product. The carbon cycle for ethanol is shown in the above figure. It can be seen that the carbon dioxide which was sequestered by the corn plant for its growth is eventually put back completely or partly to the atmosphere closing the loop. The main difference lies in the amount sequestered and the amount emitted to the atmosphere since some carbon might be trapped or excess carbon introduced to the system by the intermittent processes.

Net Carbon Balance:

Net carbon balance indicates the difference between the amount of carbon released to atmosphere in various forms and the amount of carbon which is sequestered from atmosphere, during the entire life time of a product. The figures below indicate the net carbon balance for ethanol and gasoline.

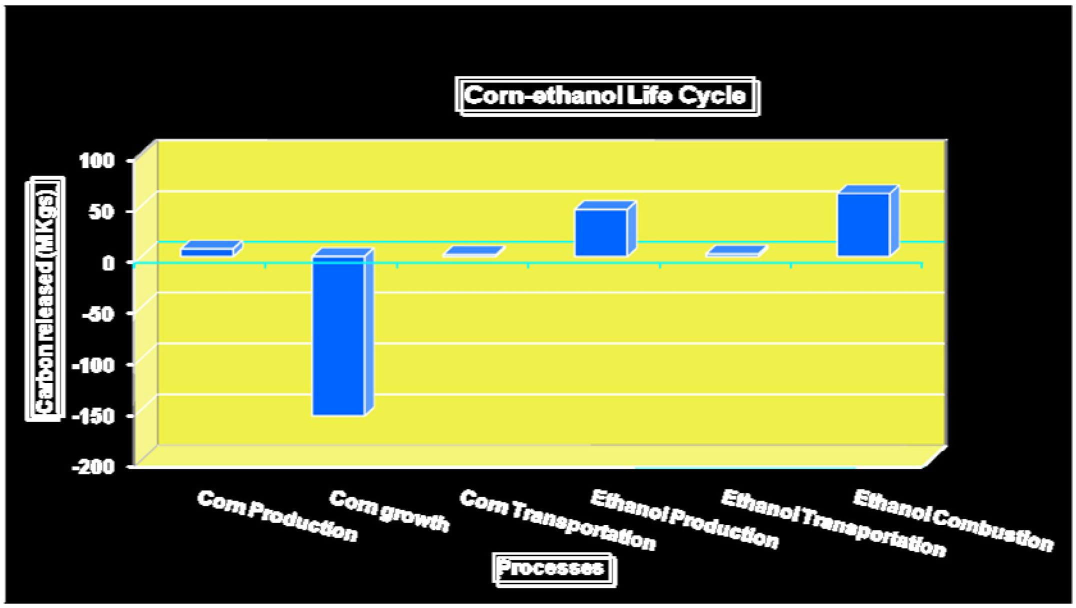


Figure 12: Carbon balance – ethanol

Each bar in the above figure indicates the total amount of carbon absorbed or released by the stages they represent. These bars are calculated by taking into account each and every process which contributes to the carbon content in that stage. It might be in the way of fuel combustion to run equipment or carbon content of the raw materials used in these processes. It is evident from the graphs that except corn growth all other processes or stages are net carbon emitters. The sole reason for corn growth stage to be a net energy absorber is due to photosynthesis, by the virtue of which the corn plant makes its food.

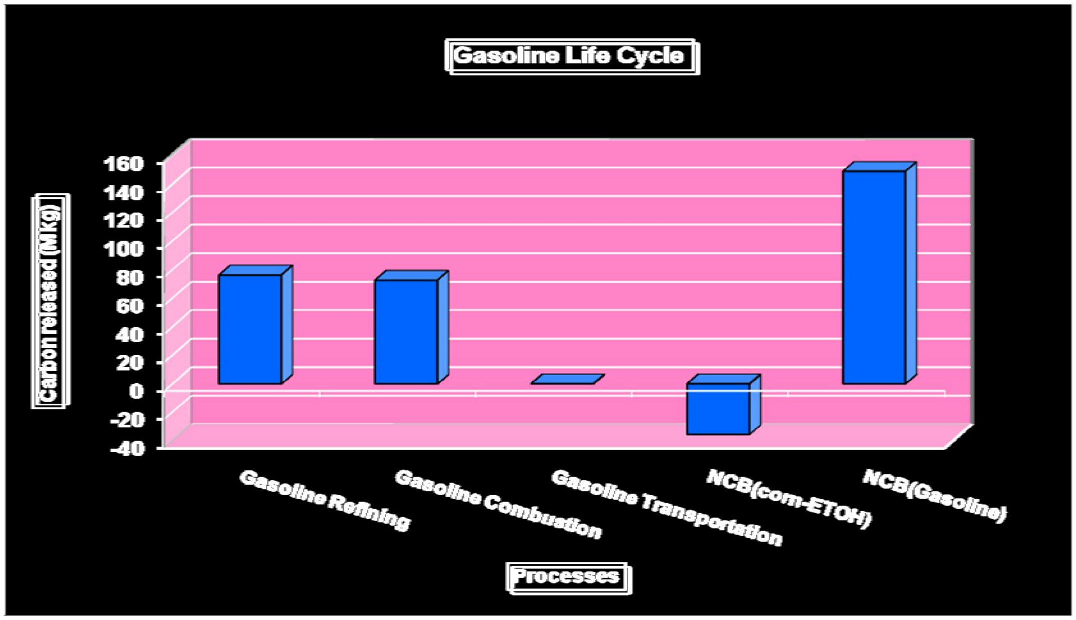


Figure 13: Gasoline & Ethanol, Net carbon balance

Evaluation of the net carbon balance of ethanol and gasoline leads to the conclusion that ethanol has a negative net energy balance which means that over the entire life cycle of the ethanol it absorbs more carbon than it releases to the atmosphere. This is a very big advantage from environmental point of view since it helps reduce the carbon load on the atmosphere. For gasoline, it has a huge positive net energy balance. This is due to the fact that there is no process in its life cycle which absorbs any amount of carbon making it environmentally undesirable. These characteristics of net carbon balance for ethanol and gasoline are indicated by the last two bars in the above figure.

Environmental Impact Contributions:

The following figures represent the environmental impact contributions of the various stages in corn-ethanol's life cycle. The environmental categories selected for this analysis are global warming, fossil resource and acidification. These categories fall among the top areas of concern right now and are hence chosen. This analysis helps to identify the processes within the life cycle of ethanol which are the major contributors in respective categories. This will eventually help to target the efforts towards these major contributing processes to improve environmental performance.

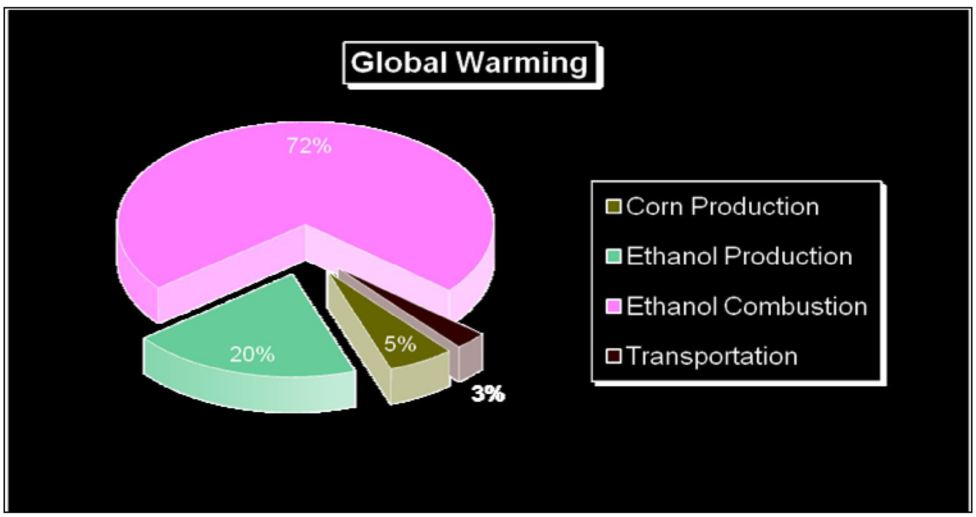


Figure 14: Process contributions to Global warming, Ethanol Life Cycle

The above figure shows the contribution of the 4 main stages in ethanol life cycle towards global warming. It can be seen from the figure that major contributors to global warming are ethanol combustion and ethanol production with ethanol combustion leading the list. Ethanol has comparatively more methane, formaldehyde and acetaldehyde in tailpipe emissions than gasoline. Work has to be done in the field of ethanol combustion in vehicles to bring about the much required reduction in global warming.

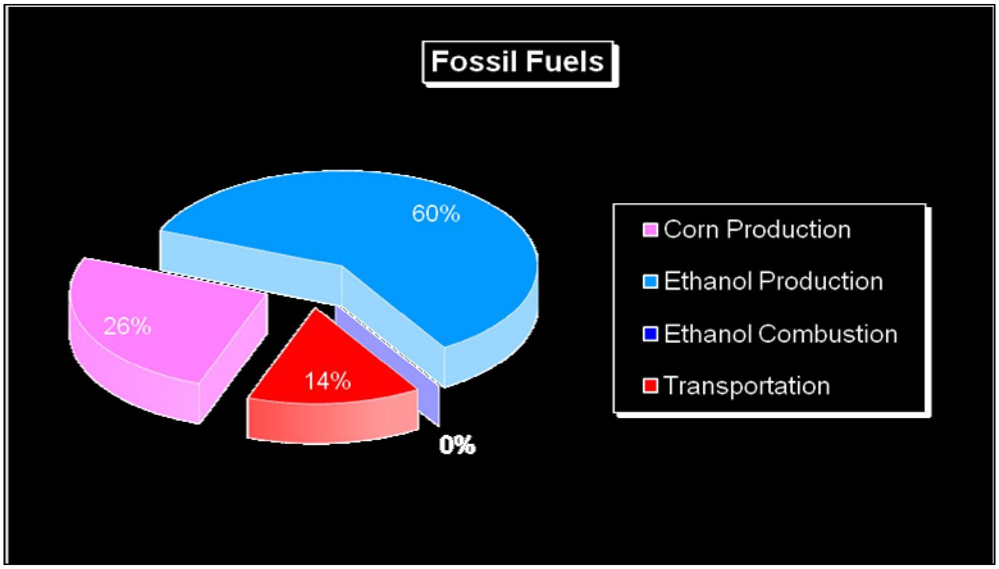


Figure 15: Process contributions in utilization of fossil resources, Ethanol Life Cycle

Ethanol production stage is clearly the top consumer of fossil fuels among all others. Use of heavy duty equipment for pumping, agitation and other operations which need high fuel supply justify the reason for ethanol production stage leading the rack. Within ethanol production itself, distillation and liquefaction are the major contributors accounting for 61% and 15.75% respectively. Another reason for high fuel consumption is the amount of purified water required for cooling and for boiler operation.

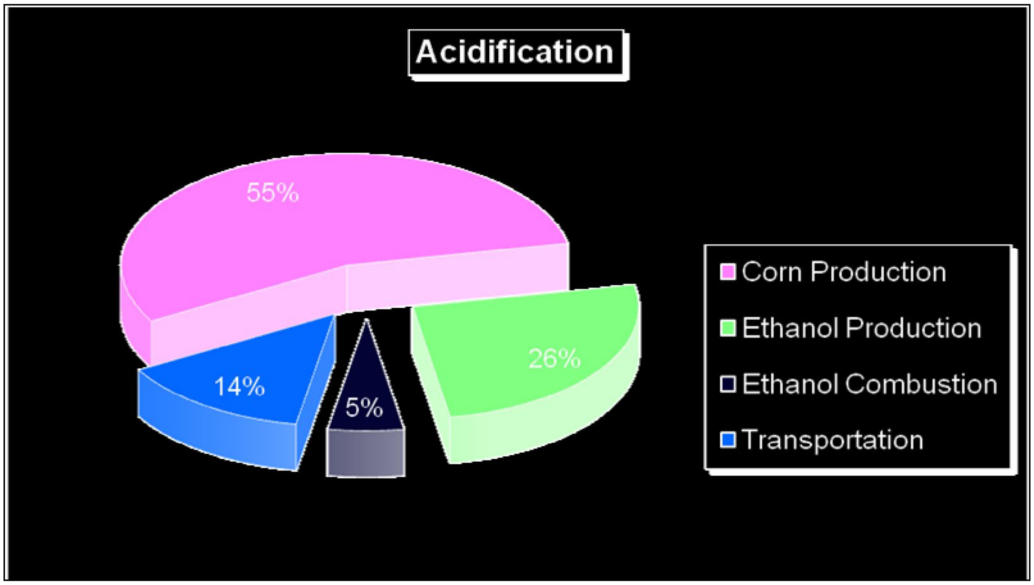


Figure 16: Process contributions to Acidification, Ethanol Life Cycle

Acidification as discussed earlier in this report, refers to the potential acid deposition in land, air and water causing damaging effects to the ecosystem. Heavy fertilizer and pesticide use make corn production top contributor in this category. The next major contributor in the list is ethanol production. The emission of carbon dioxide from burning fossil fuels is the main reason for the oceanic acidification, eroding the calcium in corals and other marine organisms. Extensive research is underway to come up with bionic seeds and other species of plants which require less fertilizer and pesticide while not compromising on the ethanol conversion rate. At the same time, research is also being focused on using more efficient equipment, reusing energy and employing sustainable energy sources like wind energy for ethanol production which would reduces global warming and acidification.

SWOT ANALYSIS

STRENGTHS:

- First and foremost advantage/strength of ethanol technology is that it utilizes abundant domestic supplies of coal and natural gas, and of course corn which is produced locally. This eliminates the need to import the very expensive crude oil for gasoline production. U.S has been heavily depending on crude oil imports for years and has been on a rising trend ever since.

Nixon Administration (1974)	37%
Ford Administration (1976)	42%
Carter Administration (1980)	41%
Reagan Administration (1988)	43%
Bush Administration (1992)	46%
Clinton Administration (2000)	58%
Bush Administration (2005)	66%

- The second strength in the ease of converting sugars to ethanol. This technology has been proven to very simple and efficient. The major hurdle new technologies are facing right now is the conversion of sugars in the new raw materials to ethanol. So, corn ethanol has an edge over other technologies in this regard.
- Ethanol has a high octane number which causes it to burn in a greener way, i.e. more efficiently causing less pollution. Ethanol was primarily used as an additive in

gasoline to increase its octane number for better combustion. Ethanol causes about 25-30% less global warming compared to gasoline due to its efficient combustion.

- Ethanol has a positive net energy balance indicating that it is a sustainable technology.
- Combustion of ethanol results in low carbon monoxide emissions. Large carbon monoxide exposures lead to significant toxicity of the central nervous system and heart. Carbon monoxide can also have severe effects on the fetus of a pregnant woman.
- Ethanol contains no sulphur and hence does not release any sulphur oxides as its combustion products. Sulphur oxide in air is one of the main reasons for acid rain which has devastating effects on aquatic life and historical monuments.

WEAKNESSES:

- One of the major areas of concerns is the heavy use of fertilizer and pesticide for corn production. It has been cited as the main reason for extensive eutrophication and acidification of water bodies.
- E85 fuel which is a blend of 85% ethanol and 15% gasoline has higher emissions of volatile organic vapors. Combustion of ethanol releases more organic vapors like acetaldehyde, formaldehyde compared to gasoline.
- Ethanol production as a whole has a huge water requirement. For average crop irrigation it takes about 785 gallons of water per gallon of ethanol and about 3-4 gallons of water per gallon of ethanol for dry-grind process. These totals up to a whooping 789 gallons of water per gallon of ethanol. This amount of water for commercial purposes competes in big way with domestic requirements.

- Another weakness of ethanol technology is that E85 fuel is not easily available all over the nation. Most of the ethanol plants are located around the corn fields i.e. in the Midwestern area and it takes a lot of infrastructure to make this fuel available everywhere. Unlike gasoline, ethanol can't be transported via pipeline since it picks up excess water and impurities along the line causing it to degrade. It has to be transported through trucks and barge making it very expensive.

OPPORTUNITIES:

- New technologies like cellulosic ethanol need much lesser amount of energy for ethanol processing. Once these newer technologies are proven they will open up avenues for reducing energy load and hence environmental impacts.
- Over the years, farming productivity has been continuously increasing. Corn grain yield has increased at a fairly constant rate of 1.6 bushels per acre per year since 1930 primarily due to improved genetics and production technology. Number of bushels of corn has risen from 40 bushels per acre in 1940 to 146 bushels per acre in 2003. This eventually corresponds to higher ethanol yields and improved environmental performance.
- Huge amount of water requirements for ethanol production process is one of the main areas of concern in corn-ethanol technology. Treatment and reuse of waste water produced is being experimented with. Success in this area could spell a major breakthrough.
- Alternative technologies to distillation such as pervaporation have the potential to significantly reduce water usage.

THREATS:

- One of the major threats to corn-ethanol technology is the non-availability of enough land for corn cultivation. By using the vast land set aside for conservation, we could partially overcome this limitation.
- Competition of ethanol technology with food products for raw material (corn) is also a significant threat.
- Another threat to this technology is the increasing price of corn. Heavy demand for corn due to rising ethanol production is driving the cost of corn out of the affordable range of common people.
- Limited infrastructure for ethanol distribution is also one another major threat to corn-ethanol technology.

CONCLUSIONS

Environmental:

Critics of corn based ethanol often say that it takes more energy to produce ethanol than we get from the resulting fuel. Over the years, the efficiency of both corn farming and ethanol production has dramatically increased resulting in a turnover of the results. Our analysis concludes that the NEV is positive when fertilizers are produced by modern processing plants, corn is converted in modern ethanol facilities, farmers achieve normal corn yields, and energy credits are allocated to co-products. We estimate a NEV of 39,062.87 Btu/gal for corn-ethanol and this does not include energy credits for plants that sell carbon dioxide. Corn ethanol is clearly energy efficient, as indicated by an energy ratio of 2.05 that is for every Btu dedicated to produce ethanol, there is a 105 percent energy gain. Moreover, producing ethanol from domestic corn stocks achieves a net gain in a more desirable form of energy.

Ethanol production utilizes abundant domestic energy supplies of coal and natural gas to convert corn into a premium liquid fuel that can replace petroleum imports. Even if the net energy ratio were less than one, ethanol production and use still displaces oil imports with domestic nonpetroleum energy, which is a major plus in terms of reducing our dependence on imported fuel.

Ethanol's reduction of global warming by 10-20% and utilization of only half the amount of fossil resources compared to gasoline substantially answers the top two challenges faced by the U.S. With a net energy gain and the benefits associated with its production namely, reduction in fuel imports and co-product utilization as animal feed, clearly corn ethanol turns out to be a promising alternative to gasoline. Though corn ethanol forms only a part of the solution in meeting our growing energy demands in a sustainable manner, coupled with emerging sustainable technologies like cellulosic ethanol, hydrogen energy, biodiesel etc., it can prove to be a nearly complete solution.

Economic:

Economically corn ethanol faces quite a number of challenges like:

- rising corn prices,
- increasing trend of ethanol production causing shift in farming to ethanol and scarcity of other products like sorghum, wheat etc,
- heavy infrastructure for ethanol production and transportation.

As the ethanol boom stabilizes, the price of ethanol and increasing trend should be reaching moderation. This will help in shifting the corn prices into more affordable range. Also the discovery of newer complimenting technologies will help in achieving this goal of reduced price at the much faster face.

A lot of research and success has also been achieved in the field of ethanol production and transportation which are among the major economic challenges faced by ethanol technology. Ways to transport ethanol economically through pipelines are being developed. So, in future we can expect to see corn ethanol leading the way in fuel sector not only environmentally but also economically.

SUGGESTIONS FOR ADDITIONAL WORK

Additional work in this area would involve:

- Parametric sensitivity analysis. It is very important to determine how the results change with minor changes in parameters and variables. Most of the variables and parameters used in the study are best known averages and the effect of deviation from these values should be well documented.
- Extend the work to LCA of E85 which is a blend of 85% ethanol and 15% gasoline. This project evaluates the impacts of 100% ethanol which forms a baseline study for analysis of other blends of ethanol fuels like E85, E15 etc. The commercial ethanol fuel used in vehicles is E85 and it is important to extend this study to E85 to understand the practical application of ethanol fuel in real world.
- Evaluate emerging energy crops against corn.
- Discovering new farming technologies which would yield more corn per acre and reduce the amount of fertilizer and pesticide use. Right now corn yield is a major limiting factor in determining sufficiency of corn ethanol for energy demands. So higher the yield higher the ethanol produced and better we are positioned to meet the demand.
- Improvement in the ethanol conversion technology to maximize ethanol output.
- Technologies to replace fossil energy use for running equipment during ethanol production stage with more environmental benign energy sources like wind energy. Fossil fuels are the major contributors to global warming in ethanol production stage. Use of renewable energy sources like wind energy can not only reduce green house emissions but also preserve the limited fossil reserves.

- Improvement in combustion system of vehicles which is a major source of greenhouse gas and acetaldehyde emissions. In comparison to gasoline, ethanol has higher acetaldehyde and formaldehyde emissions when burnt in vehicles. These emissions can be reduced by better designing the combustion system of the flex fuel vehicles.

Apart from the above mentioned additional work, researching new technologies which will support our goal of green engineering is also important. Few technologies which are in developmental stage and can prove to be futuristic sustainable technologies are mentioned below:

Cellulosic Ethanol

The starchy material in corn kernels now used to produce most of our ethanol is only a small fraction of the biomass – the plant based materials and waste products – that could be used. Two other components of plants, cellulose and hemicellulose, are also made of sugars, but those sugars are linked in long polymer chains that are not easy to convert to ethanol. Advanced biomass conversion technologies break down the polymer chains into their component sugars and then ferment them into alcohol to produce cellulosic ethanol. As end products, cellulosic and conventional ethanol are indistinguishable; gallon-for-gallon, both yield roughly two-thirds the energy of gasoline.

Cellulosic ethanol is attractive because it can be produced from a wide variety of cellulosic biomass feedstocks including wheat straw, corn stover, grass, and wood chips, which are cheap and abundant. Also, an acre of grasses or other crops grown specifically to make ethanol could produce more than two times the number of gallons of ethanol as an acre of corn, in part because the whole plant can be used instead of just the grain. This technology turns ordinary, low value plant materials such as corn stalks, sawdust and fast growing trees into ethanol and other valuable fuels and chemicals. Cellulosic ethanol could do much to reduce our dependence on imported oil and curb U.S greenhouse emissions. Corn-based ethanol provides 26 percent more energy than is required for its production, while cellulosic provides 80 percent more energy. Conventional ethanol reduces greenhouse-gas emissions 10 to 20 percent below gasoline levels, the reductions with cellulosic range from 80 percent below gasoline to completely CO_2 neutral.

The technology works – but it's still too expensive. Sugars in cellulose and hemicellulose are locked in complex carbohydrates called polysaccharides (long chains of monosaccharides or simple sugars). Separating these complex polymeric structures into fermentable sugars is essential to the efficient and economic production of cellulosic ethanol.

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APPENDIX

ASSUMPTIONS

- Functional unit: 40 million gallons of ethanol, equivalent to 30 million gallons of gasoline in terms of vehicle mileage.
- Energy for co-product (DDGS) is excluded from net energy calculations.
- Production process taken from SimaPro database. Underlying SimaPro database assumed reliable for this level of LCA.
- Operating power for agitators = 10 kJ/s.
- Steam used for heating purposes with 60% heat transfer efficiency.
- Natural gas used as fuel in steam generating boilers.
- Cooling water for cooling requirements.
- Thermal energy from burning of natural gas.
- Enzyme production is not energy intensive.
- CO2 emissions attributed to corn are not included. [carbon absorbed from environment is released back to it] --- fermentor (119270 kg of CO2).
- Gasoline gives 21 miles/gal and Ethanol gives 14 miles/gal. Ford Tahoe used as a test a vehicle.
- Transportation of 15 tons of corn per trip 60 miles away.
- Yield: 3.18 Mg / acre.
- Coal used to generate the required electrical energy.
- Diesel used in transport vehicles.
- Gasoline transportation - 100 miles pipeline between refining and fueling stations.

Estimating Net Energy Balance for Ethanol (40 M gals):

- Estimating energy for corn production (1000 lb)

  - Natural gas – 204 cuft = **208284 BTU**

    (1 cuft – 1021 BTU)

  - Gas, natural – 9.2 lb = **185296.02 BTU**

    1 kg – 46.8 MJ --- (ref: SimaPro)

  - Coal – 1.28 lb = **13282.56 BTU**

  - Gasoline – 0.0017 gal = **210.7592 BTU**

  - Diesel – 0.63 gal = **87375.33 BTU**

  - Electricity – 3.09 KWh = **10543.08 BTU**

  - RFO – 0.29 gal = **4292 BTU**

    1 gal = 148000 BTU

  - DFO – 0.0066 gal = **910.8 BTU**

    1 gal = 138000 BTU

  - Trailer diesel – 1.36 tmi = **1944.65 BTU**

    155319 tkm – DFO [1000 gal] --- (ref: SimaPro)

  - Diesel locomotive – 6.96 tmi = **2540.95 BTU**

    608333 tkm – DFO [1000gal] – (ref: SimaPro)

  - Ocean Freighter – 5.35 tmi

    768421 tkm – DFO [53 gal]

RFO [947 gal]

DFO = **81.952 BTU**

RFO = **1570.42 BTU**

- Barge – 1.35 tmi

521429 tkm – DFO [714 gal]

RFO [286 gal]

DFO = **410.55 BTU**

RFO = **176.366 BTU**

- Pipeline natural gas – 0.73 tmi = **1889.61 BTU**

1460 – Nat. gas eq. 2300 cuft ---- (ref: SimaPro)

- Pipeline petrochemical – 0.32 tmi = **26.47712 Btu**

1460 tkm – 22 KWh ---- (ref: SimaPro)

- **Total energy consumed (1000 lb) = 518835.5243 BTU**
- Net energy consumed for ***358.2 M Kg*** of corn = **409722.2461 M BTU**
- Energy per gal **= 10268.73 BTU**

➢ Estimating energy for corn transportation

- Transportation of 15 tons of corn per trip 60 miles away.
- 15tons-60miles ---- 900 ton-mile = 1448.4096 tkm
- Total corn to be transported = 358.244 million kg
- Total tkms for corn transportation = 38131059.13 tkm
- Truck Diesel - 38131059.13 tkm = **95511.057 M BTU**
- Energy per gal **= 2393.8 BTU**

- <u>Estimating energy for ethanol conversion</u>

  Feed rate: 45200 kg/hr of corn

  - Hammer Mill

    Specific power = 0.0068 KJ/s per Kg/hr feed

    Electrical energy consumed = 8737158 MJ/yr

  - Slurry Mix tank

    Slurry recirculation pump operating power = 14.493 KJ/s

    Slurry tank residence time = 0.25 hr

    Energy consumed by recirculation pump = 413220 MJ/yr

    Energy required by agitator = 10 KJ/s

    = 285120 MJ/yr

    Electrical energy consumed = 413220 + 285120 = 698344.4 MJ/yr

  - Liquefaction tank

    Liquid heating requirement = 17007009.59 KJ/h

    = 134700000 MJ/yr

    Steam required = 83.91 M kg/yr

    Energy required by agitator = 10 KJ/s

    = 285120 MJ/yr

    Electrical energy consumed = 285120 MJ/yr

- Saccharification tank

  Energy required by agitator = 10 KJ/s

  Electrical energy consumed = 285120 MJ/yr

- Fermentors: (6 tanks)

  Energy required by recirculation pump = 0.01 KJ/s per pump

  Electrical energy consumed = 1720.98 MJ/yr

- Molecular sieve

  Recirculation pump power requirement = 0.744 KJ/s

  Electrical energy consumed = 21212.9 MJ/yr

- Whole stillage tank

  Operating power for agitator = 4.76 KJ/s

  Electrical energy consumed = 135717.12 MJ/yr

- Process condensate tank

  Process condensate pump power requirement = 11.196 KJ/s

  Electrical energy consumed = 319220.352 MJ/yr

- DDGS dryer

  0.06 Kg natural gas per Kg of water evaporated

  Final product = 119 M kg/yr DDGS with 9.9 % water

Total energy required = 521195.25 MJ/yr

Natural gas consumed = 10.5804 M Kg/yr

- Thermal oxidizer = 23641.44 MJ/yr

- Centrifuge, Wet DDGS conveyer, Misc = 63788286.22 MJ/yr

- Steam requirements = Beer , Rectifier, Stripping Column + Liquefaction

  = 199.15 + 83.91

  = 283.07 M kg/yr

- LIMESTONE

  Feed rate: 54kg/h

  Working days in a year = 330 days

  Per year limestone consumption = 427680 kg

- AMMONIA

  Feed rate = 90 kg/hr

  Per year consumption = 712800 kg

- Total electricity consumed – 21.26 M KWh = **72539.12 M BTU**
- Total natural gas consumed – 11.15 M kg = **549170.95 M BTU**
- Total steam consumed – 295.901 M kg = **741721.9931 M BTU**

- Total energy consumed **= 1363432.063 M BTU**
- Energy per gal **= 34,171 BTU**

➢ Estimating energy for ethanol transportation

- Energy to transport 1 gal of ethanol to refueling stations – 3173 BTU (Reference: http://www.ethanol-gec.org/corn_eth.htm)
- Total energy consumed for transporting 40 M gal of ethanol **– 126321.26 M BTU**
- Energy per gal **= 3165.9 BTU**
- 1 gallon of diesel = 139,000 BTU
- Diesel required to transport ethanol = **910810.79 gal = 2907.31 tons**

❖ **Total energy consumed for 40 M gal of ethanol and 40 M kg of DDGS:** 409722.2461 M BTU + 95511.057 M BTU + 1363432.063 M BTU + 126321.26 M BTU **= 1994986.6 M BTU**

❖ **Total energy consumed per gal of ethanol = 49999.7 BTU**

❖ LHV: Low heat value --76,000 Btu per gallon of ethanol.

❖ **Net energy balance (w/o co-product allocation)** = 76000 BTU – 50440.79 BTU

= **25,559.2 BTU/gal**

- **Ethanol production (w/o dryer for DDGS production)**

- ***Ethanol production***

  - Total electricity consumed **–** 21.26 M KWh = **72539.12 M BTU**
  - Natural gas **–** 0.568 M kg = **27975.704 M BTU**
  - Total steam consumed – 295.901 M kg = **741721.9931 M BTU**
  - Total energy consumed **= 842236.81 M BTU**
  - Energy per gal **= 21108.7 BTU**

- **Total energy for 40 M gal of ethanol = 1473791.373 M BTU**
- **Total energy consumed per gal of ethanol = 36937.13 BTU**
- **Net energy balance (with co-product allocation) =** 76000 BTU – 36937.13 BTU

  = **39,062.87 BTU/gal**

Estimating Net Energy Balance for Gasoline (30 M gals):

- <u>Gasoline extraction and refining</u>
  - Coal = 3.3 M lbs = **34244.1 M Btu**
  - Gas, Natural = 13.59 M lbs = **273714.44 M Btu**
  - Crude oil = 195.27 M lbs = **3526658.04 M Btu**

    [42 MJ/ kg; ref: SimaPro]
  - Uranium = 13.5 lbs = **13296.998 M Btu**

    [2291 GJ/ kg; ref: SimaPro]
  - Wood = 0.1395 M lbs = **569.87 M Btu**
  - Total energy input **= 3848483.488 M Btu**

- <u>Gasoline Transportation</u>
  - 100 miles pipeline between refining and fuel station
  - Gasoline Transportation = 13472027.84 tkm

    [1460 tkm – 22 KWh; ref: SimaPro]
  - Energy required to transport gasoline = **692.65 M Btu**

- **Total energy from gasoline (30 M gal) = 3849176.138 M gal**

  [1 gal of gasoline = 125,000 Btu]

- **Net energy balance of gasoline** = 3719280 – 3849176.138 M Btu

  = - 129896.138 Btu

- Net energy ratio = **0.97**

Estimating carbon balance for Ethanol (40 M gals):

- <u>Estimating carbon used for corn production</u>

  - Natural gas = 6567047.049 kg

    Carbon content = **4219333.96 kg**

  - Corn seed = 537366 kg

    32.04% grain = carbon

    [ref: bio.net]

    Carbon content = **172172.0064 kg**

  - Limestone = 6018499.2 kg

    100 kg of limestone – 12 kg of carbon

    Total carbon content = **722219.904 kg**

  - Coal = 1010934.818 lb

    60% of coal (weight basis) – carbon

    [ref: EIA.doe]

    Carbon content = **268660.95 kg**

  - DFO = 5212.63 gal

    Gallon of DFO = 138000 Btu

    5212.63 gal = 0.72 billion Btu

    19.95 metric tons of carbon – per billion Btu DFO

    [ref: carbon content of fuels]

    Carbon content = **14350 kg**

  - RFO = 22903.992 gal

    Gallon of RFO = 148000 Btu

    22903.992 gal – 3.39 billion Btu

    Carbon content = **72850 kg**

- Gasoline = 1342.65 gal

  Gasoline carbon content – 2.421 kg per gal

  [ref: EPA]

  Carbon content = **3250.56 kg**

- Diesel = 497569.5 gal

  Diesel carbon content – 2.788 kg per gal

  Carbon content = **1382248.071 kg**

- Electricity = 2440459.834 KWh

  2000 lb of coal – 2500 KWh electricity

  Total coal required = 1952367.867 lbs

  Carbon content in 1952367.867 lbs coal = **520877.44 kg**

- Trailer Diesel = 1074118.244 tmil

  1074118.244 tmil – 1117.14 gal of Diesel

  [1000 gal – 155319 tkm; ref: SimaPro]

  Carbon content = **30911.2 kg**

- Diesel Locomotive = 5496958.072 tmil

  5496958.072 tmil = 14539.08 gal of diesel

  [1000 gal – 608333 tkm; ref: Simapro]

  Carbon content = **40389.58 kg**

- Ocean freighter = 4225391.622 tmil

  DFO = 442.38 gal, RFO = 8405.187 gal - 4225391.622 tmil

  [ref: SimaPro]

  Total carbon content = **27940.77 kg**

- Barge = 1066220.316 tmil

  RFO = 2335.96 gal, DFO = 690.92 gal - 1066220.316 tmil

  [ref: SimaPro]

  Carbon content = **8628.63 kg**

- Pipeline natural gas = 576548.76 tmil

  576548.76 tmil = 1461393.15 cuft natural gas

  [2300 cuft natural gas - 1460 tkm; ref: SimaPro]

  Carbon content in 1461393.15 cuft natural gas = **21590.43 kg**

- Pipeline petrochemical = 252733.7045 tmil

  252733.7045 tmil = 6127.581 KWh

  [22 KWh – 1460 tkm; ref: SimaPro]

  Carbon content in 6127.581 KWh = **1307.84 kg**

- **Total carbon released due to corn production = 7.51 M kg**

➢ <u>Estimating carbon sequestered during corn growth</u>

- Corn required = 358244000kg
- Carbon content = **156194384 kg**

➢ <u>Estimating carbon used for corn transportation</u>

- Truck diesel = 38131059.13 tkm

  38131059.13 tkm = 692109.1068 gal of Diesel

  [1000 gal = 55094 tkm; ref: SimaPro]

  Carbon content in 692109.1068 gal of Diesel = **1922679.1 kg**

➢ <u>Estimating carbon used for ethanol conversion</u>

- Centrifuge, Misc = 17560000 KWh

  Carbon content = **3747903.428 kg**

- Fermentor = 478051.2 KWh + CO2 released due to fermentation

  Carbon content for 478051.2 KWh = 102032.06 kg

  $$C_6H_{12}O_6 (s) \longrightarrow 2\ CO_2 (g) + 2\ C_2H_5OH (l)$$

  According to stoichiometry,

  119 M kg of ethanol $\longrightarrow$ 113.8 M kg CO2

  Carbon content in 113.8 M kg CO2 = 31.04 M kg

  Total carbon content = 102032.06 + 31.04 M kg

  = **31142032.06 kg**

- Liquefaction = 79200 KWh + 134699516 MJ nat. gas

  Carbon content = 16903.92 + 1849242.881

  Total carbon content = **1866146.801 Kg**

- Molecular sieve = 5892.47 KWh

  Carbon content = **1257.65 kg**

- Process condensate tank = 88672.32 KWh

  Carbon content = **18925.63 kg**

- Saccahrification tank = 79200 KWh

  Carbon content = **16903.92 kg**

- Slurry mix = 193984.56 KWh

  Carbon content = 41402.77 kg

  Lime = 594660 kg

  [100 kg lime – 12 kg carbon; weight basis]

  Carbon content = 71359.2 kg

  Total carbon content = **112761.97 kg**

- Thermal oxidizer

  Natural gas = 23760000000 BTU

  Carbon content = **343807.2 kg**

- Whole stillage = 37699.2 KWh

  Carbon content = **8046.27 kg**

- Distillation

  Natural gas = 498752312800 BTU

  Carbon content = **7216945.97 kg**

- Hammer mill = 2426988.3 KWh

  Carbon content = **518000.201 kg**

- **Total carbon released due to ethanol production = 44.99 M kg**

➢ Estimating carbon used for ethanol transportation

- Diesel = 2907.31 tmil = 910810.79 gals of Diesel

  Carbon content = **2530232.375 kg**

➢ Estimating carbon released from ethanol combustion

- 40 gals of ethanol

  [46 kg of ethanol – 24 kg of carbon; weight basis]

  Carbon content = **62.1 M kg**

Total carbon used/released from corn-ethanol process (excluding carbon sequestered during corn growth) = 119.03 M kg

Carbon sequestered during corn growth = 156.2 M kg

Net carbon balance for Corn-ethanol = -37.17 M kg

Estimating carbon balance for Gasoline (30 M gals):

- Gasoline extraction and refining
  - Coal = 3.3 M kg

    [60% of coal – carbon]

    Carbon content = **876991.401 kg**

  - Natural gas = 13.59 M lb

    Carbon content = **3960.65 kg**

  - Crude oil = 195.27 M lb

    [Carbon share – 85%; ref: carbon in crude oil]

    Carbon content = **75.29 M kg**

  - Limestone = 0.1914 M kg

    [100 kg of lime – 12 kg carbon, weight basis]

    Carbon content = **10418.11 kg**

  - Total carbon released due to gasoline production = **76.1844 M kg**

- Gasoline transportation
  - 100 miles pipeline between refining and fueling stations

    Carbon content = **43327.13 kg**

- Gasoline combustion
  - 30 M gals of gasoline

    [2.421 gm of carbon per gallon of gasoline]

    Carbon content = **72.63 M kg**

Total carbon balance for Gasoline = 76.1844 + 43327.13 + 72.63

= 148.86 M kg